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Original Article

Experimental Investigation of Nitrided Helical Gear with Different Helix Angles for Oil Drag Power Loss

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Abstract *- Gears are broadly utilized for raised RPM and prevalent torque capabilities in vehicles and engineering equipment. The majority of these drives are lubricated by splashing oil. This way a colossal measure of energy is squandered in overcoming the thick drag of oil experienced by gear. This adversity is known as drag loss. The drag loss happens because of the interaction between oil and gear surfaces. The test rig is planned and grown so testing of single helical gear for drag power loss can be measured precisely. Helical gear with a helix angle of 22° produced using SAE 9310 gear material is tried for drag power loss without Nitriding treatment. Then, the same Nitrided gear was tried for drag power loss. Nitriding of gear will, in general, solidify the outer layer of gear up to specific profundity by the testimony of nitrogen. The Central Composite Design (CCD) based Response Surface Methodology (RSM) was utilized to assess and streamline the drag power loss impact for nitrided and non-nitrided helical gears. The controlling factors gear rotating speed (RPM), volume of oil and oil temperature were thought of. A model was created, and in view of that, preliminary attempts were proposed to couple the controlling boundaries for limiting the drag power loss for the single helical gear at the ideal state of the cycle. It is seen that oil volume was the best affecting parameter for the drag power loss of gear in assessment with different other parameters like oil temperature, gear RPM etc. It very well might be because of most noteworthy F-insights an incentive for drag power loss. Furthermore, it is found that the nitrided helical gear encounters less drag from encompassing oil when contrasted with non nitrided gear. That might be because of the covering of the nitrogen layer over gear material, which furnishes a better surface with higher hardness subsequently, less oil drag is acting.*

Keywords *- Helical gear, Drag power loss, Nitriding, RSM, CCD.*

1. Introduction

The ongoing state of the fuel cost climb demonstrates that one ought to monitor it through critical activities. Assuming mileage is accomplished by profoundly proficient main players (motor), the issue of NOx outflow expands at a high level. This will confine the usage of high-productivity motors according to emanation control regulations. The main way to deal with trimming down fuel utilization is by overhauling transmission proficiency. Transmission proficiency in outfitted drives can be compacted in the wake of controlling losses. Heightening the overall proficiency of transmission includes careful assessment of all wellsprings of force losses inside the design. Highlighting on the equipped instrument of the transmission, the significant reasons for power losses can be divided into two classes [1, 2]: load-subordinate (mechanical) influence losses and burden autonomous (spin) influence losses. Mechanical power losses in gears essentially comprise frictional gear tooth contacts at the gear network, where the two significant methods of influence losses are the moving erosion and sliding rubbing related to joined sliding-moving speeds, typical powers, contact calculations, and outside unpleasantness. Then again, spin power losses in gears relate to the contacts of the gear bodies with a gooey medium encompassing them. Two critical parts of gear spin power losses are:

- Drag losses related to churning of the oil along the side faces and border of gears.
- Pocketing losses allied with the pumping of viscous medium from pockets formed between adjoining teeth at the gear mesh.

All component of force loss is connected with distinct working circumstances. Mechanical loss is the larger part huge at grand burden, short speed circumstance when the liquid film made at the contact connection points is the smallest good, causing significant grating. In gearboxes, working at low gear proportions makes such circumstances, while in a fast circumstance, spin losses are significant.

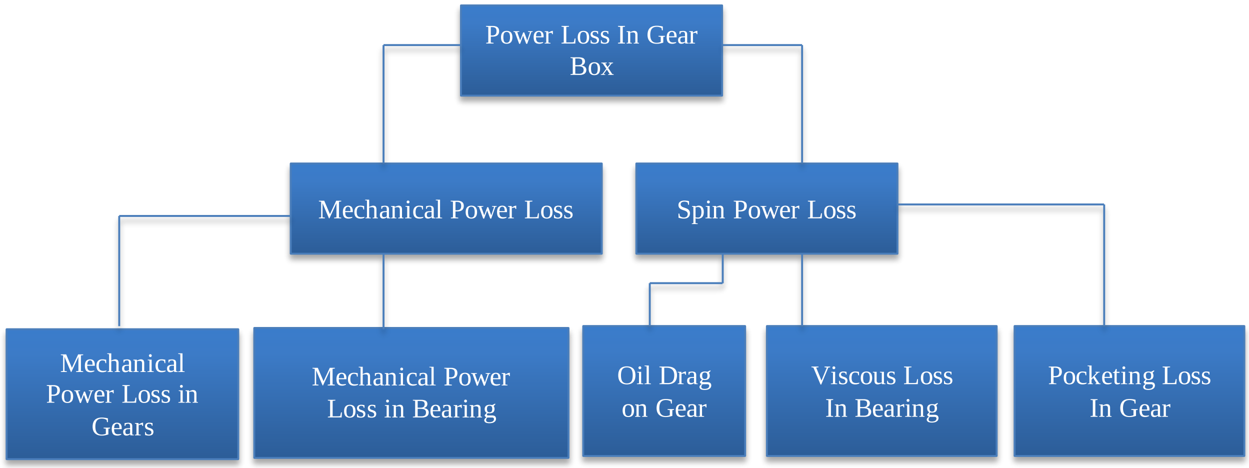


Fig. 1 Key factor of power losses of a gearbox

That is the reason interest in drag power losses of gearboxes is in most extreme need; writing on such losses is to some degree uncovered. The majority of the previous examinations focused on alternating plates so the multifaceted nature of the liquid stream in the locale of gear teeth is uninterested.

