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Experimental Modelling and Robust Parameter Design in Bevel Gear Lapping

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Abstract

Gear lapping is done to improve the gear teeth surface along with geometry and form accuracy. The lapping of gear depends on lap speed, lap time, and applied load. This research aims to study the effects of these input process parameters (lapping speed, lapping time, and braking torque) on gear surface roughness. For this experiment, 20MnCr5 is used as workpiece material which is employed where medium to high strength, wear-resistance, and toughness is required. Taguchi's L9 orthogonal array is used to optimize the effect of input parameters on surface roughness. The optimization trend shows that lapping speed has maximum impact on surface roughness, followed by lapping time, and braking torque. The results confirm a variation of surface roughness for pinion and crown by 9.30% and 7.00%, respectively.

Keywords

Bevel gear, Lapping, Surface roughness

Introduction

Bevel gears are used in various applications, but it is most prominently used in the automobile industry to transfer motion between non-intersecting axes in the rear and four-wheel drive [1]. Apart from being able to transmit motion, any bevel gear is expected to fulfill two functions, i.e., it should have the maximum load-carrying capacity and minimum running noise. Maximum load capacity can be achieved via flank modification i.e., by various actions such as tooth correction, crowning, tip or toe relief, and topological modifications. Minimum running noise can be achieved by reducing form errors associated with the gear tooth which includes flank profile variation, pitch errors, concentricity deviation, and tumbling errors [2]. To increase the load capacity, flank modification is needed which in turn is dictated by high stresses acting on the gear tooth. These stresses on the gear arise from external load condition, gear macro geometry, and tribological system of tooth contact which is also influenced by the surface quality of the tooth contact. For gearing, a higher quality of the surface finish of the tooth flank means a decrease in tribological load due to reduced friction. It also means increased permissible stress due to a reduced notch effect [2]. So, it can be inferred that to fulfill both the functions of a bevel gear surface quality plays an important role along with macro geometry. Bevel gears have a high sliding-to-rolling ratio and due to this sliding friction apart from rolling friction plays an important role in power loss [1]. Some theoretical studies related to the mechanical efficiency of bevel gears have shown that surface finish has a substantial effect on its efficiency. Hence to improve the surface quality and contact pattern of bevel gears, the lapping process has been employed in this research.

Lapping is defined as the finishing process to produce a flat, smooth, and unpolished surface to achieve close tolerances among mating parts with a very ultra-high surface finish. Lapping, which is one of the oldest machining processes, is still a leader in surface finishing on a very wide range of materials due to its incomparable advantages in obtaining high surface quality, very fine dimensional tolerance, and form accuracy. Evans et al. [1] have described the fundamental mechanism associated with lapping by addressing first its various process components then pairwise interactions between them and their effect on the lapped component. Karpuschewski et al. [2] have described the need associated with gear finishing, influences on dimensional distortions of gear in general, and have done a detailed analysis of the prevailing processes associated with geometrically non-defined cutting edges. Brnic et al. [3] have obtained various experimental data associated with various properties such as ultimate tensile strength, creep behavior, yield strength of 20MnCr5 and compared these data with the respective data of various other similar steels such as ASTM A618 steel, S355JO steel, and 50CrMo4. 20MnCr5 is sometimes referred to as special structural steel and is a low-carbon, low-chromium steel. These types of steel are used in applications where a union of medium to high strength, wear resistance, and toughness is required. Ming et al. [4] have analyzed the effect of grinding depth, wheel granularity, wheel speed, and gear generative speed on response variables material removal rate, metamorphic layer depth, and surface roughness using L16 orthogonal array. The range and variance analysis method has been used to find the effect of strength of each factor and to check experiment accuracy respectively. Kang and Hadfield [5] have optimized the MRR of ceramic balls using L9 orthogonal array and level average response analysis. The input variables selected by Kang and Hadfield are lapping load, lapping speed, paste concentration, and particle size each at three levels. Deaconescu et al. [6] have made use of robust parameter design to improve surface finish quality by lapping three different materials i.e., 18MoCr10, 38MoCr09, and 50WCr11. A non-linear relation between surface roughness and input process parameters for all three different materials was developed using regression analysis and based on this relationship, the impact of input parameters on response i.e., surface finish is calculated. Masseth and Kolivand [7] have presented a study about calculating the surface finish of both pinion and ring gears using an accurate form measuring machine coupled with 'FormTracePack' software. The study shows that the surface finish of gear deteriorated after lapping while no steady result can be obtained for the pinion. Zheng et al. [8] have analyzed the surface roughness and flatness of 9Cr18 using L9 orthogonal array. Zheng et al. have divided lapping into rough (grit size 600) and ultra-precision lapping (grit size 2000). Aluminum oxide has been used as an abrasive for the lapping process and experimental results have been analyzed using the ANOVA (analysis of variance) method. Ramadass and Sambasivam [9] have optimized the surface roughness of EN8 material in flat lapping using lapping time, abrasive size, and abrasive carrier concentration. Firstly, a mathematical model associated with surface roughness and stress has been discussed and then the L9 orthogonal array and S/N ratio have been used to optimize the response. Parate and Yarasu [10] have optimized the MRR using L8 orthogonal array and 'larger the better, type S/N ratio. The effect of the individual input parameter has been analyzed using level average response analysis. Su et al. [11] have analyzed the effect of abrasive concentration, loading pressure, and lapping speed on the machining precision of cylindrical roller using an orthogonal array. The optimum parameter of the response has been determined using ANOVA and S/N ratio.

