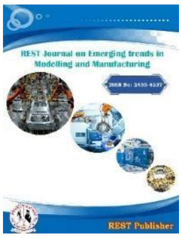
REST Journal on Emerging trends in Modelling and Manufacturing
Vol: 10(4), December 2024
REST Publisher; ISSN No: 2455-4537
Website: https://restpublisher.com/journals/jemm/
DOI: https://doi.org/10.46632/jemm/10/4/1



Experimental Studies On Surface Roughness of Spur Gear

***[1, 2, 4]Govind Shantaram Dhage, [3]Ramkisan Pawar, [5]Jotiba Patil**
[1]Dr. Babasaheb Ambedkar Marathwada University, Maharashtra, India
[2]Maharashtra Institute of Technology, Maharashtra, India
[3]Padmabhooshan Vasantdada Patil Institute of Technology, Bavdhan, Pune, India
[4]Hi-Tech Institute of Technology, Maharashtra, India
[5]MIDC Waluj, Maharashtra, India
*Corresponding Author Email: govinddhage029@gmail.com

Abstract. *Spur gears are used as a convenient way to transfer motion and power between shafts. One of the critical characteristics of spur gears is their surface roughness which affects their performance and durability. Proper hobbing techniques improve surface roughness, resulting in smoother operation and longer gear life. Hence, optimizing the hobbing processes during its manufacturing is an important step in achieving increased profitability and customer satisfaction. This paper investigates surface roughness of spur gear hobbing processes at various Taguchi levels, focusing on cutting speed and feed rate. The findings of the study revealed that Taguchi Grey Relational Analysis is an effective method for optimizing the hobbing process and reducing surface roughness. The research will contribute to the broader manufacturing field by inspiring further investigations into related processes and technologies.*

Keywords: *Interstitial Complex, Multiple Configurations, Reversible Reactions, Large Lattice Relaxation.*

1. INTRODUCTION

Gear is an essential component in machines and vehicles, transferring power and speed between rotating shafts. Common gear types include spur gears, helical gears, bevel gears, and worm gears. Spur gears are commonly used in high-speed and low-torque applications [1]. They are easy to manufacture and widely available in various sizes [2]. The quality of spur gear teeth is important for their performance, as imperfections can cause noise, vibration, and wear. Different tooth profiles and pressure angles can optimize the load-carrying capacity and efficiency in specific applications [3].

Designing gears involves considering how the hob affects the surface of the teeth on spur gears. The hobbing process can affect the surface finish and accuracy of gear teeth, impacting their performance and lifespan [4], [5]. The fatigue resistance of machined components is indeed affected by both surface finish and residual stress. It has been proven that a superior finish and compressive stress have a positive impact on the lifespan of these components [6]. Optimizing gear surface smoothness can reduce micropitting damage, but may shorten pitting life [7]. Regular evaluation and optimization of hobbing processes help manufacturers identify potential issues before they become major problems, preventing costly downtime and repairs. This proactive approach contributes to cost savings and improved product quality. Measurement of surface roughness is necessary to ensure that the required surface finish is achieved [8]. The ASP2052 Hob is an example of a high-speed hobbing tool that can produce excellent surface finishes. Hobbed gears that are complete are extensively utilized in diverse industries for their exceptional performance and affordability.

To evaluate surface roughness, several parameters are considered. The Ra, or roughness average, is the mean of the absolute values of the profile heights measured across the entire evaluation length [9]. Surface roughness is a complex property that necessitates the consideration of several parameters, including Ra, and Rmax [10] . These parameters, when taken together, provide a more complete understanding of the surface texture and its impact on the performance and functionality of the gear [8], [9], [11], [12].

Keche and Gajhans [13] conducted 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. [14] used ANSYS tools to analyze tool wear behavior and chip-forming characteristics in order to optimize the gear manufacturing process.