A simply modest number of fresher examinations has consolidated the gear teeth on the turning part. Early exertion by Terekhov [3] worried that drag power losses transfer generally on-stream system and not as much on tooth math and oil consistency. Boness [4] subsequently became famous for utilizing turning circles that drag power losses intensify with rising Reynolds number.

Luke and Olver [5] quick to firm conflict between the results of Terekhov and Boness and made information to make sense of a couple of them. Correspondingly, S.Jeon [6] and Seetharaman et al. [7] broadened the drag power misfortune exploratory record through a shut circle gear test apparatus to check the viability of spike and helical pinion wheels through changing module and outside wraps up under fly and plunge oild up environmental elements. Most recent preliminaries completed by Changenet and Velex [8, 9] noticed the impact of lodging extents in the encompassing region of a solitary turning gear pair on drag power losses.

They recognized under conditions where mating gears were bringing oil into draw in that the complete drag power misfortune was not just the expansion of the drag influence losses of the singular pinion wheels. There is no literature found on the effect of the nitriding case hardening process on drag power losses of a single gear. The prime content of this paper is the study of drag power loss when helical gear rotates in viscous oil and to find the amount of loss difference in carburized and non-carburized helical gear. With this aim, a helical gear test rig was constructed to discover the impact of nitriding on the drag power loss of helical gear.

2. Methodology

There are a few techniques to find the drag power loss in plunge oil for gear drive: Estimation of intensity loss, Torque estimation with torque sensor, and dormancy summary strategy.

The test rig was built in view of the direct estimation of torque is displayed in Figure 2. The testing set-up was built to evaluate the input torque of the helical gear shaft. Significant parts are the gearbox having single helical gear, 3 Horse Power (HP) and 1440 Rpm 3phase motor.

Motor speed fluctuates by factor recurrence drive, Temperature of oil is estimated by Thermocouple, Input torque is estimated by Optical torque sensor, Pneumatic stress inside the gearbox is estimated by pressure check, and Oil level inside the gearbox is estimated by glass tube level pointer. The entire set-up is introduced on the evened-out metal design, as displayed in Figure 2.

The space inside the gearbox is set for constant volume (190mmX190mmX260mm). A firm volume of oil was filled in the gearbox. With the assistance of a variable recurrence drive and speed controller motor was set to turn at a specific RPM. The torque sensor estimated input torque, and the equivalent was shown on the torque sensor regulator show.

The thermocouple fitted inside the gearbox was showing perusing of temperature inside the gearbox on the presentation. Level pointer glass tube assisted with concluding drenching profundity of gear in greasing up oil.

At first, a non-nitrided single helical gear with 22° helix point was tried for various oil levels, Rpm, and temperature inside the gearbox. The same size nitrided helical gear was tried for the same cycle boundary. The contrast of input torque was recorded to know the impact of nitriding on drag power loss of test examples.

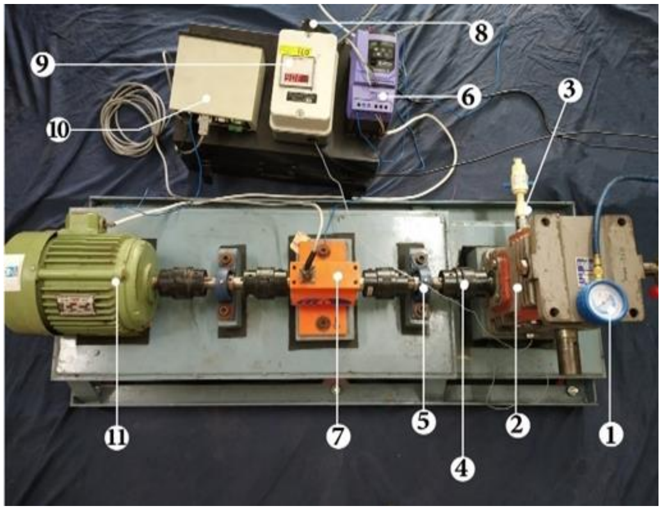


Fig. 2 Gearbox drag power loss test rig

1) Pressure gauge. 2) Gearbox with single helical gear inside 3) Level indicator glass tube port r 4) Jaw coupler 5) footstep bearing 6) VFD 7) Torque sensor 8) Speed regulator 9) Display of thermocouple temperature 10) Display of torque sensor reading 11) 3HP 3Phase AC motor

2.1. Test Specimen Gear

Single helical gear with helix point 18° produced using SAE9310 gear material was utilized as a test sample, as displayed in Figure 3. Determinations of the test sample are given in Table 1.

