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Optimization of the operating parameters to minimize gear tooth wear rate and surface temperature of glass fiber filled HDPE based homogeneous and FGM gears

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Abstract. This study emphasis on the optimization of the operating parameters viz. gear fabrication technique, rotational speed and applied torque on fabricated gears to improve their performance. Polymer gears are injection molded using conventional and horizontal centrifugal casting technique known as homogeneous and FGM gears, respectively. Material used to fabricate the gear is High Density Polyethylene (HDPE). Taguchi technique is used to optimize the performance output of homogeneous and FGM gears with respect to input parameters such as torque and rotational speeds. Three different rotational speeds of 400, 700 and 1000 rpm along with three different torque levels of 1, 2 and 3 Nm are selected for this investigation. Number of cycles of 1.5×10^5 was fixed for the experimentation. The influence of input control parameters on performance output is analysed by ANOVA analysis. The results finding show that the thermal behavior of gear is very much affected by torque whereas the specific wear rate (WR) is utmost pointedly influenced by the gear fabrication technique i.e. FGM gear has small tooth wear in the compression of homogeneous and neat HDPE gears.

1. Introduction

Traditionally, gears have been used for transmitting power in machines. The function of gearbox of a vehicle is not possible without gears. Power and motion transmission from gear is more efficient as compared to chain drives, belt drives and rope drives. Now days, polymer gears have emerged as a substitute of metallic gears in many applications. It is happening due to the advancement in the polymer gearing field. Polymer gear has low noise, speedy manufacturing, light weight, self-lubricating nature and capability to dampen moderate shock and impact (Adams, 1986). Temperature, time and stress level are the variables at which the properties of polymer gears depends (Targett and Nightingale, 1969). Normally, machining of a rod or injection molding is used to fabricate the polymer gears (Narracott, 1969).

Polymer gears have got the attention of many researchers in the last two decades (Singh et al. 2017). It has observed that performance of polymer gear in very much depends on the torque, speed and gear material. Most commonly thermoplastic materials like Polyamide 66, Nylon, Acetal etc. are used to manufacture the plastic gears. Thermosetting materials like Polyester and Polyurethane are also used to fabricate polymer gears (Adams, 1986). Senthilvelan and Gnanamoorthy (2007) observed that performance of gears is influence only at high stress levels causes due to the rotational speed. Less wear on the polymer gear teeth is observed at high rotational speed because of contact period of single tooth decrease. (Senthilvelan and Gnanamoorthy, 2004). It has been observed by Mao et al. (1996, 2006, 2007, 2009, and 2015) and Hooke et a. (1993) that at critical value of transmitted torque a sudden increment is observed in WR. The reason for this is the temperature of granules used to fabricate gear attains a value near to its melting point at critical torque. Therefore, it is clear that polymer gears are very sensitive to the surface temperature (ST) and it should be taken care off. Damping of vibrations, transmission efficiency and noise are other important characteristics of polymer gears except ST and WR. (Senthilvelan and Gnanamoorthy, 2009) observed that transmission efficiency of plastic gear decreases with increasing number of cycles. Deterioration in the gear tooth is the main reason for this phenomenon. The generation of noise in polymer gears is mainly caused by rotational speed. However, the role of torque is negligible in noise generation from polymer gears (Dearn and Walton, 2009). Usually, the sound level is directly depends on the speed for nearly all plastic gears excluding the fabricated gears of Polyoxymethylene (POM). Reverse trend is observed for POM fabricated gears (Hoskins et al. 2011). It is observed that gear pair of PC/ABS performs comparatively well at low load conditions because gear tooth surface melting is observed at high load (Yakut et al. 2011). Composite gears filled with fibers performed better in the context of thermal behavior and wear of polymer gear teeth (Gurunathan et al. 2011, Kurokawa et al. 2003, Singh et al. 2017). It has also observed that composite gears have better transmission efficiency (Senthilvelan and Gnanamoorthy, 2009, Walton et al. 2002). A novel polymer gear fabrication technique known as functionally graded materials (FGMs) based polymer gears is developed by Singh and Siddhartha (2017). The performance of FGM based gears are observed better as compared to conventionally fabricated polymer composite gears.

Experimental work is a costly and time taking process. Therefore, least number of experimental runs using design the experiment is required without compromising the quality of results. To make this possible, Taguchi technique is used in this work which also provides the optimized combination of control parameters for the performance output (Phadke, 1989, Ross, 1996, Naik and Reddy 2018, Liu et al. 2019). Orthogonal array (Kumar and Singh, 2019) is used in Taguchi technique for the analysis of each input factors having various levels. The analysis is done in the term of signal-to-noise ratio (S/N) in Taguchihtechnique.

