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Experimental Investigation on Surface Characteristics of Finish Hobbed Gear using Grey Relational Analysis

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Abstract:

Introduction: Spur gears are important for transferring motion and power among shafts. The surface characteristics of these gears are important for their life and smooth operation. To improve profitability and customer satisfaction, a study was conducted to analyze the surface quality of spur gears produced through CNC hobbing machining.

Objectives: The objective this investigation is to conduct experimental trials to estimate the best hobbing parameters to minimize surface roughness and microgeometric deviations. In this investigation, effect of varying cutting speed and feed rate on surface finish have been reported.

Methods: An experiment are conducted according to Taguchi L9 experimental design. Grey Relational Analysis is performed to estimate the optimum machining parameters.

Results: The experimental finding reveals, at cutting speed 400 rpm, the feed rate 8 mm/min, and depth of cut 3.91 mm gives good quality of surface (Ra 0.5530). The gear hobbing process has increased to a greater level of performance. The roughness of the flank surface and microgeometry deviations decreases with an increase in hob cutter speed.

Conclusions: This ultimately reduces the inherent vibrations between the hob cutter and the gear blank, thus minimizing microgeometric deviations. The variation in feed rate was noticed and had a very significant impact on the efficiency and surface quality of the gear. The study recommends that a cutting speed of 400 rpm is the most effective for obtaining the best results.

Keywords: Surface Roughness, Microgeometric Deviations, Optimization, Taguchi-Grey Relational Analysis, Manufacturing Processes.

1. Introduction

Gears are essential machine components that transmit power and speed between rotating shafts in machines and vehicles. Spur gears, helical gears, bevel gears, and worm gears are among the most common gear types. Spur gears are often utilized for high-speed and low-torque applications [1]. They are easy to manufacture and commonly available in a variety of sizes [2]. The quality of spur gear teeth is important to their performance since imperfections can cause noise, vibration, and wear [3]. Different tooth profiles and pressure angles can be used to improve load-bearing capacity and efficiency in specific applications [4].

The effect of the hob on the surface of the teeth on spur gears should be considered at the time of gear design The hobbing process parameters can affect the surface finish and accuracy of gear teeth, impacting their performance and durability [5], [6], [7]. The fatigue resistance of machined components is indeed influenced by both the surface finish and the residual stress. It has been proven that a superior finish and compressive stress have a positive impact on the lifespan of these components [8]. Optimizing gear surface smoothness can reduce micropitting damage, but may shorten the pitting life [9]. Manufacturers can prevent costly downtime and repairs by regularly evaluating and optimizing hobbing processes to detect and address potential issues before they become major problems. This proactive approach contributes to cost savings and improved product quality. Surface roughness measurements have to be performed to ensure that the desired surface finish has been achieved [10]. The ASP2052 Hob is example of a high-speed hobbing tool that can produce excellent surface characteristics. Several parameters are important to determine the surface quality of gears. One such parameter is average roughness, Ra, which is the mean of the absolute values of the profile heights measured across the entire evaluation length [11]. Another significant parameter is the maximum height of the profile, or Rt, which refers to the vertical distance between the highest and lowest points of the profile within the evaluation length [11], [12]. Microgeometric deviations are used to measure gear accuracy and quality. These deviations include irregularities in the form and position of teeth. These are defined by runout error and pitch error related to the real tooth location, as well as profile error and lead error with the actual form of the teeth. Form deviations, also known as profile deviations and lead deviations, are variations in the contour and inclination of the lead form line of teeth. Radial runout is the largest variation in the positioning of gear teeth in the radial direction estimated about the nominal position, whereas location deviations, or accumulated pitch deviations, are variations in the sum of ideal pitches and practical pitches throughout each of the teeth. The degree of inaccuracy in these factors affects the operating characteristics of the gear. Pitch (Fp) and radial runout (Fr) errors have effects on the transfer of motion and gearbox accuracy, respectively; profile (Fa) and lead (Fβ) errors have an impact on the origination of noise and the gear strength. Surface roughness characteristics such as average roughness (Ra) and maximum roughness (Rmax) govern both the service life and the workable performance of a gear. Understanding the causes of errors in spur gears during manufacturing is essential, as these errors can have a detrimental effect on gear performance. Therefore, it is necessary to manufacture good-quality gear. It needs an error-free shape to improve speed, power, and torque transmission without loss. Microgeometric deviations or errors in gears are classified based on their impact on location and form. Form errors are responsible for the capacity for carrying loads and noise-producing properties. Errors in location have an undesirable effect on transferred performance and the transfer of motion properties of gear. Fig.1 shows various deviations and its effect.

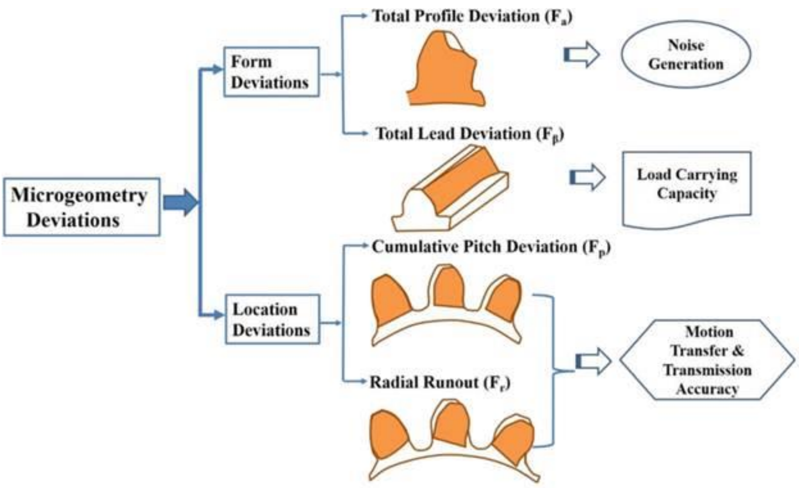


Fig.1. Types of microgeometric deviations in Gear [13].