Moru and Borro [15] introduced Vision2D, an enhanced machine vision program that can improve quality control and optimize inspection processes. The purpose of this research was to investigate 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 finish, 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 of the teeth. Furthermore, research on minimizing surface roughness 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 [16]. 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 roughness. While some studies have explored the relationship between gear hobbing and surface quality, there remains a need for more comprehensive investigations that address the following aspects:

- Previous research has frequently concentrated on conventional gear hobbing processes. However, with the increasing demand for high-speed gear applications, there is a knowledge gap about how gear hobbing factors affect surface quality under these conditions. The impact of high-speed rotation on hob cutters and their consequences for surface roughness are areas that need to be investigated further.
- The investigation of gear hobbing processes with a single, constant depth of cut also represents a research gap. While different depths of cut can influence surface quality, the impact of a single depth of cut on different gear hobbing parameters needs to be thoroughly investigated.

It is essential to convert study findings into suggestions that manufacturers can actually implement. For the industry to implement optimal gear hobbing processes, a bridge must be built between theoretical research and its application in real-world manufacturing conditions. This research aims to optimize the manufacturing process for better quality spur gears by analyzing the responses to a parameter such as surface roughness. The outcomes of this study may improve the overall performance and reliability of high-speed gear systems, thereby reducing noise and vibration levels while improving gear tooth accuracy and durability. As spur gears are utilized in various industries, the information gained from this research can enhance their productivity and efficiency, potentially leading to advancements in gear design and performance.

2. MATERIALS AND METHODS

Pre-experimentation Stage: Gear quality is achieved by optimizing the CNC hobbing operation. A cause-and-effect diagram of the CNC hobbing operation is used to determine the impact of process factors on gear quality as shown in Fig. 1. Manufacturers can adjust their processes to produce gears with higher precision and durability by identifying key factors that affect gear quality.

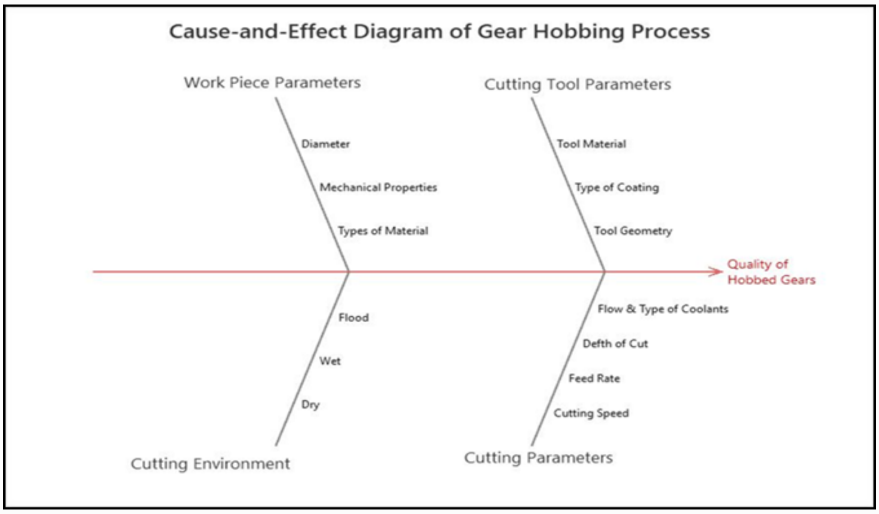


FIGURE1. Cause and Effect Diagram of the Gear Hobbing Process [20]

The Shobber Pfauter 300-gear hobbing machine as shown in Fig. 2 is being utilized in this work to produce gears with a module size of 1.75 mm and a workpiece diameter of 140 mm, although it can create gears with a maximum module size of 6 mm and a workpiece diameter of 300 mm. The machine is highly capable of performing intricate and precise gear cutting operations at high spindle speed. It is also equipped with an integrated coolant system that aids in dissipating heat and enhancing tool life, resulting in improved cutting efficiency and reduced downtime for cooling. Operators can easily 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.

FIGURE 2. Shobber 300 Gear Hobbing Machine[17]

The ASP2052 hob cutter as used in this work is 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 wears resistance, making it suitable for demanding cutting applications. 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. Modules of hob and gear to be cut should be the same.