Fig. 3 Test specimen after testing

Table 1. Test sample dimensions and property

Test Specimen	**Gear-1**	**Gear-2**
Material	SAE9310	SAE9310
Pitch Circle Dia.	125mm	125mm
Addendum	130mm	130mm
Root Dia.	120mm	120mm
Face Width	35mm	35mm
Chordal Thickness	6mm	6mm
Number of Teeth	29	29
Module	4.3	4.3
Shaft Hole Dia.	45mm	45mm
Heat Treatment Process	None	Nitriding
Effective Case Depth	None	0.63mm
Surface Hardness	HRC39	HRC62

In the vast majority of cases, gearboxes used in ventures are loaded up with mineral oil or manufactured oil [10, 11]. Presently, a day's Polyalphaolefin (PAO) turn into the best option for gearbox applications inferable from properties of diminishing erosion and expanded life. PAO was utilized for the testing and its properties are signified in Table 2.

Table 2. Gearbox oil properties

Lubricant PAO Grade 320 Synthetic Oil Property	**Value**
Kinematic Viscosity@ 40°C	330cSt
Kinematic Viscosity@ 100°C	36cSt
Viscosity Index	162
Density@15°C	790kg/m^3

2.2. Testing Work

All tests were completed stands on the strategy for direct input torque estimation. Response Surface Methodology (RSM) was utilized to go over the best test conditions, which required the least number of testicles to accomplish adequate outcomes. As the RSM method is a mix of factual and quantitative methodology, it can assist with accomplishing the required test results. This work is performed by Central Composite Design (CCD) to find the drag power loss of a single helical gear. For three test factors, 6 pivotal focuses, six reproduces at the mid places, and eight factorial focuses were utilized for the CCD design [12-16].

Table 3. The level of independent variables for the experiments

Independent Variable	**Symbol**	**Level of Coded variable**				
		-α	**Low**	**Medium**	**High**	**+α**
		-1.6817	-1	0	+1	+1.6817
Helical Gear Speed (RPM)	A	764	900	1100	1300	1436
Lubricant Volume (lit.)	B	0.3	1	2	3	3.7
Lubricant Temperature (°C)	C	37	40	45	50	54

Table 4. The design of experiments with their observed and predictive values

Std Run No	Run	Independent Variable in Coded Form			Experiment work		
		A	B	C	Input Torque for Non-Nitriding Gear (N.m)	Input Torque for Nitriding Gear (N.m)	Difference of input torque for Nitrided and Non Nitrided Gear (N.m)
5	1	-1	-1	1	1.63	1.59	0.04
13	2	0	0	-α	1.79	1.78	0.01
10	3	+α	0	0	1.81	1.80	0.01
12	4	0	+α	0	2	2	0
19	5	0	0	0	1.35	1.32	0.03
8	6	1	1	1	1.87	1.87	0
18	7	0	0	0	1.27	1.25	0.02
9	8	- α	0	0	1.03	0.92	0.11
16	9	0	0	0	1.41	1.4	0.01
17	10	0	0	0	1.51	1.45	0.06
14	11	0	0	+α	1.26	1.23	0.03
3	12	-1	1	-1	1.56	1.54	0.02
7	13	-1	1	1	1.13	1.1	0.03
4	14	1	1	-1	2.1	2.1	0
6	15	1	-1	1	0.79	0.6	0.19
20	16	0	0	0	1.41	1.4	0.01
1	17	-1	-1	-1	-0.381	0.8	-1.181
15	18	0	0	0	1.56	1.53	0.03
11	19	0	-α	0	0.202	0.2	0.002
2	20	1	-1	-1	1.08	0.6	0.48

The gear Rpm, Oil volume and oil temperature were chosen as components for the CCD to find the drag power loss of a single helical gear gearbox. Torque of these elements had been browsed and concentrated on writing. Drag power loss was picked as a reaction. Each variable was explored for five levels. The helical speed, volume of oil, and temperature of the oil were picked as elements in the CCD to research the drag power loss for helical gear. Their level had been chosen in light of pilot examinations and writing surveys. As a reaction, the drag power loss was picked. Every variable was broken down into five distinct levels: −α, −1, 0, +1, and +α, as displayed in Table 3. The result (Input torque) of the trials is displayed in Table 4. The measurable programming "Design Expert 10" was utilized to concentrate on the relapse examination of trial information and used to plot the chart. The examination of variance (ANOVA) was utilized to break down the meaning of the factual parameters [15]. The 95% certainty level ($\alpha = 0.05$) was utilized in all examinations to decide factual importance.

3. Results and Discussion

A variety of descriptive statistics, including degree of freedom (df), p-value, and F-value, were used to assess the results. Tables 5 and 6 demonstrate that the model was very significant and may be utilized to predict the response function due to its low probability value ($p < 0.001$).