Keche and Gajhas [14] carried out a study that compared the durability of gears made from AI-SiC material with those made from 20MnCr5 material. Their findings showed that the former was more durable. Klocke et al. [15] used ANSYS tools to analyze tool wear behavior and chip-forming characteristics to optimize the gear manufacturing process. Moru and Borro [16] introduced Vision2D, an enhanced machine vision program that can improve quality control and optimize inspection processes. The purpose of this research was to examine the effect of hobbing factors on the surface quality of spur gears, particularly under high-speed conditions and with a constant single depth of cut. To improve the surface characteristics, a single depth of cut was recommended for hobbing, which required a larger cutting force and high-speed rotation of the hob cutter. When optimizing cutting speed and feed parameters, it is important to balance the desired outcomes with potential tool wear, decreased tool lifespan, and minimum surface roughness and microgeometric deviations of teeth. Furthermore, research on minimizing surface characteristics in hobbing can contribute to the development of advanced manufacturing techniques and processes, resulting in cost savings and improved competitiveness for companies in these industries [17]. While the optimization of gear hobbing parameters to improve the surface quality of spur gears holds significant potential, there is a noticeable research gap in understanding the specific influences and interactions of these parameters on surface characteristics.

Previous studies are mainly focused on conventional gear hobbing processes. With the increasing demand for high-speed gear applications, gear hobbing factors affect the surface quality. Investigation on gear hobbing processes with a single, constant depth of cut is not reported in the literature. This study provides new insights into the improvement of the surface quality of spur gears using CNC hobbing machining. Previous research on the surface quality of spur gear produced through CNC gear hobbing is not enough to satisfy the influence of process parameters on surface quality.

The objective this investigation is to conduct experimental trials to estimate the best hobbing parameters to minimize surface roughness and microgeometric deviations. The impact depth of cut with different process parameters on surface quality is also reported. The findings may help improve the performance of high-speed gear manufacturing systems by reducing noise and enhancing tooth accuracy and life. This information could lead to improvements in gear design and performance across a variety of industries.

2. Materials and Methods

2.1. Pre-experimentation Stage

Optimisation of the CNC hobbing process should produce high-quality gears. The Shobber 300-gear hobbing machine as shown in Fig. 2 was employed in this work to produce gears with a module of 1.75 mm and a workpiece diameter of 140 mm, although it can manufacture gears with a maximum module size of 6 mm and a workpiece diameter of 300 mm. The machine is highly capable of performing complex, delicate and precise gear-cutting operations at high spindle speeds. It is also equipped with a coolant system that contributes to dissipate heat and enhancing tool life, resulting in improved cutting efficiency and reduced downtime for cooling. Operators are easily able to set parameters such as feed rates, tool paths, and cutting depths through the user-friendly control panel. This leads to accurate machining results without the need for extensive training or manual adjustments. The machine is CNC-controlled, which ensures precise and accurate machining.

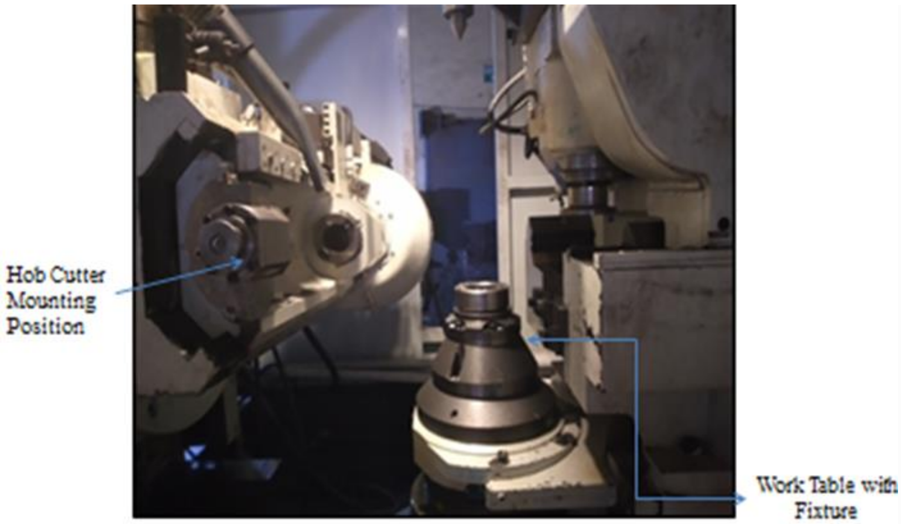


Fig 2. Shobber 300 Gear Hobbing Machine

The ASP2052 hob cutter as used in this work is well known for its exceptional durability and performance as shown in Fig 3[18]. Its chemical composition, as shown in Table 1, ensures high hardness and wear resistance .Moreover, the specifications outlined in Table 2 guarantee precise and efficient machining, resulting in quality finished products. The pressure angle of the hob cutter is 20 degrees with a module of 1.75 mm. The modules of hob and gear to be cut should be the same.

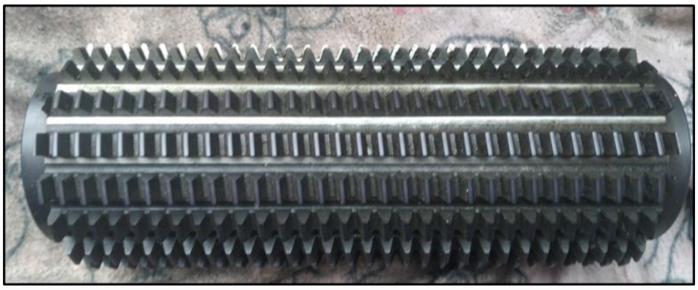


Fig 3.ASP2052 Hob Cutter

Table 1.Chemical Composition of Hob Cutter [19]

Chemical Composition	C	V	W	Co	Mo	Cr
ASP2052	1.6	5.0	10.5	8.0	2	1.8

Table 2. Specifications of Hob Cutter

Sr No	Data Type	Specification
1	Material	ASP2052
2	Pressure Angle	20^{0}
3	Number of Start	3
4	Number of gashes	17
5	Helix angle	$4^{0}31"$
6	Number of Teeth in one gash	30
7	Module mm	1.75
8	Diameter of Hob mm	70

Table 3 includes detailed design specifications for spur gear, including the number of teeth, root diameter, outside diameter, module and pressure angle etc. It is essential to ensure that these specifications should align with the hob cutter used to cut the gear. Hob cutter and the spur gear to be cut should have the same module to start cutting operation. Table 4 displays information on the chemical composition of the material used to produce the spur gear, which was the carbon alloy steel 20MnCr5.This material has excellent durability, strength and wear resistance [20]. It is suitable for high-demand applications that require a high level of toughness and resistance to wear and tear.