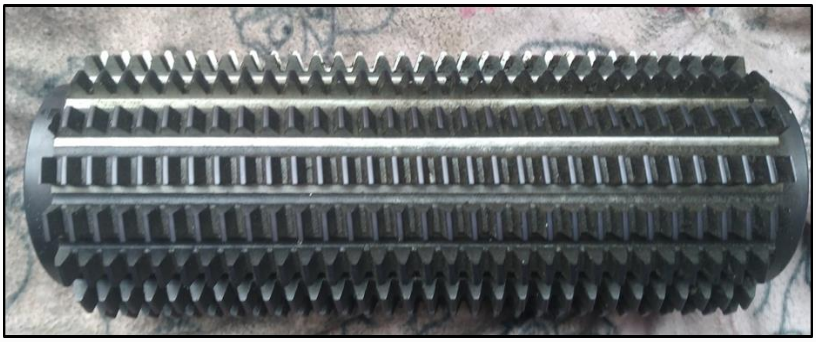


FIGURE 3. ASP2052 Hob Cutter[17], [19]

Table 1.Chemical Composition of Hob Cutter [19], [20]

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[17], [19]

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 contains detailed specifications for the spur gear, including the number of teeth, root diameter, outside diameter and pressure angle etc. It is essential to ensure these specifications align with the hob cutter used to cut the gear. For optimal results, the hob cutter and the gear to be cut should have the same module. Table 4 provides information on the chemical composition of the material used to produce the spur gear, which is 20 MnCr5. This material is known for its excellent strength, durability, and wears resistance [21]. It is a suitable material for high-demanding applications that require a high level of toughness and resistance to wear and tear.

TABLE 3. Details of Spur Gear[17], [19]

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 [19], [21], [22], [23]

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 bar of 140 mm diameter, was selected and inspected for quality as per the 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 finally; blanks were finished by 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.

FIGURE 4. Blank for Spur Gear Manufacturing[17]

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 the work, conventional hobbing with a constant depth of cut was used to ensure consistent gear tooth profiles. By conducting trial experiments, the optimal working ranges of these process parameters were determined, ensuring efficient and effective gear hobbing operations. Through Taguchi-Grey relational analysis (TGRA), the relationship between cutting speed, feed, and gear tooth surface quality was analyzed. TGRA allows for the determination of the most influential process parameters and their optimal levels, leading to improved gear hobbing performance and surface roughness of teeth. The 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[19]

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 the 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 study 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 evaluate the effects of these factors on the surface roughness of gear teeth manufactured on the Shobber 300 Gear Hobbing Machine at Sarvesh Engineering, MIDC Waluj, Chhatrapati Sambhajinagar, Maharashtra, India. Shobber 300 Gear Hobbing Machine with work fixture and hob cutter mounting position is shown in Fig. 4. The spur gear that is to be cut is shown in Fig. 5.This experiment aims to determine the optimal cutting speed and feed combination that will result in the lowest surface roughness. 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.

FIGURE 5. Spur Gear to be cut[17], [19]

Experimental Procedure: To optimize performance during the hobbing process, Taguchi designs experiments utilizing an L9 orthogonal matrix was utilized. It involved systematically varying the input factors and measuring their effects on the multiple output responses Ra, and Rmax. The Taguchi-Grey relational analysis approach uses statistical methods to determine the optimum combination of input parameters that leads to the intended output with a minimal amount of variation. 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 [24]. Moreover, statistical methods provide a scientific and objective approach to decision-making in the optimization process. Mitutoyo Surface Testing Instrument measures the surface's degree of roughness using height parameters (Ra, Rmax), which uses a stylus to scan the face of the surface of teeth and calculate various roughness parameters as shown in Table 6. In the study, experimental design L9 was utilized to analyze the impact of independent variables, specifically cutting speed and feed with uniform depth of cut, on surface roughness parameters, the dependent variable. The performance results presented in Table 7 provide quantitative data that support the analysis and help validate the findings.