2. Details of Experimentation

2.1. Sample fabrication

HDPE material filled with 30 wt% of glass fiber is used for the manufacturing of FGMs and homogeneous gears. Moisture from the HDPE granuals are removed by preheating at 80 ^{0}C for 3 hours before the fabrication of HDEP gears. Barrel temperature of three stages were used as 190 ^{0}C, 200 ^{0}C, 210 ^{0}C and the injection pressure was maintaned at 50 MPa. A punce is used to manufacture the FGM gears. Punch was rotated with the help of servomoter at 1800 rpm for 2 minutes after pouring the molten HDPE material into the cavity of punch. Rotation of the punch is not required to fabricate the homogeneous gears. The same fiber reinforced HDPE material is used for homogeneous gear fabrication as it is used for the fabrication of FGM gear. Neat HDPE gear is also manufactured for the comperasion with FGM and homogeneous gears performance. Fabricated neat HDPE, homogeneous and FGM gears are presented in Figure 1 (a), (b) and (c), respectively. Injection molding parameters for HDPE gears fabrication are shown in Table 1.

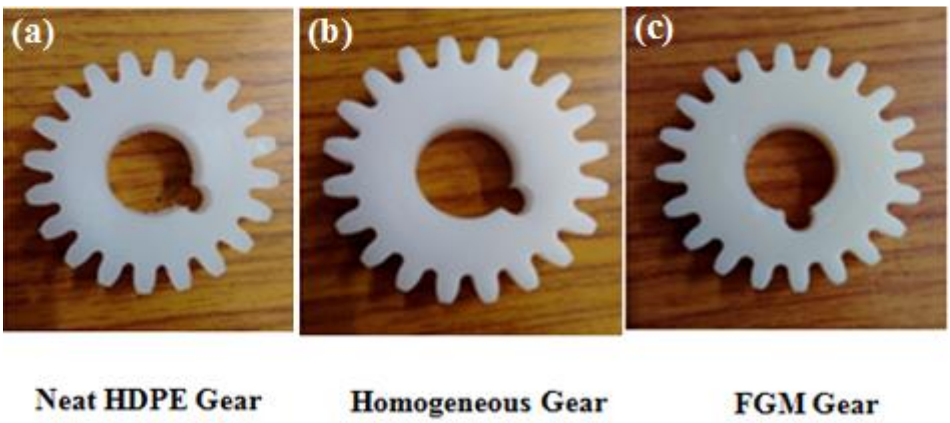

Figure 1 Injection molded HDPE gears

Table 1 Injection molding parameters for HDPE gears fabrication

	Homogeneous	**FGM**
Drying temperature of granules [℃]	80	
Injection molding pressure [MPa]	50	
Mold press temperature [℃]	140	
Injection mold temperature [℃]	55	
Waiting time of material in mold [s]	25	145
Complete cycle time for gear fabrication [s]	40	160

2.2 Gears test rig used for experimentation

A polymer gear test rig having the model number CM-9108 is used for gear testing. This test rig have the ability to run at different sets of rotational speeds and torques. The speed and torque of the test rig has a range of 400 – 2400 rpm and 0.8 – 4 Nm, respectively. The torque on the test gear is adjusted through rheostat that is fitted in the test rig. Test rig is supplied by a company named with DUCOM situated in Bangalore, India. The value of speed and torque is given to machine through a computer monitor. WINDUCOM 2010 software is used to give the command from computer monitor to the machine. Torque and temperature is measure through the torque and temperature sensors which is fitted on the test rig. Polymer gear test rig along with their components is shown in Fig. 2.