As discussed, most of the research work related to lapping has been carried out for flat surfaces and a few research that was related to the lapping of bevel gears were done only to check the improvement of surface finish after lapping. But only a handful of research has been done related to the lapping of bevel gears to optimize its surface finish for improved load-carrying capacity and reduce its running noise. To fill this research gap, critical input parameters associated with the lapping of bevel gears have been screened out using the Taguchi method, and experimentation is done using Robust Parameter Design. To maintain the uniqueness of the research a combination of three input parameters (lapping speed, lapping time, and braking torque) each at three levels has been selected. The optimization trend shows that lapping speed has maximum impact on surface roughness, followed by lapping time, and braking torque.

Materials and Methods

For this experiment, 20MnCr5 is used as workpiece material. The objective of the research is to study the effects of input process parameters on gear quality, develop an empirical relationship between input and output parameters and optimize the process parameter for better gear quality. To fulfill these objectives, three input variables have been chosen based on literature review and subject knowledge. Three levels of each input variable have been decided as shown in table 1. To decrease the number of experiments to be carried out and increase the robustness of the design and based on the degree of freedom, a L9 orthogonal array has been selected.

Table 1: Input parameters at a different level.

Symbol	Input Parameters	Units	Levels		
			Level 1	Level 2	Level 3
S	Speed	rpm	800	1000	1200
T	Torque	N-m	5	10	15
T	Time	S	66	88	98

Table 2: L9 orthogonal array.

Exp.	Speed (rpm)	Torque (N-m)	Time (s)
1	800	5	66
2	800	10	88
3	800	15	98
4	1000	5	88
5	1000	10	98
6	1000	15	66
7	1200	5	98
8	1200	10	66
9	1200	15	88

The effect of input parameters on response has been studied using MINITAB 17 software. Then, an empirical relationship between the response variable and input parameter has been developed using MINITAB 17 software as well as using the 'Least square method'. A comparison has also been made to compare the variation of experimental results from predicted results that have been obtained using MINITAB 17 software and the least square method.

To facilitate proper sitting of crown and pinion while lapping, bevel gear undergoes series of processes as shown in figure 1. After these processes are done actual lapping operation begins which is followed by cleaning of bevel gear pair and measuring surface roughness values. Before lapping all machining operations on crown and pinion are performed separately but once they are lapped in pair, they must always be used as a pair only.

In this experiment soft cutting of bevel gear pair (crown and pinion) has been performed on a C-29 bevel gear cutting machine by Oerlikon which is a 6 axis CNC machine. This C-29 machine produces bevel gear of very high surface and gearing quality with a very short tool changing time. After the soft cutting process, a proper heat treatment process has been performed on the bevel gear to increase its surface hardness to enable it to withstand high load acting on the bevel gear surface during its functionality. For this research, bevel gear has undergone the carburizing process. Post heat treatment process, bevel gears undergo surface distortion. To eliminate those surface distortions and achieve a good surface finish and contact pattern as per design specification and application requirements bevel gears are lapped. In the undertaken project, lapping is performed using 'Spiromat L22 CNC Lapper' by Oerlikon. Figure 2 shows a Spiromat L22 CNC lapping machine.