TABLE 6. Setting of Mitutoyo Surface Tester[19]

Sr No	Measurement Condition	Setting Adjusted
1	Model	SJ-410
2	Standard	ISO1997
3	λc, Cut of Length	0.8 mm
4	M-Speed	0.5 mm/s
5	Digital Filter	Gauss

TABLE 7. Experimental design and performance results

Expt No	tting Speed	Feed	tting Speed (rpm)	Feed (mm/min)	Ra µm	Rmax µm
	Coded		Uncoded			
1	1	1	300	8	0.5400	4.8833
2	1	2	300	10	0.6400	5.3150
3	1	3	300	12	0.7600	7.2010
4	2	1	350	8	0.4800	4.3203
5	2	2	350	10	0.5100	4.7200
6	2	3	350	12	0.5400	5.5240
7	3	1	400	8	0.3400	3.1988
8	3	2	400	10	0.4400	3.9580
9	3	3	400	12	0.4900	4.3340

3. RESULTS AND DISCUSSION

Experimental Results Analyzed Using Grey Relational Analysis: Grey Relational Analysis, which is based on response tables in the Taguchi Method, is used to identify the optimal values for parameters during gear hobbing for multiple responses, most notably Ra, and Rmax [17], [19]. This enables the selection of the optimal combination of cutting speed, rate of feed, and tool geometry that reduces the roughness of the tooth surface while maintaining a uniform depth of cut. By analyzing the response table, it is easy to determine the relative importance of each parameter in relation to surface roughness. This information helps in making informed decisions to achieve the desired surface finish 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[24]. Normalization of the experimental data between zero and one allows for easier 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 roughness notably Ra, and Rmax are important responses in gear hobbing operations that determine the quality of gear. notably Ra, and Rmax are surface roughness height parameters that are essential for determining the level of surface quality of gear teeth manufactured during hobbing operations. Comparing and analyzing these parameters across different datasets is made simpler by normalizing the experimental data within the range of 0 to 1. 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 notably Ra, and Rmax, the original or initial sequence can be transformed or normalized using equation (1).

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

Where $maxx_i(1) = 0.7600$ and $minx_i(1) = 0.3400$ for Ra, $maxx_i(2) = 7.2010$ and $minx_i(2) = 3.1988$ for Rmax, 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.

Table 8 Normalization Table

Expt No	Ra	Rmax
1	0.5238	0.5791
2	0.2857	0.4712
3	0.0000	0.0000
4	0.6667	0.7198
5	0.5952	0.6199
6	0.5238	0.4190
7	1.0000	1.0000
8	0.7619	0.8103
9	0.6429	0.7164

The Eq(1) is listed in Table 8. 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.

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

The deviation sequence $\Delta_{0i}(p)$ is evaluated by using Equation (2) as follows:

Table 9 displays the results of the deviation sequences for each roughness parameter.

TABLE 9. Deviation sequences for each roughness parameter

Expt No	$\Delta_{0i}(1)$	$\Delta_{0i}(2)$
Reference Sequence	1.000	1.000
1	0.4762	0.4209
2	0.7143	0.5288
3	1.0000	1.0000
4	0.3333	0.2802
5	0.4048	0.3801
6	0.4762	0.5810
7	0.0000	0.0000
8	0.2381	0.1897
9	0.3571	0.2836

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 [24].

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

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 10. 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. 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 [24]. The experimental results can easily be ranked according to their grey relational grade, with higher grades indicating better performance as listed in Table 10.

TABLE 10. Grey Relational Coefficients and Grey Relational Grade with Rank

Expt No	Grey Relational Coefficients $\xi_i(k)$		Grey Relational Grade $\gamma_i = \frac{\xi_i(1)+\xi_i(2)}{2}$	Rank
	$\xi_i(1)$	$\xi_i(2)$		
1	0.5122	0.5430	0.5276	5
2	0.4118	0.4860	0.4489	7
3	0.3333	0.3333	0.3333	8
4	0.6000	0.6408	0.6204	3
5	0.5526	0.5681	0.5604	4
6	0.5122	0.4625	0.4874	6
7	1.0000	1.0000	1.0000	1
8	0.6774	0.7250	0.7012	2
9	0.5833	0.6380	0.2036	9

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 11. 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 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 11. According to Table 11, (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 0.5425 for all grey relational grades.