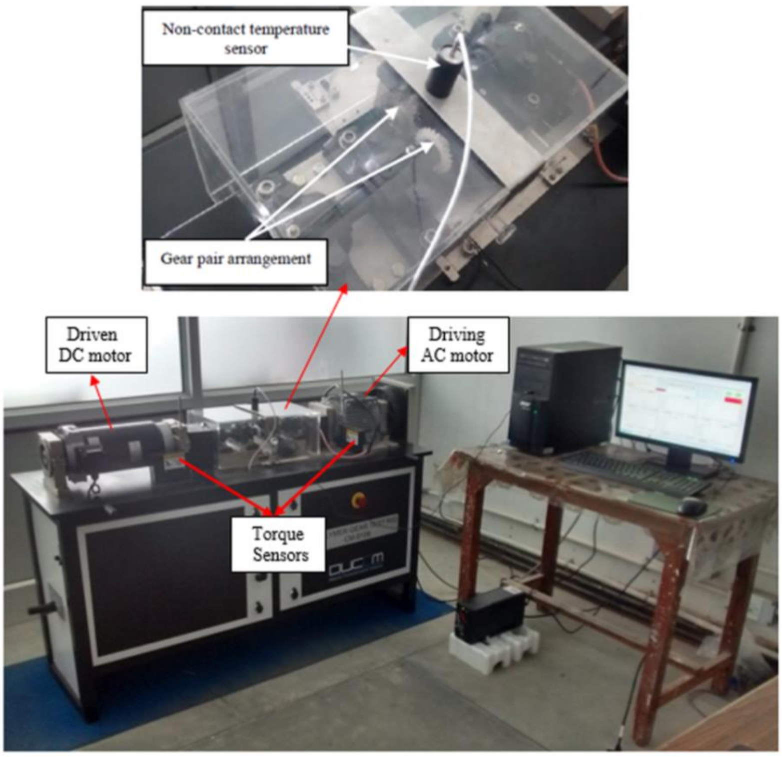

Figure 2 Test rig for polymer gears

A digital electronic balance is used to measure the weight loss from the gear tooth surface. The equation to calculate the WR of HDPE gears is given as:

$$k = \frac{m \times r_p}{2 \times \rho \times T \times z \times N_c \times \sum_{n=1}^{m} \sqrt{(x_{n+1}-x_n)^2+(y_{n+1}-y_n)^2}} \quad (1)$$

Here, k is specific WR (mm^3/N-m), ρ denotes the density of material, T is applied torque, z is the number of teeth, m is the mass loss, r_p is the pitsh circle ratius and N_c is the number of cycle.

2.3 Experimental design

Expermintal design is carried out by using Taguchi technique. As shown in Table 2, there are three factors and three levels of each factor is used in this work. Rotational speed, torque and type of gears are taken as three input parameters for current study. Based on these input parameters, a L27 array was developed with the help of MINITAB 17. ST and WR are decided as the output parameters for this study. 'Smaller-is-better' criterion has been found to be relevant for both ST and WR. Table 3 provides all combinations of input parameters and the corresponding responses for output parameters. Interaction between the input factors is also obtained as per the Figure 3.

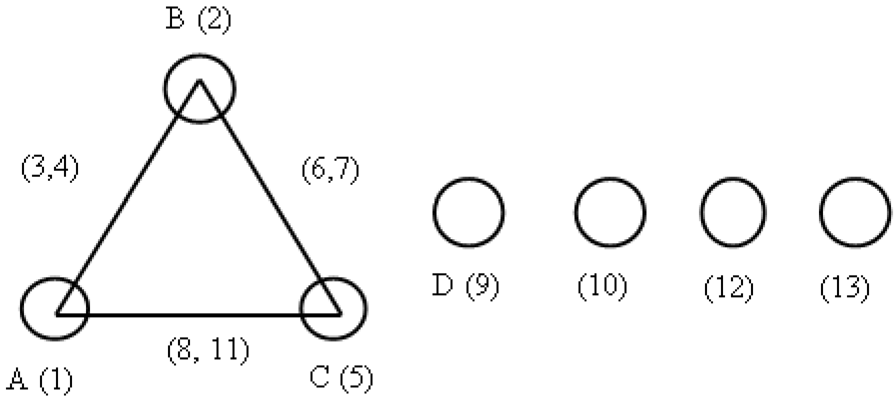

Figure 3 Representation of linear graph of L_{27} orthogonal array

Table 2 Control factors with three levels

Control Factor		**Levels**		**Units**
	I	II	III	
Rotational Speed (A)	400	700	1000	rpm
Torque (B)	1	2	3	Nm
Type of Gears (C)	Neat Gear	Homogeneous Gear	FGM Gear	

3. Results and discussion

3.1 Analysis of Taguchi experiments

Table 3 provides the outcomes of Taguchi experiment in the form of S/N ratio. Figure 4 and 5 represent the influence of the control parameters on ST and WR of plastic gears, respectively. The control factors (i.e. operating parameters) are represented at the top and their different levels at the bottom on the x-axis. The values of the S/N ratio are represented along the y-axis, as shown in Figure 4 and 5. The dashed straight lines indicate the whole mean of S/N ratio. The S/N ratio of WR is obtained as -35.0937 dB and -10.6853 dB for gear tooth ST. In case of (S/N) ratio, one needs to minimize the noise. Thus, the factor having maximum value of S/N ratio is considered to be the best value. Analysis of the results shows that factor combination of speed A_1 (400 rpm), torque B_1 (1 Nm) and polymer gear C_3 (FGM Gear) has the highest value of S/N ratios and provide the lowest ST at the interacting tooth surface of HDPE and steel gear as represented in Figure 4. Similarly, the lowest WR is found at the combination of A_3 (1000 rpm), B_1 (1 Nm) and C_3 (FGM gear) having the highest values of S/N ratios, as shown in Figure 5.