Lapping has been performed on 9 bevel gear sets having identical design specifications and has undergone the same processes before lapping. The lapping paste used for the research purpose is 'HIGRIND LAP 4' from Hard Castle Petrofer Pvt. Ltd. This lapping paste is a mixture of lapping paste and silicon carbide grits in the ratio of 60:40 with silicon carbide abrasives having a grit size of 280. The lapping paste is grey and thixotropic having a specific gravity of 1.2. One of the most difficult problems with post lapping is to get rid of lapping paste from the surface of gears. For this purpose, gears have been washed in an indigenously developed setup that strikes the gear surface with hot water at a high velocity to remove lapping paste. After that gear surface is cleaned with a clean cotton cloth before being taken to the surface measuring machine. Surface roughness has been measured using the P40 machine by Klinglnberg. This P40 machine is capable of measuring various parameters associated with bevel gears such as tooth spacing error, pitch error, and roughness value in terms of Ra, Rz, Rt, Rmax in a single task. The very smooth and constant rotary motion of the P 40 machine table, even at low speed permits a very accurate and fast measurement of data. This P 40 machine has a 3-D tracer head that has 'digital measurement acquisition' capability in all co-ordinate directions.

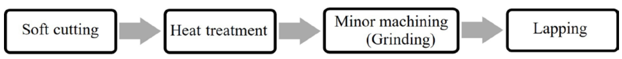

Figure 1: A process map to gear lapping.

Figure 2: Spiromat L22 CNC lapping machine [12].

Table 3: S/N ratio for pinion for each experiment.

Exp.	Speed (rpm)	Torque (N-m)	Time (s)	Pinion avg. surface roughness	S/N ratio
1	800	5	66	0.94	0.48177
2	800	10	88	1.12	-0.99566
3	800	15	98	1.12	-1.01289
4	1000	5	88	1.173333	-1.40361
5	1000	10	98	0.816667	1.748553
6	1000	15	66	1.046667	-0.41998
7	1200	5	98	1.31	-2.35065
8	1200	10	66	1.073333	-0.6203
9	1200	15	88	1.266667	-2.09962

Results and Discussion

ANOVA of pinion

Using 'smaller-the better' type signal to noise ratio for pinion, S/N ratios for all 9 experiments have been calculated in table 3.

As can be seen from table 4, the maximum impact on the surface finish of pinion is due to lapping speed, followed by lapping time and torque respectively. The response table for S/N ratio (Table 5) for pinion also shows that among all three input parameters, the surface response is most affected by speed followed by time and torque respectively which is the same as that of results interpreted from the ANOVA table. As

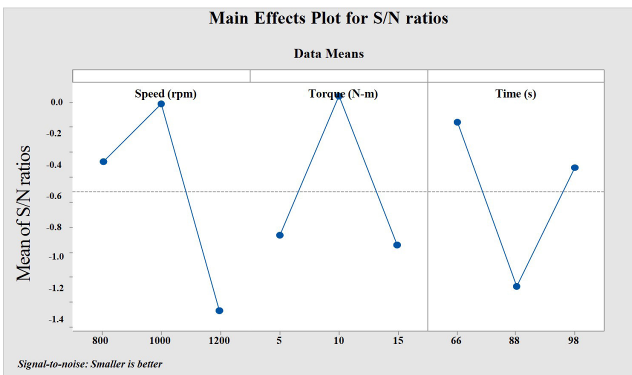

Figure 3: Main effect plot for S/N ratio of pinion.

the level of speed increases, the S/N ratio increases reaching a maximum value at 'level 2' of speed and then decreases as seen from figure 3. The same S/N ratio pattern is followed for torque. But, as the level for factor 'Time' increases, the S/N ratio decreases reaching a minimum value at 'level 2' and then further increases. The above results are because as the lapping speed increases more and more abrasive particles rub against the pinion surface thus improving surface finish, but as lapping speed is increased beyond a certain value the effective contact time between an abrasive particle and asperity to be flattened to improve surface finish decreases i.e. at relatively high speed the abrasive particles are moved to another point of the surface to be lapped before flattening the asperity. With the increase in lapping torque material removal rate increases thus increasing the surface finish but at high lapping torque, the abrasive particles start plowing into the lapping surface thus deteriorating the surface finish.