3.1. The Analysis of Variance for Nitrided Helical Gear (Helix Angle 18°)

By comparing the coefficients of the variables in the equation, one can use the equation expressed in terms of coded factors to ascertain the relative importance of the variables. They can also be used to predict the responses of each variable to various amounts of variables. The low level of variables is coded as -1, and the high level of variables has a default value of +1. The model equation that depicts, in terms of actual values, the following equation gives the relationship between the response and the operating variables. A final equation in terms of actual factors:

Input Torque = -6.53003 + 4.61083E-003 * Speed + 0.13226 * Lubricant Volume + 0.20264 * Lubricant Temperature + 1.20000E-003 * Speed * Lubricant Volume - 1.47500E-004 * Speed * Lubricant Temperature - 0.021500 * Lubricant Volume * Lubricant.

The model is significant, as indicated by the model's F-value of 9.91. The probability that an F-value this great may be the result of noise is only 0.03%. "Prob > F" values less than 0.0500 suggest the significance of the model terms. AB is a crucial model term in this instance. The model terms are not important if the value is bigger than 0.1000. The "Lack of Fit F-value" of 4.06 indicates that noise has a 6.97% probability of causing a "Lack of Fit F-value" this high.

Table 5. ANOVA for the response for nitrided gear (Helix Angle 18°)

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob> F	Remark
Model	4.04	6	0.67	9.91	0.0003	Significant
A-Speed	0.079	1	0.079	1.17	0.2992	
B-Lubricant Volume	1.251E-003	1	1.251E-003	0.018	0.8942	
C-Lubricant Temperature	0.24	1	0.24	3.47	0.0853	
AB	0.46	1	0.46	6.78	0.0219	
AC	0.17	1	0.17	2.56	0.1336	
BC	0.092	1	0.092	1.36	0.2645	
Residual	0.88	13	0.068			
Lack of Fit	0.77	8	0.096	4.06	0.0697	Not Significant
Pure Error	0.12	5	0.024			
Cor Total	4.93	19				

Table 6. Fit summary of the quadratic regression model

Std. Dev.	0.26	R^2	0.9206
Mean	1.33	Adj R^2	0.9079
C.V. %	19.62	Pred R^2	0.8975
PRESS	3.05	Adeq Precision	12.262
-2 Log Likelihood	-5.63	BIC	15.34
		AICc	17.71

As one might typically assume, the "Pred R2" of 0.8975 is rather near to the "Adj R2" of 0.9079; that is, the difference is less than 0.2. Confirmation runs should be used to test all empirical models."Adeq Precision" calculates the ratio of signal to noise. Ideally, the ratio should be higher than 4. Our ratio of 12.262 shows a sufficient signal. The design area can be navigated with the help of this model.

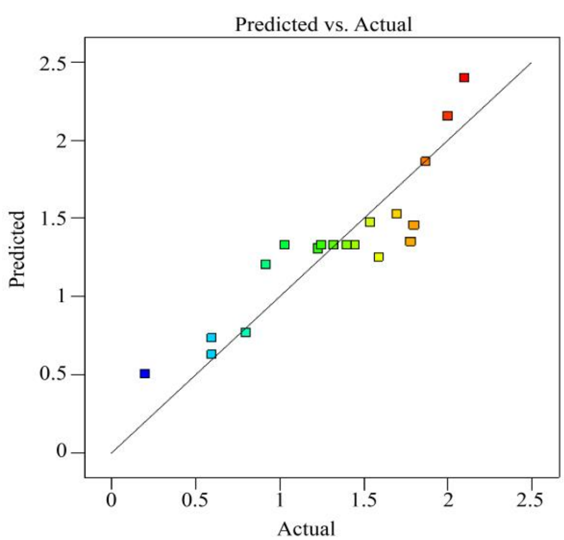


Fig. 4(a) Predicted versus experimental input torque

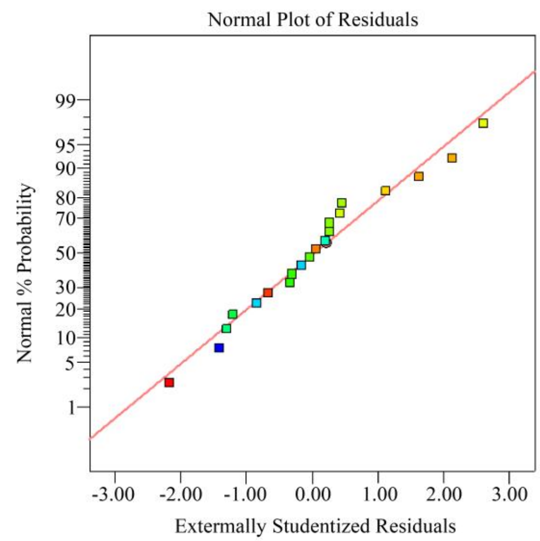


Fig. 4(b) Normal probability plots of the residual (normal distribution of residuals)