Table 3. Details of Spur Gear

Sr No	Data Type	Specification
1	Material	20MnCr5
2	Pressure Angle (Degree)	20^{0}
3	Root Diameter(mm)	131.08
4	Outer Diameter(mm)	138.9
5	Pitch Circle Diameter (mm)	134.75
6	Number of Teeth	77
7	Module mm	1.75
8	Actual Depth of teeth (mm)	3.91

Table 4.Chemical Composition of Spur Gear Material [20], [21], [22]

Chemical Configuration	C	Mn	Si	S	P	Cr
20MnCr5	0.17-0.22%	1.10-1.40%	≤0.40%	≤0.035%	≤0.035%	1.00-1.30%

2.2 Blank Preparation:

The preparation of blanks for gear involved several steps. First, the raw material, usually 20 MnCr5 bars of 140 mm diameter, was selected and inspected for quality as per drawing. Then, the material was cut into the desired shape and size using a saw-cutter machine. The raw blanks were drilled and machined through rough turning. After that, the blanks were heat treated to improve their strength and durability by a normalizing process. The heat-treated blanks were then subjected to a hard-turning machining process. The blanks were finished by a hard-turning machining process to achieve precise dimensions and smooth surfaces, which were ready to be used in gear manufacturing, as shown in Fig. 4. This process ensured that the gear blanks had the desired strength and hardness.

Fig 4. Blank for Spur Gear Manufacturing

2.3 Selection of Process Parameters

The cutting speed and feed rate were determined as input parameters in this research to optimize gear hobbing. The rate at which the hob rotates is known as the cutting speed, and the rate at which it enters the workpiece is known as the feed. These two factors are important in achieving optimum gear productivity as well as quality. Different methods of hobbing, such as conventional hobbing or climb hobbing, can affect the cutting speed and feed rate. While the conventional hobbing procedure involves the downward movement of the hob, climb hobbing is the opposite, with the hob moving in an upward direction. In general, conventional hobbing creates a superior finish, but climb hobbing produces a longer tool life. The conventional hobbing procedure is mostly recommended on CNC hobbing machines. In this work, conventional hobbing with a constant depth of cut was used to ensure consistent gear tooth profiles. The optimal working ranges of these process parameters were decided, ensuring effective gear-hobbing operations by carrying out pilot experiments. The relationship between cutting speed, feed, and gear tooth surface quality was discussed and analyzed through Taguchi-Grey relational analysis (TGRA). TGRA allows for the determination of the most influential process parameters and their optimal levels, leading to improved gear hobbing performance and surface characteristics of teeth. Taguchi orthogonal array L9 was used to generate the experimental design, which was composed of two factors as well as three levels.

Table 5. Hobbing Process factors along with levels

Factors	Level One	Level Two	Level Three
Cutting Speed, N (rpm)	300	350	400
Feed rate, f (mm/min)	8	10	12

Table 5 reveals hobbing process factors and levels, which include the cutting speed (N) in rpm and the feed rate (f) in mm/min. In the research, the cutting speed was varied between three levels: 300 rpm, 350 rpm, and 400 rpm. On the other hand, the feed rate was adjusted at three levels: 8 mm/min, 10 mm/min, and 12 mm/min. By altering these parameters, it is possible to examine the impact of different cutting speeds and feed rates on the gear hobbing process. The experimental investigation was carried out with a single depth of cut of 3.91 mm to assess the effects of these factors on the surface characteristics of gear teeth manufactured on the Shobber SH-300 Gear Hobbing Machine at Sarvesh Engineering, MIDC Waluj, Chhatrapati Sambhajinagar, Maharashtra, India. CNC Shobber Pfauter SH-300 Gear Hobbing Machine with a work fixture and hob cutter mounting position is shown in Fig. 2. The spur gear that is to be cut is shown in Fig. 5.

The gear quality was evaluated using a Mitutoyo surface roughness measuring instrument, which allowed for accurate measurements and an assessment of the influence of various parameters on the final output. This information can assist manufacturers in optimizing their gear hobbing processes to achieve the best outcomes, resulting in more effective and higher-quality gear manufacturing operations. This experiment aims to decide the optimal cutting speed and feed combination that will result in the lowest flank surface roughness and microgeometric deviations. Wenzel coordinate measuring machine (CMM) was used to evaluate microgeometric deviations or errors on gear teeth, enabling a comprehensive analysis of the gear profile and identifying areas for improvement in manufacturing processes, thereby ensuring high-quality and precision gears. It is possible to see how changing the feed rate at 8, 10, and 12 mm/min impacts the surface imperfection while maintaining a constant depth of cut.

Fig 5. Spur Gear to be cut

2.4 Experimental Procedure

To optimize performance during the hobbing process, Taguchi design of experiments utilizing an L9 orthogonal matrix was utilized. It involved systematically varying the input factors and measuring their effects on the multiple output responses R_a, R_{max}, F_a, F_{β}, F_P and F_r. The Taguchi-Grey relational analysis approach uses statistical methods to fix the optimum combination of input parameters that leads to the intended output with a minimal amount of variation [23], [24]. This method enables more efficient and cost-effective hobbing process optimization. It ensures that all aspects of the process have been considered when determining the optimal combination of input factors by considering multiple output responses [23]. Moreover, statistical methods provide a scientific and objective approach to decision-making in the optimization process.

In this study, experimental design L9 was utilized to investigate the impact of independent variables, specifically cutting speed and feed using uniform depth of cut, on surface parameters, the dependent variable. The performance results presented in Table 6 provide quantitative data that support analysis and help validate the findings.