TABLE 11. Response Table for γ_i

Parameters	Level one	Level two	Level three	Main effect	Rank
Cutting Speed, N, rpm	0.4366	0.5561	**0.6349***	0.1983	2
Feed, f, mm/min	**0.7160***	0.5702	0.3414	0.3746	1

The total mean value of γ_i is 0.5425.

*Levels for optimum GRG

Influence on roughness of surface by hobbing machining parameters: In the present work, the influences of hobbing factors on surface roughness were investigated. Different combinations of cutting speed and feed rate were tested to determine their impact on surface roughness. As a result of certain parameter combinations, surface roughness was significantly reduced. The Ra and Rmax values increased as the feed rate during hobbing increased (as illustrated in Fig. 6). This indicates that lower feed rates resulted in a better surface finish on gear tooth surfaces. Specifically, it was observed that lower feed rates resulted in reduced waviness and improved flatness of the 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. These findings can be validated with a study conducted by Jain et al. [4], in which hobbing parameters such as cutter speed, axial feed, and minimum quantity lubrication factor significantly affect gear flank surface roughness. It was also presented by Jain et al. that the depth of cut, however, has minimal impact on surface roughness; hence, it is considered uniform in the present study. Jain et al. study also found that the tooth flank surface roughness decreased with an increase in hob cutter speed and depth of cut and increased with an increase in axial feed [4], [25].The results of the present study demonstrate that by optimizing the hobbing process parameters, such as cutting speed and feed with uniform depth of cut, it is possible to significantly reduce the surface roughness of spur gears[19]. This improvement in surface roughness leads to gears with superior performance and increased durability. Overall, this work provides insights into how to enhance the quality of spur gears through the optimization of the hobbing process

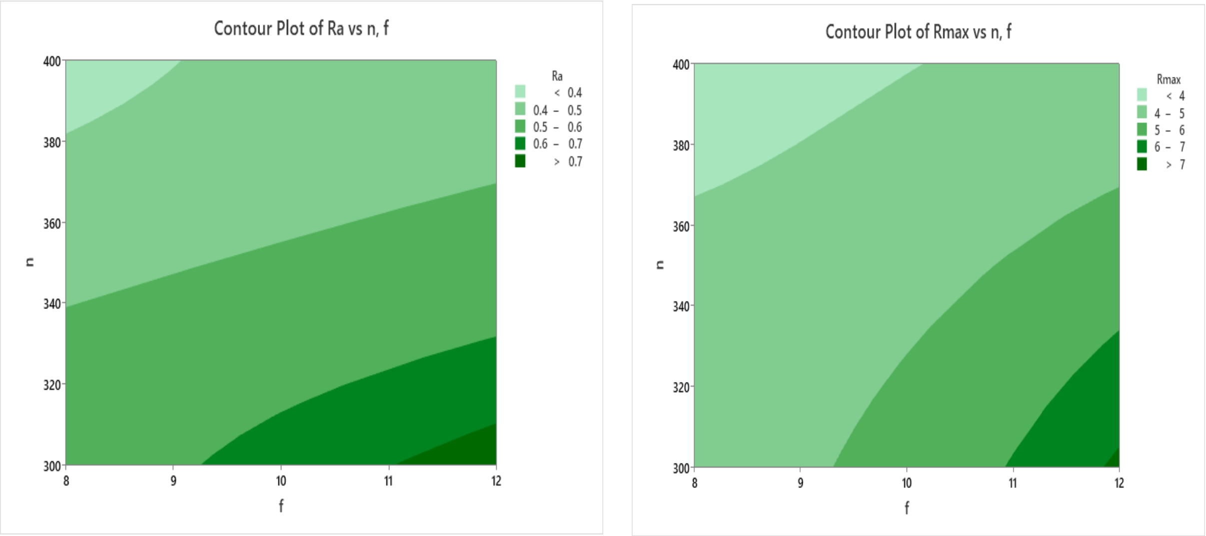


FIGURE 6. Contour Plot of Ra µm and Rmax µm vs N rpm vs f mm/min[19]