Table 3 L_{27} orthogonal array table

Runs	Speed (rpm)	Torque (Nm)	Type of Gears	Surface Temperature [℃]	S/N Ratio [dB]	Specific Wear Rate (mm^3/Nm)	S/N Ratio [dB]
1	400	1	Neat	50	-33.9794	4.17068	-12.4041
2	400	1	Homogeneous	44	-32.8691	3.79723	-11.5893
3	400	1	FGM	33	-30.3703	3.15979	-9.9932
4	400	2	Neat	62	-35.8478	4.22943	-12.5256
5	400	2	Homogeneous	56	-34.9638	3.92634	-11.8798
6	400	2	FGM	44	-32.8691	3.26481	-10.2772
7	400	3	Neat	74	-37.3846	4.33352	-12.7368
8	400	3	Homogeneous	68	-36.6502	4.15645	-12.3745
9	400	3	FGM	53	-34.4855	3.40443	-10.6409
10	700	1	Neat	57	-35.1175	3.78364	-11.5582
11	700	1	Homogeneous	51	-34.1514	3.49834	-10.8772
12	700	1	FGM	39	-31.8213	2.79372	-8.9237
13	700	2	Neat	68	-36.6502	3.68401	-11.3264
14	700	2	Homogeneous	59	-35.4170	3.69824	-11.3599
15	700	2	FGM	47	-33.4420	2.92719	-9.3290
16	700	3	Neat	78	-37.8419	3.75934	-11.5022
17	700	3	Homogeneous	67	-36.5215	3.85261	-11.7151
18	700	3	FGM	56	-34.9638	3.12871	-9.9073
19	1000	1	Neat	60	-35.5630	3.40647	-10.6461
20	1000	1	Homogeneous	54	-34.6479	2.87989	-9.1875
21	1000	1	FGM	42	-32.4650	2.42494	-7.6940

22	1000	2	Neat	72	-37.1466	3.39143	-10.6077
23	1000	2	Homogeneous	66	-36.3909	3.27538	-10.3052
24	1000	2	FGM	51	-34.1514	2.68261	-8.5712
25	1000	3	Neat	83	-38.3816	3.38048	-10.5796
26	1000	3	Homogeneous	77	-37.7298	3.49578	-10.8709
27	1000	3	FGM	61	-35.7066	2.85746	-9.1196