Table 6 Experimental design and performance results

Expt No	Cutting Speed	Feed	Cutting Speed (rpm)	Feed (mm/min)	R_a µm	R_{max} µm	F_a µm	F_β µm	F_p µm	F_r µm
	Coded		Uncoded							
1	1	1	300	8	0.5830	6.3430	15.5	25.7	51.85	84
2	1	2	300	10	0.7070	5.2100	20.95	35.35	62.7	78.5
3	1	3	300	12	0.9440	7.0290	29.95	18.55	181.5	207.9
4	2	1	350	8	0.6310	5.9190	13.7	51.8	117.9	115.3
5	2	2	350	10	0.5260	6.9920	15.85	90.2	136.05	120.9
6	2	3	350	12	0.7770	7.5050	17.5	21.1	122.35	125.3
7	3	1	400	8	0.5530	5.3430	14.35	20.45	51.85	78.5
8	3	2	400	10	0.6980	5.1030	16.5	26.7	140.45	156.7
9	3	3	400	12	0.7230	5.9740	14.8	22.3	187.8	168.9

3. Results and Discussion

3.1 Experimental Results Analyzed Using Grey Relational Analysis

Grey Relational Analysis, which is established on response tables in the Taguchi Method, is used to identify the optimal values for parameters during gear hobbing for multiple responses, most notably R_a, R_{max}, F_a, F_β, F_P and F_r. This enables the selection of the optimal combination of cutting speed, rate of feed, and tool geometry that reduces the flank roughness and microgeometric deviations on flank surface while maintaining a uniform depth of cut. By analyzing the response table, it is easy to decide the relative importance of each parameter about surface characteristics. This information helps in making informed decisions to achieve the desired surface characteristics while maintaining a consistent depth of cut. Furthermore, this optimization process ensures that the gear hobbling operation is efficient and produces high-quality results. Data preprocessing is a technique for converting what was originally sequenced into a comparable sequence that may be more easily studied and interpreted. The experimental data must be normalized in this case to lie between 0 and 1[23], [25] where 1 is considered a reference or ideal value [24]. Normalization of the experimental data between zero and one makes it easy for comparison and analysis across different datasets. This step is important in ensuring accurate and reliable results during the optimization process for gear hobbling operations. The surface characteristics i.e.R_a, R_{max}, F_a, F_β, F_P and F_r are important responses in gear hobbing operations that determine the quality of gear. Comparing and analyzing these parameters across different datasets are made simpler by normalizing the experimental data within the range of 0 to 1 [23]. During the optimization process for gear hobbing operations, this normalization step is essential for obtaining reliable and accurate results, ultimately resulting in high-quality gear production. By normalizing the experimental data, it becomes easier to identify any variations or trends in the surface roughness parameters. This allows manufacturers to make informed decisions and adjustments to improve the quality of their gear production processes. Additionally, the normalization step ensures that comparisons can be made between different datasets, enabling manufacturers to benchmark their performance against industry standards and best practices. For the "smaller-the-better" replies such as R_a, R_{max}, R_z, and R_t, the original or initial sequence can be transformed or normalized using equation (1).

$$x_I^*(p) = \frac{maxx_i(p) - x_i(p)}{maxx_i(p) - minx_i(p)} \quad (1)$$

where $maxx_i(1) = 0.9440$ and $minx_i(1) = 0.5260$ for R_a, $maxx_i(2) = 7.5050$ and $minx_i(2) = 5.1030$ for R_{max}, $maxx_i(3) = 29.95$ and $minx_i(3) = 13.7$ for F_a, $maxx_i(4) = 90.2$ and $minx_i(4) = 18.55$ for F_β , $maxx_i(5) = 187.8$ and $minx_i(5) = 51.85$ for F_p , $maxx_i(6) = 207.9$ and $minx_i(6) = 78.5$ for F_r .

The sequences $x_I^*(p)$ and $x_i(p)$ are acquired following the data preprocessing and comparability steps. For experimental runs 1 through 9, i = 1, 2 ... 9, with p = 1 for Ra, 2 for Rmax, 3 for F_a, 4 for F_β, 5 for F_P and 6 for F_r. The normalized sequence, represented by $x_I^*(p)$ enables accurate comparisons between different datasets. x_1^*(1)=0.8636, x_1^*(2)=0.4838, x_1^*(3)=0.8892, x_1^*(4)=0.9002,…, x_9^*(4)=0.3014. Equation (1) is listed in Table 7.

Table 7 Normalization Table

Expt No	R_a	R_{max}	F_a	F_β	F_p	F_r
1	0.8636	0.4838	0.8892	0.9002	1.0000	0.9575
2	0.5670	0.9555	0.5538	0.7655	0.9202	1.0000
3	0.0000	0.1982	0.0000	1.0000	0.0463	0.0000
4	0.7488	0.6603	1.0000	0.5359	0.5142	0.7156
5	1.0000	0.2136	0.8677	0.0000	0.3807	0.6723
6	0.3995	0.0000	0.7662	0.9644	0.4814	0.6383
7	0.9354	0.9001	0.9600	0.9735	1.0000	1.0000
8	0.5885	1.0000	0.8277	0.8863	0.3483	0.3957
9	0.5287	0.6374	0.9323	0.9477	0.0000	0.3014

The deviation sequence is calculated by subtracting $x_i^*(p)$ from$x_0^*(p)$.This deviation sequence explains the distinctions between the reference and comparability sequences.

$$\Delta_{0i}(p) = |x_0^*(p) - x_i^*(p)| \quad (2)$$

The deviation sequence $\Delta_{0i}(p)$ is evaluated by using Equation (2) as follows:
$\Delta_{01}(1) = |x_0^*(1) - x_1^*(1)| = |1 - 0.8636| = 0.1364$, $\Delta_{01}(2) = |x_0^*(2) - x_1^*(2)| = |1 - 0.4838| = 0.5162$, $\Delta_{01}(3) = |x_0^*(3) - x_1^*(3)| = |1 - 0.8892| = 0.1108$, $\Delta_{01}(4) = |x_0^*(4) - x_1^*(4)| = |1 - 0.9002| = 0.0998$ so on, $\Delta_{09}(6) = 0.6986$.Table 8 displays the results of the deviation sequences for each Surface parameter.