Table 4: ANOVA table for surface roughness of pinion.

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F-value	% contri-bution
Speed (rpm)	2	0.06862	0.06862	0.03431	1.84	36.63
Torque(N-m)	2	0.03891	0.03891	0.01945	1.04	20.76
Time (s)	2	0.04256	0.04256	0.02128	1.14	22.71
Error	2	0.03728	0.03728	0.01864		19.90
Total	8	0.18737				100.00

Table 5: Response table for S/N ratio of pinion

Level	Speed (rpm)	Torque (N-m)	Time (s)
1	-0.47709	-1.06547	-0.15781
2	-0.00850	0.05335	-1.47535
3	-1.67112	-1.14459	-0.52356
Delta	1.66262	1.19794	1.31754
Rank	1	3	2

Regression analysis of pinion

A quadratic regression model to express response variables in terms of input process parameters has been developed using MINITAB 17 software. The equation developed is as follows,

$$R_a = (-3.140) - (0.005398S) + (0.07708T) + (0.1590t) + (0.000003S^2) + (0.00442T^2) - (0.00106t^2) - (0.000162 * S * T) + (0.000013 * S * t)$$

As can be seen from table 6, on comparing the experimental surface roughness value with the data obtained from two regression methods it has been found that the relative error in surface roughness using the least square method (9.3048%) is way lesser than relative error using the quadratic model (15.14%).

ANOVA of crown

Using the 'smaller-the better' type signal to noise ratio for a crown, S/N ratios for all 9 experiments have been calculated as shown in table 7.

As can be seen from table 8, the maximum impact on the surface finish of the crown is due to lapping speed, followed by lapping time and torque, respectively. However, the significance of lapping speed on surface roughness in the case

Table 6: Surface roughness comparison using different regression methods.

Exp.	Speed (rpm)	Torque (N-m)	Time (s)	Average surface roughness after lapping	Predicted roughnessvalue using quadratic equation	% Error	Roughness value using least square method	% Error
1	800	5	66	0.94	0.837	10.87	0.978	4.12
2	800	10	88	1.12	1.015	9.32	1.024	8.55
3	800	15	98	1.12	1.013	9.50	1.039	7.20
4	1000	5	88	1.17	1.013	13.62	1.109	5.45
5	1000	10	98	0.81	0.654	19.89	1.120	37.2
6	1000	15	66	1.04	0.884	15.57	1.031	1.46
7	1200	5	98	1.31	1.08	17.54	1.198	8.50
8	1200	10	66	1.07	0.843	21.45	1.098	2.30
9	1200	15	88	1.26	1.032	18.49	1.154	8.88
Avg						15.14		9.30

Table 7: S/N ratio for the crown for each experiment.

Exp.	Speed (rpm)	Torque (N-m)	Time (s)	Pinion avg. surfaceroughness	S/N ratio
1	800	5	66	1.83	-5.261
2	800	10	88	1.56	-3.959
3	800	15	98	1.54	-3.804
4	1000	5	88	1.74	-4.815
5	1000	10	98	1.89	-5.536
6	1000	15	66	1.7	-4.661
7	1200	5	98	1.34	-2.610
8	1200	10	66	1.54	-3.792
9	1200	15	88	1.57	-3.957

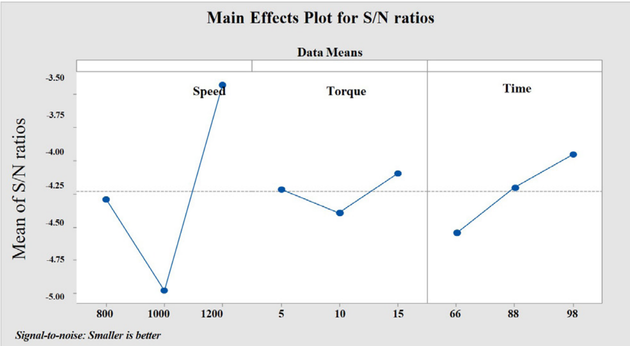

Figure 4: Main effects plot for S/N ratio of crown.