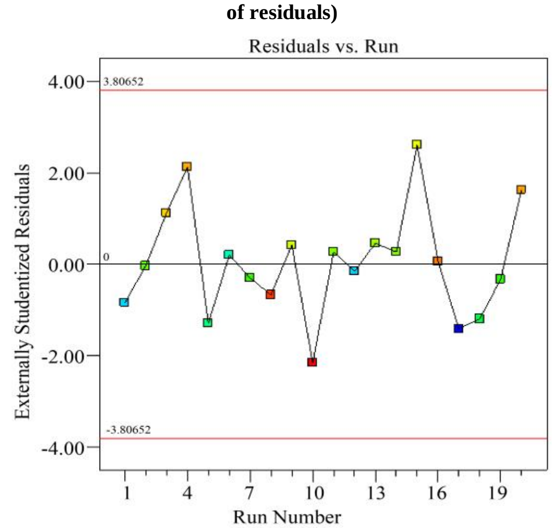


Fig. 4(c) Residual versus run orders

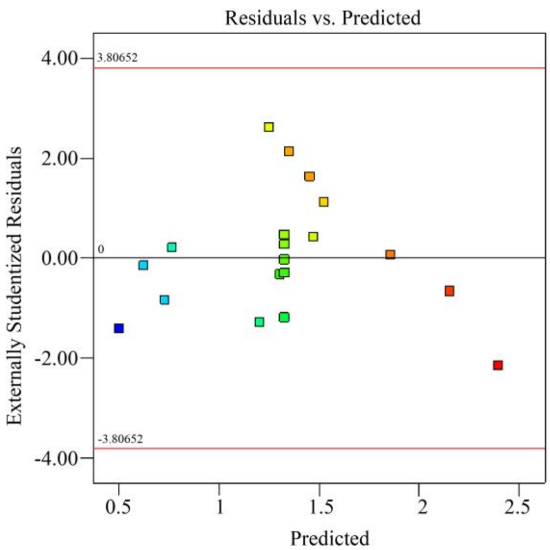


Fig. 4(d) Residual versus predicted response

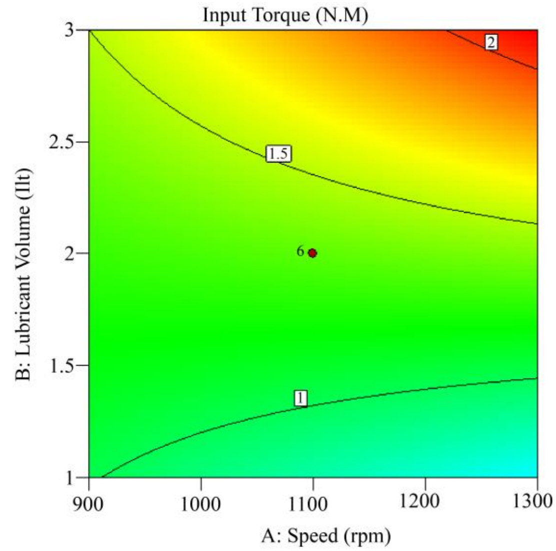


Fig. 5(a) Contour plot showing the effects of speed and lubricant volume

The discrepancy between the estimated and actual response estimates is displayed in residual plots, which are used to assess the quadratic model's validity. As illustrated in Figures 4(a), 4(b), 4(c), and 4(d), respectively, this inquiry is conducted utilizing the expected against experimental input torque, normal probability plot of residuals, residual versus run orders, and residual versus the predicted response. A straight line that has been harmonized in the ordinary residual plot, as shown in Figure 4(b), indicates a high degree of conformance. This graph illustrates how the error is negligible and regularly distributed in a straight line. The random patterns in the residuals would show how accurate the model was. A studentized plot of residuals vs predicted response is shown in Figures 4(c) and 4(d), suggesting that.

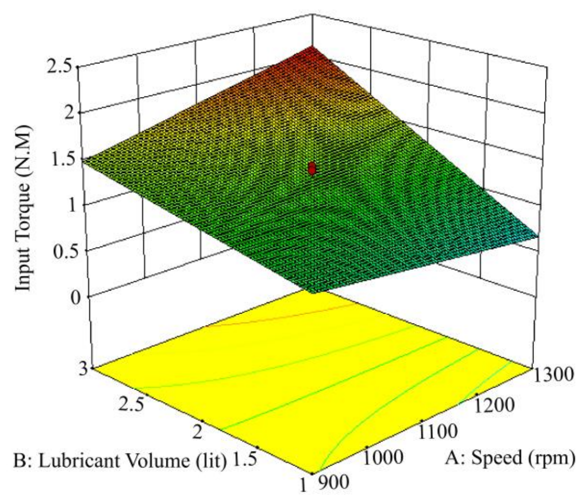


Fig. 5(b) Response surface plot showing the effects of speed and lubricant volume

3.2. Aggregate Involvement of the Autonomous Operating Variables on the Input Torque for Nitrided Helical Gear (Helix Angle 18°)

Although researching the autonomous operational variable's involvement can offer some insight into how these factors impact the input torque, it does not offer a comprehensive understanding of the relationships between these variables and how they collectively affect the input torque. Response surface and contour plots were created to verify how operational factors collectively affected the input torque.