Table 8. Deviation Sequences for each roughness parameter

Expt No	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$	$\Delta_{0i}(3)$	$\Delta_{0i}(4)$	$\Delta_{0i}(5)$	$\Delta_{0i}(6)$
Reference Sequence	1.000	1.000	1.000	1.000	1.000	1.000
1	0.1364	0.5162	0.1108	0.0998	0.0000	0.0425
2	0.4330	0.0445	0.4462	0.2345	0.0798	0.0000
3	1.0000	0.8018	1.0000	0.0000	0.9537	1.0000
4	0.2512	0.3397	0.0000	0.4641	0.4858	0.2844
5	0.0000	0.7864	0.1323	1.0000	0.6193	0.3277
6	0.6005	1.0000	0.2338	0.0356	0.5186	0.3617
7	0.0646	0.0999	0.0400	0.0265	0.0000	0.0000
8	0.4115	0.0000	0.1723	0.1137	0.6517	0.6043
9	0.4713	0.3626	0.0677	0.0523	1.0000	0.6986

$\Delta_{max}(p)$ and $\Delta_{min}(p)$ are obtained from the data presented in Table 8 and are as follows:
$\Delta_{max}(p) = \Delta_{03}(1) = \Delta_{06}(2) = \Delta_{03}(3) = \Delta_{05}(4) = \Delta_{09}(5) = \Delta_{03}(6) = 1.000$ and
$\Delta_{min}(p) = \Delta_{05}(1) = \Delta_{08}(2) = \Delta_{04}(3) = \Delta_{03}(4) = \Delta_{01}(5) = \Delta_{07}(5) = \Delta_{02}(6) = \Delta_{07}(6) = 0.0000$.
The preprocessed sequence was used to calculate a grey relational coefficient $\xi_i(p)$ after data preprocessing was completed. It outlines the connection between ideal and actual normalized experimental results [23].

$$\xi_i(p) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(p) + \zeta.\Delta_{max}} \tag{3}$$

where ζ is a distinguishing or identification coefficient and $\Delta_{0i}(p)$ is the deviation sequence of the reference sequence $x_0^*(p)$and the comparability sequence$x_i^*(p)$. If ζ is chosen to be 0.5, all other parameters are given equal weight. $\xi_i(p)$ is given in Table 9. The average of all grey relational coefficients is used to compute the grey relational grade γ_i. The grey relational grade γ_i is used to interpret the different performance qualities. A higher grey relationship grade means that the associated experimental result and the ideal normalized value are more closely aligned. A greater grey relational grade implies that the experimental result performed better than the ideal normalized value. The grey relational grade is a quantitative indicator used to assess the performance characteristics of experimental findings[23]. This enables us to compare the effectiveness of various experimental findings and determine which is closest to ideal. Furthermore, the grey relational grade can be used to identify areas in the experimental procedure or design that need to be improved [23], [24], [25]. The experimental results can easily be ranked according to their grey relational grade, with higher grades indicating better performance as listed in Table 9.

Table 9 Grey Relational Coefficients and Grey Relational Grade with Rank

Expt No	Grey Relational Coefficients $\xi_i(k)$						Grey Relational Grade $\gamma_i = \frac{\xi_i(1)+\xi_i(2)+\xi_i(3)+\xi_i(4)+\xi_i(5)+\xi_i(6)}{6}$	Rank
	$\xi_i(1)$	$\xi_i(2)$	$\xi_i(3)$	$\xi_i(4)$	$\xi_i(5)$	$\xi_i(6)$		
1	0.7857	0.4920	0.8186	0.8336	1.0000	0.9217	0.8086	2
2	0.5359	0.9182	0.5285	0.6808	0.8624	1.0000	0.7543	3
3	0.3333	0.3841	0.3333	1.0000	0.3440	0.3333	0.4547	9
4	0.6656	0.5954	1.0000	0.5186	0.5072	0.6374	0.6541	5
5	1.0000	0.3887	0.7908	0.3333	0.4467	0.6041	0.5939	7
6	0.4543	0.3333	0.6813	0.9336	0.4909	0.5803	0.5790	8
7	0.8856	0.8334	0.9259	0.9496	1.0000	1.0000	0.9324	1
8	0.5486	1.0000	0.7437	0.8147	0.4341	0.4528	0.6656	4
9	0.5148	0.5796	0.8808	0.9052	0.3333	0.4172	0.6051	6

By rank, it is clear that experiment no.7 is the best solution among experiments 1–9 in terms of performance. This indicates that experiment no. 7 outperformed the other experiments in terms of its grey relational grade. Therefore, further investigation of the factors that contributed to the superior performance of experiment No. 7 is necessary to optimize the experimental design. This investigation will help identify key factors for optimizing experimental designs. To establish the optimal cutting speed for the experimental designs, the mean grey relational grade was computed at all three levels of cutting speed (N = 1, 2, and 3) as shown in Table 10. This can be gained by averaging the grey relational grade for experiments 1 to 3, 4 to 6, and 7 to 9. By comparing the mean grey relationship grades across every cutting speed level, it is easy to identify which level produces the highest quality performance. This information is essential for determining the best cutting speed for experimental designs. Averaging the grey relational grade for trials 1-4-7, 2-5-8, and 3-6-9 produces the mean of the grey relational grade for feed f for levels 1, 2, and 3. The relationship between cutting speed and the roughness and microgeometric deviations of the tooth surface can be thoroughly examined when considering additional data. It is simple to identify the optimal combination of cutting speed and feed rate for experimental design L9 by calculating the mean grey relational grades for each feed and cutting speed level. The overall means for the grey relational grade (GRG) for the nine investigations are displayed in Table 10. According to Table 10, (N3f1) has the best product quality in terms of the minimum surface roughness because its grey relation grade is the highest of all the parameter settings. This implies that using (N3f1) as the optimal combination of cutting speed and feed rate can lead to better performance and higher-quality output. The calculation gives a mean value of 0.6248 for all grey relational grades.