of a crown is 55.42% which is way larger than the percentage contribution of the other two parameters. The response table for S/N ratio (Table 9) for crown also shows that among all three input parameters, the surface response is most affected by speed followed by time and torque respectively which is the same as that of results interpreted from table 8. As the level of speed increases, the S/N ratio decreases reaching a minimum value at 'level 2' of speed and then increases as seen from figure 4. The same S/N ratio pattern is followed for torque. But, as the level for factor time increases, the S/N ratio increases reaching a maximum at 'level 3'. Due to the gear ratio associated with crown and pinion, the crown undergoes lesser revolutions per minute than pinion. Hence when the lapping speed, torque, and time are at the maximum value more and more abrasive particles rub against the surface of the crown with enough pressure and time to flatten all the asperities on the crown surface thus achieving a better surface finish. As the crown has a greater surface area to be lapped than pinion so abrasive particles get distributed throughout the surface thus avoiding plowing into its surface.

Table 8: ANOVA table for surface roughness of crown.

Source	DOF	Seq. SS	Adj. SS	Adj. MS	F-value	% contribution
Speed	2	0.126477	0.126477	0.063238	1.57	55.42
Torque	2	0.005847	0.005847	0.002923	0.07	2.56
Time	2	0.015262	0.015262	0.007631	0.19	6.69
Error	2	0.080632	0.080632	0.040316		35.33
Total	8	0.228217				100.00

Table 9: Response table for S/N ratio of crown.

Level	Speed (rpm)	Torque (N-m)	Time (s)
1	-4.293	-4.215	-4.542
2	-4.983	-4.393	-4.203
3	-3.424	-4.092	-3.955
Delta	1.559	0.301	0.587
Rank	1	3	2

Regression analysis of crown

A quadratic regression model to express response variables in terms of input process parameters has been developed using MINITAB 17 software following the same procedure as followed for the pinion. The equation developed is as follows,

$$Ra = 1.995 + (0.009825S) - (0.2668T) - (0.09557t) - (0.000005S^2) + (0.000457T^2) + (0.000766t^2) + (0.000247 * S * T) - (0.000025 * S * t)$$

Where, S, T, and t represent speed, torque, and time, respectively.

As can be seen from table 10, on comparing the experimental surface roughness value with the data obtained from two regression methods it has been found that the relative error in surface roughness using the least square method (7.008%) is way lesser than the relative error using a quadratic model (20.02%).

Conclusion

Bevel gear lapping with input process parameters (lapping speed, lapping time, and braking torque) to improve gear surface roughness is done. The following conclusions can be drawn from this work.

- In the optimization of surface finish of both pinion and crown, the most significant parameter is lapping speed followed by lapping time and braking torque.
- The optimum parameter levels (speed, torque, and time) predicted for minimum surface roughness of pinion are 1000 rpm, 10 Nm, and 66 s. Such behavior is due to increased contact time and reduced ploughing effects.

Table 10: Surface roughness comparison using different regression methods.

Exp.	Speed (rpm)	Torque (N-m)	Time (s)	Average experimental surface roughness after lapping	Predicted roughness value using quadratic equation	% Error	Roughness value using least square method	% Error
1	800	5	66	1.83	2.029	10.90	1.778	2.82
2	800	10	88	1.56	1.770	13.24	1.687	7.93
3	800	15	98	1.54	1.75	13.67	1.653	7.33
4	1000	5	88	1.74	2.05	18.05	1.611	7.40
5	1000	10	98	1.89	2.20	16.85	1.575	16.65
6	1000	15	66	1.7	2.01	17.93	1.677	1.34
7	1200	5	98	1.34	1.795	33.30	1.518	12.73
8	1200	10	66	1.54	1.975	28.02	1.613	4.52
9	1200	15	88	1.57	2.01	28.25	1.533	2.30
Avg						20.02		7.00

- The optimum parameter levels (speed, torque, and time) predicted for minimum surface roughness of crown are 1200 rpm, 15 Nm, and 98 s. Such behavior is due to the greater surface area of the crown, which leads to lower average pressure, thus minimizing ploughing.
- The absolute percentage error of surface roughness of pinion based on quadratic equation and least square method is 15.01%, and 9.30%, respectively.

The absolute percentage error of surface roughness of crown based on quadratic equation and least square method is 20.02%, and 7.08%, respectively.

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None.

Conflict of Interest

There are no relevant financial or non-financial competing interests to report.

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