3.2.1. Aggregate Involvement of Gear Speed (A) and Lubricant Volume (B)

Figures 5(a) and (b) display the contour plot and surface plot for the tested nitrided helical gear (Helix angle 18°) with the combined effects of gear speed (900–1300RPM) and lubricant volume (1-3ltr) on input torque. At 45°C, the lubricant temperature (C) is maintained consistently. Greater input torque is the result of increased gear speed (A) and lubricant volume (B), both of which affect the input torque.

As the gear speed (RPM) and lubricant volume (B) rose, the input torque rapidly climbed and reached over 2.39 Nm at 1300 RPM and 3 liters of lubricant volume. An increase in input torque results in a sharp increase in drag power loss. The maximum input torque was achieved at 1300 RPM when the lubricant volume (B) was equal to 3 liters. At 1 liter of lubricant volume (B) and 900 RPM, the lowest input torque (0.6 Nm) was recorded. A torque of 1 Nm was obtained as the input at 1300 RPM and 1 liter of lubricant volume. At 900 RPM and 3 liters of lubricant capacity, a moderate input torque of 1.51 Nm was achieved. The results above demonstrate that a gear encounters more oil drag at a higher rotational speed and lubricant volume, necessitating the provision of more torque in comparison to a lower rotational speed and lower lubricant volume. In this case, the input torque is significantly impacted by both the gear speed (A) and lubricant volume (B) parameters at the same time.

3.2.2. Aggregate Involvements of Gear Speed (A) and Lubricant Temperature (C)

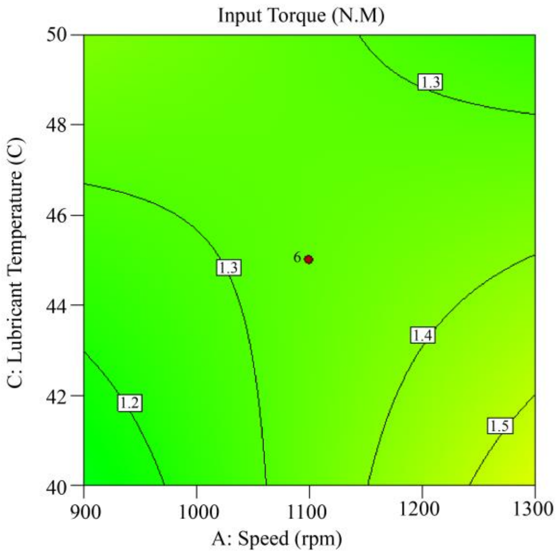


Fig. 6(a) Contour plot showing the effects of Speed and lubricant temperature

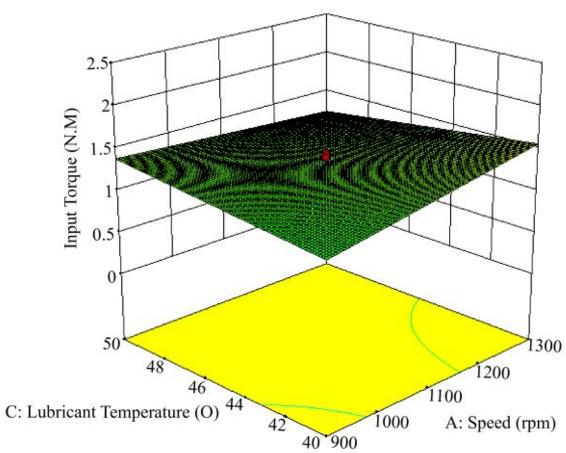


Fig. 6(b) Response surface plot showing the effects of speed and lubricant temperature

Figures 6(a) and (b) depict the contour plot and surface plot for the tested nitrided helical gear (Helix angle 18°) with the combined effects of the gear speed (900–1300RPM) and the lubricant temperature (40´–50℃) on the input torque. Two liters is the constant lubricant volume (B). Higher input torque is the result of a significant relationship between gear speed (A) and input torque. As the gear speed (RPM) increased, the input torque rapidly increased and reached around 1.56 Nm at 40´C. An increase in input torque results in a sharp increase in drag power loss. 1300 RPM yielded the maximum input torque at 40´ C oil temperature. At 900 RPM and 50°C, the lowest input torque (1.38 Nm) was recorded. 1.47 Nm of input torque was obtained at 50°C and 1300 RPM. At 40´ C and 900 RPM, the intermediate input torque was measured. The data above make it evident that a gear encounters more oil drag at higher rotational speeds, necessitating the provision of greater torque in comparison to lower rotational speeds. The amount of input torque needed to rotate a gear is inversely related to the temperature of the oil. It is evident that as the temperature rises, oil viscosity decreases, reducing the amount of drag that the gears must resist.