Table 10 Response Table for γ_i

Parameters	Level one	Level two	Level three	Main effect	Rank
Cutting Speed, N, rpm	0.6725	0.6090	**0.7344***	0.1254	2
Feed, f, mm/min	**0.7984***	0.6713	0.5463	0.2521	1

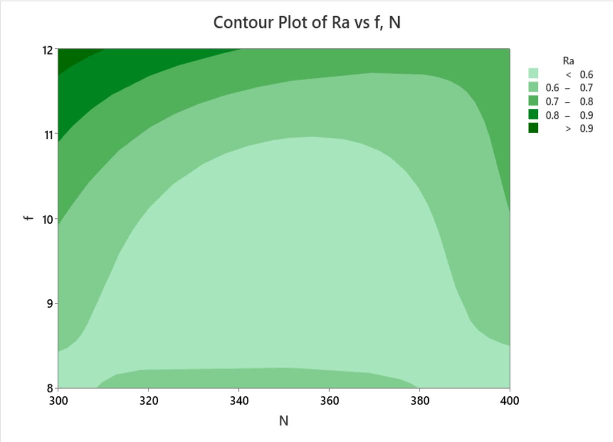
The total mean value of γ_i is 0.6248. *Levels for optimum GRG.

3.4 Influence of hob cutter speed

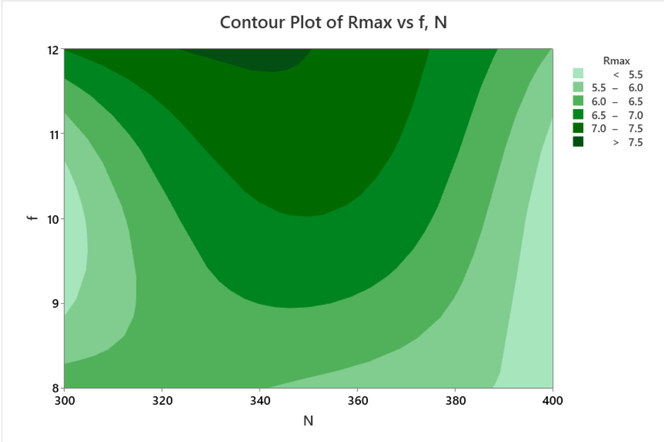
It can be cleared from Fig. 6(a-f) that the roughness of the flank surface and microgeometry deviations decreases with an increase in hob cutter speed [5], [26]. The reason for this is that as hob cutter speed increases, cutting forces decreases. This substantially reduces the inherent vibrations between the hob cutter and the gear blank, minimizing microgeometric deviations of the spur gear that is generated. Manufacturers can produce spur gears that are more durable and perform better by optimizing the hobbing process. A more effective gear-production process is also facilitated by the decrease in cutting forces and vibrations. A higher hob cutter speed also results in rapid chip flow which reduces heat transmission to the workpiece. This is because most of the heat generated during the process is carried away by the flowing chips. Additionally, rapid chip flow reduces the formation of built-up edge (BUE), resulting in a smoother flank surface and decreasing the flank roughness values, as shown in Figure 6 [26].

3.5 Influence of axial feed

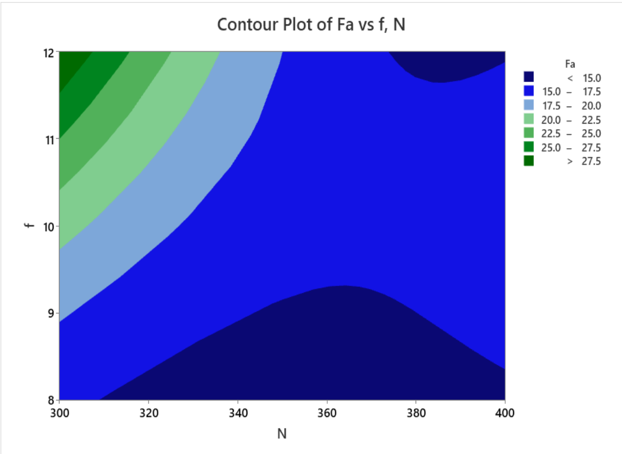
In the present work, the influences of hobbing factors on surface characteristics focusing on microgeometric deviations and surface roughness were investigated. Different combinations of cutting speed and feed rate were tested to determine their impact on surface characteristics. As a result of certain parameter combinations, surface roughness was significantly reduced, according to the results. The Ra and Rmax values increased as the feed rate during hobbing increased (as illustrated in Fig. 6). This indicates that lower feed rates result in a better surface finish on gear tooth surfaces .Therefore, it is important to carefully select the optimal combination of cutting speed and feed rate to obtain the desired surface roughness for gear teeth. Based on the observation of Figs.6 (a), and 6 (b), it appears that the flank roughness parameters and microgeometric deviations increased with an increase in axial feed. This could be due to the increased cutting forces generated by the higher axial feed, which leads to more heat generation at the machining zone. This increased heat facilitates the formation of more built-up edge (BUE) at the tooth flank surface, which could explain the increase in tooth flank roughness observed with an increase in axial feed. Optimizing feed rates is essential for precise gear tooth geometry because microgeometric deviations are minimized at lower feed rates, while irregularities caused by vibration and tool deflection are introduced at higher rates. Additionally, higher wear of the hob cutter, caused by higher temperatures, could also contribute to the increase in tooth flank roughness, as it increases the radial cutting force and vibrations [26], [27], [28]. The findings of the present study can be validated with a study conducted by Neelesh Kumar Jain et al. [5], in which hobbing parameters such as cutter speed, axial feed, and minimum quantity lubrication factor significantly affect gear flank surface roughness and microgeometric deviations. It was also presented by Neelesh Kumar Jain et al. that the depth of cut, however, has minimal impact on surface roughness; hence, it was considered uniform in the present study [22], [26], [27], [28], [29]. The study conducted by Neelesh Kumar Jain et al. suggested that the surface roughness of the tooth flank reduces as the hob cutter speed, depth of cut increase, while it increases with an increase in axial feed, which is in line with the findings of the current study [5], [26].