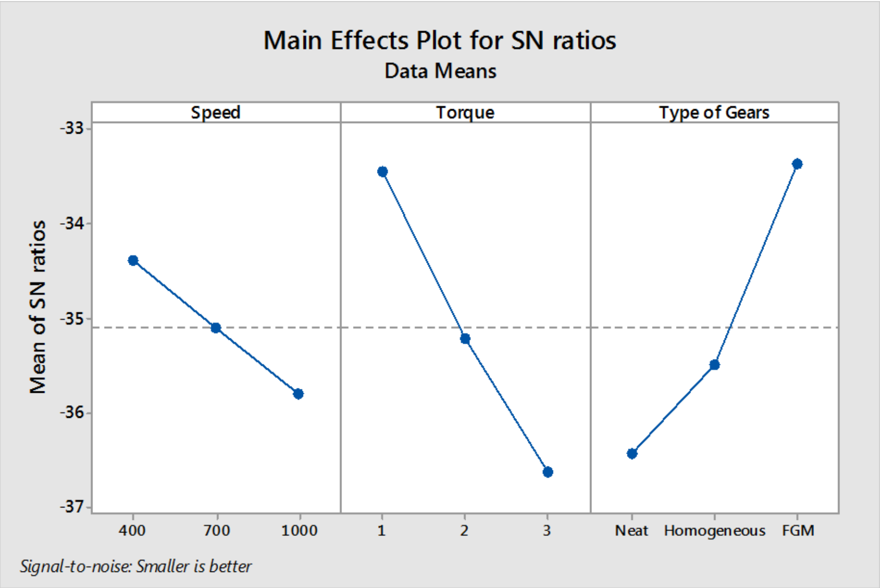

Figure 4 Influence of input factors on gear tooth temperature

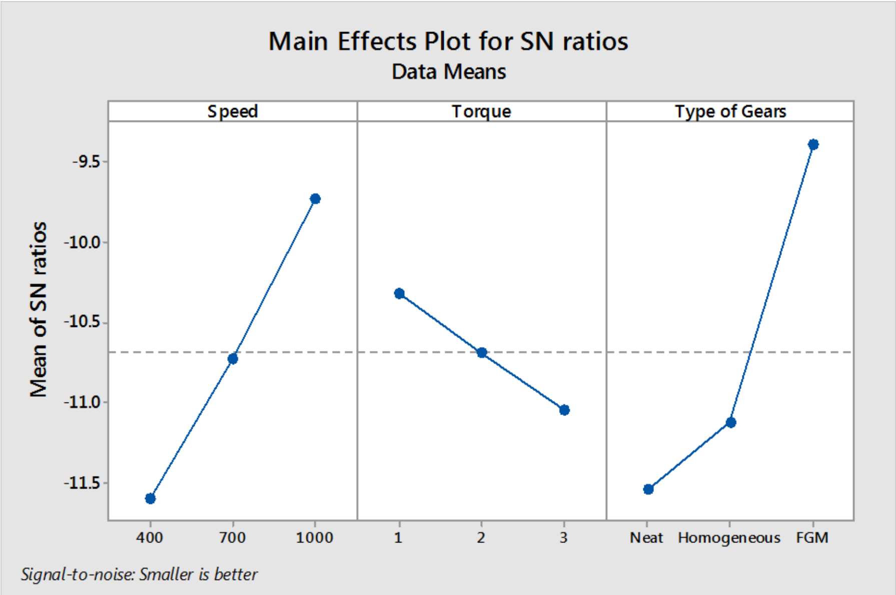

Figure 5 Influence of input parameters on WR of polymer gears

3.2 Analysis of variance (ANOVA)

ANOVA determines the importance of each parameter as well as the importance of their mutual interactions. It provides an information that which parameter or combination of parameters cause a significant impact on the performance output. Table 4 provides the results of analysis of variance for the performance outputs of homogeneous and FGM gears.

Table 4 ANOVA table for ST and WR of polymer gears

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**%P**
A	2	9.051	9.051	4.5255	267.47	8.98
B	2	45.878	45.878	22.9388	1355.78	45.52
C	2	44.476	44.476	22.2380	1314.36	44.13
A*B	4	0.857	0.857	0.2143	12.67	0.85
A*C	4	0.162	0.162	0.0404	2.39	0.16
B*C	4	0.228	0.228	0.0570	3.37	0.22
Error	8	0.135	0.135	0.0169		0.13
Total	26	100.787				100.00
ANOVA table for WR						
Source	DF	Seq SS	Adj SS	Adj MS	F	%P
A	2	15.7724	15.7724	7.8862	208.88	36.22
B	2	2.4006	2.4006	1.2003	31.79	5.51
C	2	23.6314	23.6314	11.8157	312.96	54.27
A*B	4	0.2424	0.2424	0.0606	1.60	0.56
A*C	4	0.1833	0.1833	0.0458	1.21	0.42
B*C	4	1.0134	1.0134	0.2533	6.71	2.33
Error	8	0.3020	0.3020	0.0378		0.69
Total	26	43.5455				100

It is detected from Table 4 that input torque (P = 45.52 %) and type of gear (P = 44.13 %) have substantial influence on the surface temperature of the contacting HDPE and steel gears while speed (P = 8.98 %) causes less significant influence on ST of HDPE gears. Input torque has the highest contribution on surface temperature which is caused due to the fact that the torque acting on the gear causes the loosening in the gear material more effectively in comparison to speed. The type of the gear is the second significant factor because the fabrication technique decides that what extent of loosening will occur with the increasing torque. The interface speed/torque (P=0.85%) affects the gear tooth ST expressively in evaluation to other interfaces i.e. speed/type of gear (P=0.16%) and torque/type of gear (P = 0.22%). Since the torque and type of gear are the two main contributing factors and therefore their interaction (i.e. torque/type of gear) causes more influence on ST. Also, it is witnessed that type of gear (P=54.27%) and speed (P=36.22%) have substantial influence on WR of HDPE gears whereas torque (P=5.51%) has less substantial influence on WR of gears. Highest contribution of type of gear on specific wear rate is observed due to the fact that the phenomenon of wear rate is much influenced by elastic modulus of the gear material. The teeth of a gear material having low elastic modulus bends easily and a rotational lag takes place between the meshing gear teeth. Improper meshing occurs between the gear teeth due to the rotational lag and results in the excessive wear of gear teeth. The interaction torque/type of gear (P=2.33%) influences WR of HDPE gears considerably which shows a contrast in case of other interfaces i.e. speed/torque (P=0.56%) and torque/type of gear (P=0.42%). Here, P indicates the percentage influence of the control input factors anddtheir contacts on the performance output.