4. CONCLUSION

From the study, it was revealed that the feed rate was a significant factor in improving the surface roughness of gear teeth. As the feed rate decreases, the surface roughness decreases, resulting in a better surface finish. Reducing hobbing time with a better surface finish is only possible by increasing the speed and decreasing feed rate and keeping a single depth of cut simultaneously. If multiple depths of cut are used, then hobbing time increases. However, it is essential to ensure that the gear hobbing machine and cutting tool are capable of handling higher speeds without compromising the quality of the gear teeth. Surface quality has a key role in transferring motion between gears and ensuring smooth and efficient operation. Poor surface quality can lead to increased friction, noise, and wear, ultimately affecting the overall performance and lifespan of gears. Therefore, optimizing hobbing parameters to achieve a better surface finish is important for ensuring reliable gear functionality. The gear hobbing operation for 20MnCr5 steel was optimized for improved surface finish by Taguchi grey relational analysis, and optimal parameters were found to minimize surface roughness and enhance gear performance.

- For the best results, the process parameters should be set at a cutting speed of 400 rpm, a feed rate of 8 mm/min, and a single depth of cut of 3.91 mm. Therefore, for minimum surface roughness, these hobbing parameter levels are recommended.
- This indicates that adjusting the feed rate can have a significant impact on the overall performance of the gear hobbing process.

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 Vol. 1 Geom. Kinematic Des.*, pp. 1–38, 2020.

[3]. Y. Dixit and M. S. Kulkarni, “Multi-objective optimization with solution ranking for design of spur gear pair considering multiple failure modes,” *Tribol. Int.*, vol. 180, p. 108284, 2023.

[4]. 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,” *J. Mater. Res. Technol.*, vol. 9, no. 5, pp. 9646–9656, 2020.

[5]. Y. Luo, N. Baddour, and M. Liang, “Dynamical modeling and experimental validation for tooth pitting and spalling in spur gears,” *Mech. Syst. Signal Process.*, vol. 119, pp. 155–181, 2019.

[6]. 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.

[7]. E. Bergstedt, J. Lin, and U. Olofsson, “Influence of gear surface roughness on the pitting and micropitting life,” *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.*, vol. 234, no. 24, pp. 4953–4961, Dec. 2020, doi: 10.1177/0954406220931541.

[8]. P. G. Benardos and G.-C. Vosniakos, “Predicting surface roughness in machining: a review,” *Int. J. Mach. Tools Manuf.*, vol. 43, no. 8, pp. 833–844, 2003.

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

[10]. Ch. M. Rao, K. Venkatasubbaiah, and K. J. Rao, “Experimental Investigation of Surface Roughness Characteristics Ra, Rq and Rz,” *Int. J. Hybrid Inf. Technol.*, vol. 9, no. 7, pp. 373–388, Jul. 2016, doi: 10.14257/ijhit.2016.9.7.34.

[11]. T. R. Thomas, “Characterization of surface roughness,” *Precis. Eng.*, vol. 3, no. 2, pp. 97–104, 1981.

[12]. G. Mikoleizig, “Surface Roughness Measurements of Cylindrical Gears and Bevel Gears on Gear Inspection Machines”.

[13]. 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.

[14]. 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.

[15]. D. K. Moru and D. Borro, “A machine vision algorithm for quality control inspection of gears,” *Int. J. Adv. Manuf. Technol.*, vol. 106, pp. 105–123, 2020.

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

[17]. Govind Shantaram Dhage, “Experimental Investigation on Surface Characteristics of Finish Hobbed Gear using Grey Relational Analysis,” *Commun. Appl. Nonlinear Anal.*, vol. 31, no. 3s, pp. 419–434, Jun. 2024, doi: 10.52783/cana.v31.799.

[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,” *J. Mater. Process. Technol.*, vol. 209, no. 11, pp. 5152–5160, Jun. 2009, doi: 10.1016/j.jmatprotec.2009.02.014.

[19]. G. S. Dhage, R. Pawar, and J. Patil, “Influence of cryogenically treated hob on surface characteristics of spur gear,” *Mater. Manuf. Process.*, pp. 1–13, Dec. 2024, doi: 10.1080/10426914.2024.2437751.

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

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

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

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

[24]. 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.

[25]. 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.