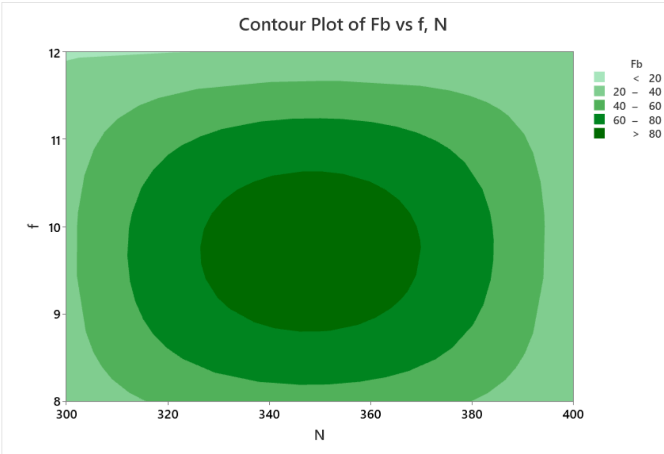
(a) Contour plot of Ra µm vs N rpm vs f mm/min



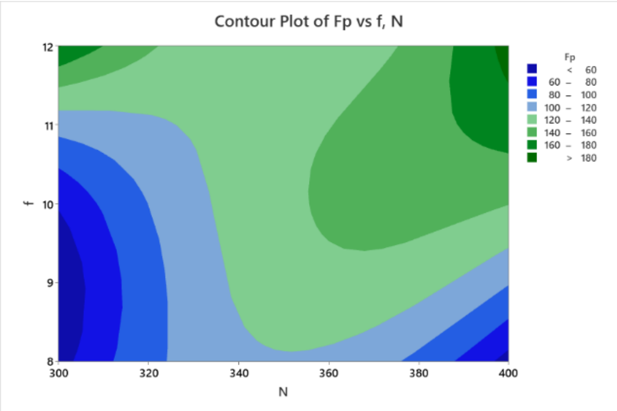
(b) Contour plot of Rmax µm vs N rpm vs f mm/min



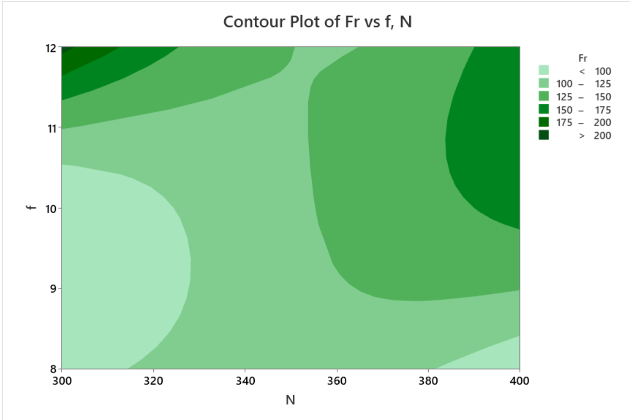
(c) Contour plot of Fa µm vs N rpm vs f mm/min



(d) Contour plot of Fb µm vs N rpm vs f mm/min



(e) Contour plot of Fp µm vs N rpm vs f mm/min



(f) Contour plot of Fr µm vs N rpm vs f mm/min

Fig. 6. Influence on Surface Characteristics i.e., R_a, R_{max}, F_a, F_β,F_p and F_r by N and f

4. Conclusion

In this study, surface roughness and microgeometric errors have been studied. The research findings revealed that optimizing hobbing parameters by increasing speed and decreasing feed rate while maintaining a consistent depth of cut led to a reduction in hobbing time without sacrificing surface quality. The research findings strongly recommend that for optimal results in gear hobbing and specific process parameters are very crucial. According to the present study, it is recommended to set the cutting speed at 400 rpm, the feed rate at 8 mm/min, and maintain a single depth of cut of 3.91 mm. It was found that the parameter levels had minimum surface roughness and microgeometric deviations. The gear hobbing process has increased to a greater level of performance. Tthe variation in feed rate was noticed and had a very significant impact on the efficiency and surface quality of the gear. The variation in feed rate was noticed and had a very significant impact on the efficiency and surface quality of the gear. It is expected to pay careful attention to controlling process parameters. Manufacturers significantly improve surface finish and microgeometric accuracy. Ultimately, it is contributing to the reliability and functionality of gears in various applications.

References

[1] B. Karpuschewski, M. Beutner, J. Eckebrecht, J. Heinzel, and T. Hüsemann, "Surface integrity aspects in gear manufacturing," *Procedia CIRP*, vol. 87, pp. 3–12, 2020.

[2] V. Vullo and V. Vullo, "Gears: General Concepts, Definitions and Some Basic Quantities," *Gears: Volume 1: Geometric and Kinematic Design*, pp. 1–38, 2020.

[3] S. Pathak, N. K. Jain, and I. A. Palani, "Experimental investigations on redefining the surface quality of bevel gears by pulsed electrochemical honing," *Transactions of the IMF*, vol. 94, no. 2, pp. 64–69, Mar. 2016, doi: 10.1080/00202967.2016.1148245.

[4] Y. Dixit and M. S. Kulkarni, "Multi-objective optimization with solution ranking for design of spur gear pair considering multiple failure modes," *Tribology International*, vol. 180, p. 108284, 2023.

[5] V. Kharka, N. K. Jain, and K. Gupta, "Influence of MQL and hobbing parameters on microgeometry deviations and flank roughness of spur gears manufactured by MQL assisted hobbing," *Journal of Materials Research and Technology*, vol. 9, no. 5, pp. 9646–9656, 2020.

[6] Y. Luo, N. Baddour, and M. Liang, "Dynamical modeling and experimental validation for tooth pitting and spalling in spur gears," *Mechanical Systems and Signal Processing*, vol. 119, pp. 155–181, 2019.

[7] G. S. Dhage, D. R. S. Pawar, and M. J. Patil, "Surface Characteristics of Finish Hobbed Gear- A Review," vol. 08, no. 01, 2023.

[8] A. M. Abrão, J. L. S. Ribeiro, and J. P. Davim, “Surface Integrity,” in *Machining of Hard Materials*, J. P. Davim, Ed., London: Springer, 2011, pp. 115–141. doi: 10.1007/978-1-84996-450-0_4.