3.3 Confirmation experiment

Validation of experimental results is necessary. Confirmation experiment is done to fulfil this requirement. It is executed by enchanting random set of factor grouping $A_1B_1C_3$ for ST and $A_3B_1C_3$ for WR of HDPE gears. The collaboration among the factors A, B and B, C has a substantial influence on gear tooth ST and WR of HDPE gear, respectively which is apparent from Table 3. Therefore, it is also considered in the confirmation experiment. Predictive equations 2 and 3 (Glen, 1993) are utilized for computing the S/N ratio for ST and WR of HDPE gears:

$$\bar{\eta}_{Temp} = \bar{T} + (\bar{A}_1 - \bar{T}) + (\bar{B}_1 - \bar{T}) + (\bar{C}_3 - \bar{T}) + [(\bar{A}_1\bar{B}_1 - \bar{T}) - (\bar{A}_1 - \bar{T}) - (\bar{B}_1 - \bar{T})] \quad 2$$

$$\bar{\eta}_{Wear} = \bar{T} + (\bar{A}_3 - \bar{T}) + (\bar{B}_1 - \bar{T}) + (\bar{C}_3 - \bar{T}) + [(\bar{B}_1\bar{C}_3 - \bar{T}) - (\bar{B}_1 - \bar{T}) - (\bar{C}_3 - \bar{T})] \quad 3$$

$\bar{\eta}_{Temp}$ and $\bar{\eta}_{Wear}$: Average value of ST and WR
$\bar{A}$: Total experimental average
$\bar{A}_1$, $\bar{A}_3$, $\bar{B}_1$, $\bar{C}_3$ and $\bar{T}_1$: mean retort for input factors and interactions
After simplifying Eq. (2) and (3), we get

$$\bar{\eta}_{Temp} = \bar{A}_1\bar{B}_1 + \bar{C}_3 - \bar{T} \quad 4$$

$$\bar{\eta}_{Wear} = \bar{B}_1\bar{C}_3 + \bar{A}_3 - \bar{T} \quad 5$$

The installation rate through the above prediction equations is obtained as $\bar{\eta}_{Temp} = -30.6765$ dB and $\bar{\eta}_{Wear} = -9.3498$ dB
Experiments are performed for dissimilar factors mixtures and equated to the expected results as given in Table 5. An error of 3.75% and 5.22% is witnessed for S/N ratio of wear rate and gear tooth ST of HDPE gears. Thus, predictive model dependability is validated by these results.

4. Conclusions

The conclusions that are observed from this investigation are given below:

1. This research epitomises the manufacturing of HDPE based neat, homogeneous and FGM spur gears using conventional polymer gear manufacturing process. Gear tooth surface temperature and specific wear behaviour of fabricated HDPE gears are positively examined through the optimization of input parameters such as rotational speed, torque and type of gears using Taguchi technique.

2. The best parameter setting to minimalize the tooth ST of gear is found at 400 rpm and 1 Nm for FGM gear. Also, the beat combination of parameter with minimum WR of HDPE gear is obtained while operating with FGM gear at 1000 rpm and 1 Nm.

3. ANOVA analysis provides the information that which parameter has a significant influence on ST and WR of HDPE gears. It demonstrations that input torque is the utmost substantial factor in the situation of ST of HDPE gears with an influence of 45.52%. The fabrication technique of gear (FGM gear) is a parameter that most significantly affects the WR of HDPE gears and contributes up to 54.27%.

Table 5 Validation of surface temperature and wear rate through confirmation experiments

	Optimal control factors		Error (%)
	Prediction	Experimental	
Level S/N ratio for surface temperature (dB)	$A_1B_1C_3$ -30.6765	$A_1B_1C_3$ -29.5261	3.75
Level S/N ratio for specific wear rate (dB)	$A_3B_1C_3$ -9.3498	$A_3B_1C_3$ -8.8617	5.22

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