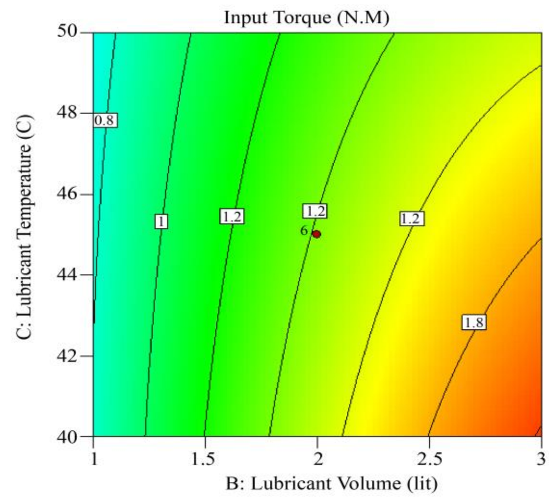


Fig. 7(a) Contour plot showing the effects of lubricant temperature and lubricant volume

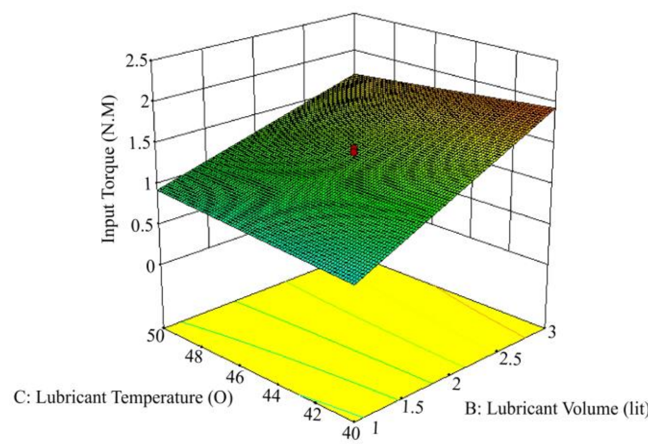


Fig. 7(b) Response surface plot showing the effects of lubricant temperature and lubricant volume

Figures 7(a) and (b) display the contour plot and surface plot for the tested nitrided helical gear (Helix angle 18°) with the combined effects of Lubricant Temperature (40-50℃) and lubricant volume (1-3ltr) on input torque. At 1100 RPM, the gear speed (B) is maintained constant. Higher lubricant volume (B) and lower lubricant temperature (C) both affect input torque, leading to a greater input torque. As the lubricant temperature (C) dropped and the lubricant volume (B) rose, the input torque rapidly climbed and reached over 1.93 Nm at 1100 RPM. An increase in input torque results in a sharp increase in drag power loss. The maximum input torque was achieved at 40℃ when the lubricant volume (B) was equal to 3 liters. The 1 liter oil volume (B) and 50´C oil temperature (C) produced the lowest input torque (0.93 Nm). With a 1 liter lubricant volume and 40´C, 0.73 Nm of input torque was achieved. With 3 liters of lubricant volume and a 45´C lubricant temperature (C), a mild input torque of 1.79 was achieved. Based on the findings above, it is evident that when the lubricant volume (B) and temperature (C) are higher, the gear encounters more oil drag. Consequently, the gear has to deliver more torque when the lubricant volume (B) and temperature (C) are lower. In this case, the parameters lubricant temperature (C) and lubricant volume (B) have less of an impact on the input torque.

Table 7. Confirmation report

Two-Sided	**Confidence**	**95%**	**n =**	**1**		
Factor	Name	Level	Low Level	High Level	Std. Dev.	Coding
A	Speed	1236.04	900	1300	0.00	Actual
B	Lubricant Volume	2.4166	1	3	0.00	Actual
C	Lubricant Temperature	44.3396	40.00	50.00	0.00	Actual

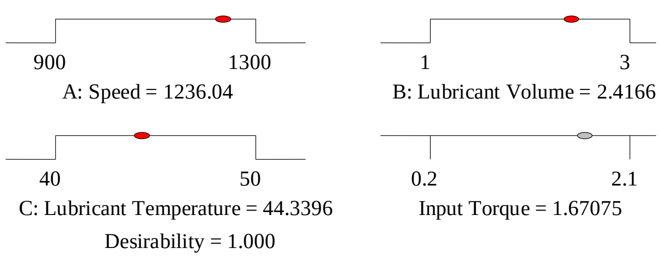


Fig. 8 Ramp graph for nitrided helical gear (Helix angle 18°)

Based on the results of the ramp graph, three confirmation tests were carried out. Tests on a test rig with identical settings were performed on nitrided helical gears (helix angle 18´), and the input torque was recorded as shown in the table.

The input torque value produced by the model with allowable error is confirmed by the above-tabulated value confirmation test, indicating that the model accurately represents the torque loss process.

3.2.3. Comparison of Optimum Parameters for Nitrided Gears with Different Helix Angles

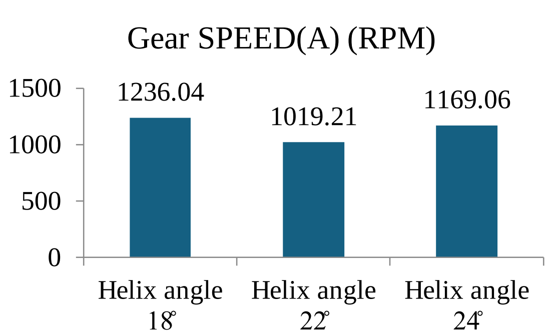
Table 9 lists the optimized parameters for nitrided gears with three distinct helix angles (18´, 22°, and 24°) that were determined from constructed models.