[9] E. Bergstedt, J. Lin, and U. Olofsson, “Influence of gear surface roughness on the pitting and micropitting life,” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 234, no. 24, pp. 4953–4961, Dec. 2020, doi: 10.1177/0954406220931541.

[10] P. G. Benardos and G.-C. Vosniakos, “Predicting surface roughness in machining: a review,” *International journal of machine tools and manufacture*, vol. 43, no. 8, pp. 833–844, 2003.

[11] K. J. Stout, “Surface roughness ∼ measurement, interpretation and significance of data,” *Materials & Design*, vol. 2, no. 5, pp. 260–265, Sep. 1981, doi: 10.1016/0261-3069(81)90069-8.

[12] T. R. Thomas, “Characterization of surface roughness,” *Precision Engineering*, vol. 3, no. 2, pp. 97–104, 1981.

[13] V. Kharka, N. K. Jain, and K. Gupta, “Predictive modelling and parametric optimization of minimum quantity lubrication–assisted hobbing process,” *Int J Adv Manuf Technol*, vol. 109, no. 5–6, pp. 1681–1694, Jul. 2020, doi: 10.1007/s00170-020-05757-1.

[14] M. S. Gajhas and A. J. Keche, “Design Analysis of Conventional and Composite Spur Gear Using Finite Element Method,” in *Smart Technologies for Energy, Environment and Sustainable Development*, M. L. Kolhe, P. K. Labhasetwar, and H. M. Suryawanshi, Eds., in Lecture Notes on Multidisciplinary Industrial Engineering. Singapore: Springer, 2019, pp. 715–723. doi: 10.1007/978-981-13-6148-7_68.

[15] F. Klocke, C. Gorgels, R. Schalaster, and A. Stuckenberg, “An innovative way of designing gear hobbing processes,” in *International Conference on Gears*, 2010, pp. 393–404.

[16] D. K. Moru and D. Borro, “A machine vision algorithm for quality control inspection of gears,” *The International Journal of Advanced Manufacturing Technology*, vol. 106, pp. 105–123, 2020.

[17] K. Gupta, R. F. Laubscher, J. P. Davim, and N. K. Jain, “Recent developments in sustainable manufacturing of gears: a review,” *Journal of Cleaner Production*, vol. 112, pp. 3320–3330, 2016.

[18] C. Claudin and J. Rech, “Development of a new rapid characterization method of hob’s wear resistance in gear manufacturing—Application to the evaluation of various cutting edge preparations in high speed dry gear hobbing,” *Journal of Materials Processing Technology*, vol. 209, no. 11, pp. 5152–5160, Jun. 2009, doi: 10.1016/j.jmatprotec.2009.02.014.

[19] J. Šerák, V. Pečinka, and D. Vojtěch, “Microstructure of advanced tool steels produced by powder metallurgy,” *Manufacturing Technology*, vol. 18, no. 5, pp. 821–827, Oct. 2018, doi: 10.21062/ujep/184.2018/a/1213-2489/MT/18/5/821.

[20] J. Brnic, G. Turkalj, D. Lanc, M. Canadija, M. Brcic, and G. Vukelic, “Comparison of material properties: Steel 20MnCr5 and similar steels,” *Journal of Constructional Steel Research*, vol. 95, pp. 81–89, 2014.

[21] J. Brnic and M. Brcic, “Comparison of Mechanical Properties and Resistance to Creep of 20MnCr5 Steel and X10CrAlSi25 Steel,” *Procedia Engineering*, vol. 100, pp. 84–89, Jan. 2015, doi: 10.1016/j.proeng.2015.01.345.

[22] D. Samantaraya, S. Lakade, and A. Keche, “An Alternate Machining Method for Hardened Automotive Gears,” *Procedia Manufacturing*, vol. 20, pp. 517–522, Jan. 2018, doi: 10.1016/j.promfg.2018.02.077.

[23] N. D. Ghetiya, K. M. Patel, and A. J. Kavar, “Multi-objective Optimization of FSW Process Parameters of Aluminium Alloy Using Taguchi-Based Grey Relational Analysis,” *Trans Indian Inst Met*, vol. 69, no. 4, pp. 917–923, May 2016, doi: 10.1007/s12666-015-0581-1.

[24] H. Boumaza, S. Belhadi, M. A. Yallese, K. Safi, and A. Haddad, “Optimization of surface roughness, tool wear and material removal rate in turning of Inconel 718 with ceramic composite tools using MCDM methods based on Taguchi methodology,” *Sādhanā*, vol. 48, no. 1, p. 1, 2022, doi: 10.1007/s12046-022-02060-5.

[25] X. Wang, “Application of grey relation analysis theory to choose high reliability of the network node,” in *Journal of Physics: Conference Series*, IOP Publishing, 2019, p. 032056. doi: 10.1088/1742-6596/1237/3/032056.

[26] V. Kharka, N. K. Jain, and K. Gupta, “Predictive modelling and parametric optimization of minimum quantity lubrication–assisted hobbing process,” *The International Journal of Advanced Manufacturing Technology*, vol. 109, pp. 1681–1694, 2020.

[27] S. Yousefi and M. Zohoor, “Experimental Studying of the Variations of Surface Roughness and Dimensional Accuracy in Dry Hard Turning Operation,” *The Open Mechanical Engineering Journal*, vol. 12, no. 1, Oct. 2018, doi: 10.2174/1874155X01812010175.

[28] S. Yousefi and M. Zohoor, “Effect of cutting parameters on the dimensional accuracy and surface finish in the hard turning of MDN250 steel with cubic boron nitride tool, for developing a knowledged base expert system,” *International Journal of Mechanical and Materials Engineering*, vol. 14, no. 1, p. 1, Jan. 2019, doi: 10.1186/s40712-018-0097-7.

[29] V. Kharka, V. Rana, N. K. Jain, and K. Gupta, “Performance Characteristics of Spur Gears Hobbed under MQL, Flood Lubrication, and Dry Environments,” *Lubricants*, vol. 10, no. 10, p. 230, 2022.