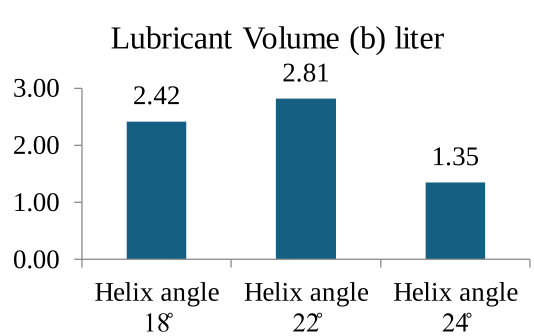
Table 8. Confirmation run nitrided helical gear Helix angle 18°

Test No.	**Gear speed (A) (RPM)**	**Lubricant Volume (B) (liter)**	**Lubricant Temp (°C)**	**Recorded Input Torque (Nm)**	**Test Average Input Torque (Nm)**	**Input Torque Predicted by Model (Nm)**	**Deviation %**
1	1236	2.4	44	1.71	1.7	1.67	0.03 (5%)
2	1236	2.4	44	1.69			
3	1236	2.4	44	1.7			

Table 9. Comparison of optimized parameters for nitrided gears

Parameters	**Helix Angle 18°**	**Helix Angle 22°**	**Helix Angle 24°**
Gear Speed (A) (RPM)	1236.04	1019.21	1169.06
Lubricant Volume (B) liter	2.4166	2.81444	1.34947
Lubricant Temperature (C)	44.3396	49.2933	45.0845
Input Torque (Nm)	1.67	1.37	1.05





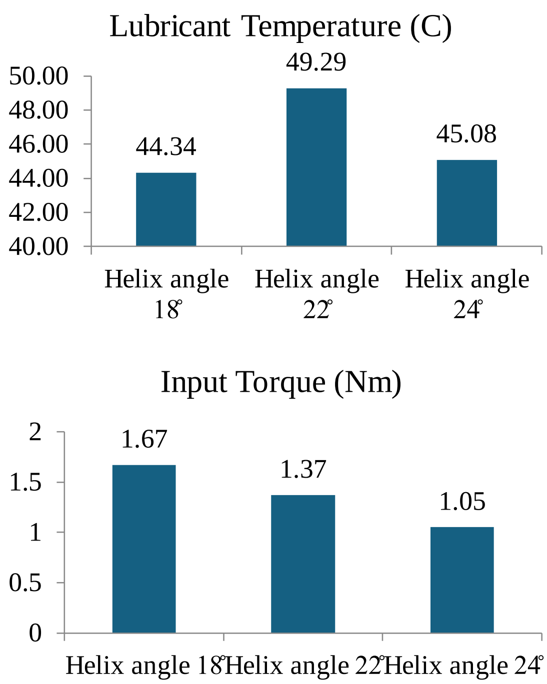


Fig. 9 Comparison graphs of helix angle vs optimized parameters for nitrided gears

For nitrided gears with three distinct helix angles, Figure 9 illustrates the fluctuation of optimum values at various helix angles. The helix angle 22° showed the lowest gear speed (1091.21 RPM), while the helix angle 18° showed the maximum gear speed (1236.04 RPM). The gear with the biggest lubricating oil capacity (2.81 liters) and the lowest (1.35 liters) had the helix angle of 22∨ and 24°, respectively. The gear with a helix angle 22¯ recorded the maximum lubricating oil temperature of 49.29∨C, while the helix angle 18¯ recorded the lowest temperature of 44.3¯C. The nitrided gear with a helix angle 24° showed the lowest input torque of 1.5 Nm, while the helix angle 18° showed the maximum input torque of 1.67 Nm.

4. Conclusion

The experimental study that led to the conclusions above:

- The analysis of the test has demonstrated that RSM is an effective technique for successfully verifying the parameters of gear drag power loss.
- The ANNOVA results show that, for both nitrided and non-nitrided gears, lubricant temperature has little effect on input torque, while gear rotation speed and lubricant volume have a significant impact.
- The testing results demonstrated that when the speed of rotation and lubricating oil volume were reduced, the gear had the least drag power loss, requiring less input torque for both nitrided and non-nitrided gears. Higher drag power loss was noted at higher rotational speeds and lubricant volumes.
- Temperature was not a major parameter within a particular range for lubricant up to 45´ C; therefore, the input torques required for both nitrided and non-nitrided gear were closer to each other.
- Furthermore, it was noted that the process of nitriding gears alters their surface asperities by producing a layer of nitrogen coating. This may be the reason for the observed reduction in surface roughness, which leads to a lower level of oil drag resistance in nitrided gear as compared to non-nitrided gear.
- Ultimately, based on the findings above, it is recommended to nitride gear in order to decrease oil drag power loss and increase gear drive efficiency.

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