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Developing optimal wear performance for nylon 6 loaded up with Boron Nitride (PA6/BN) composites using Taguchi direct and aspect ratio-based Taguchi-Pareto method

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Abstract

Although the wear performance of nylon-6/Boron Nitride (PA6/BN) composites has been studied, their concurrent optimization and prioritization are scarce in the literature. Considering this shortcoming, this paper proposes a Taguchi-Pareto-based framework incorporating a discrimination signal-to-noise ratio analysis, to enhance the wear performance of PA6/BN composites. Besides the direct factors that consider the weight percentage of particulate additives to nylon 6, sliding distance, sliding speed and normal load, the combinations of direct factors and aspect ratios of the factors were considered in eighteen cases where all four factors are considered in rotation. The novel contribution of the developed Taguchi-Pareto-oriented direct and aspect ratio (TPDA) framework based on its stepwise application to wear performance analysis is noted as follows: (1) establishment of the principal factors by contemplating their importance together with their impact levels on wear performance and (2) establishment of optimal and prioritization of the wear factors threatening the operational efficiency of the structures in which they are made up by considering their signal to noise ratios based on the 80-20 rule of Pareto analysis. The results obtained from the proposed TPDA were validated using experimental data obtained from the literature. It is thought that the application of the proposed framework to the experimental data aids the composite engineer in making prudent fabrication decisions, assisting them to successfully maintain how levels for the fabricated composites while in operation.

Keywords: Taguchi-Pareto, Optimisation, Nylon 6, Boron Nitride, Wear

Introduction

In the manufacture of nylon-6/Boron Nitride (PA6/BN) composites, the maintenance and control of the product's quality are a principal evaluation parameter influenced by reduced variability [5, 14]. Interestingly, wear performance analyses are developed in this article for monitoring and controlling the quality attributes of PA6/BN composites with the principal aim of lowering the product's variability. Consequently, the Taguchi-Pareto method is deployed in this article to evaluate the wear behaviour of PA6/BN composites and specifically optimize and prioritize the parameters in the wear process. In such treatments, a few authors would first compute the optimal parametric setting and then deploy the analysis of variance tool (ANOVA) to establish which of the parameters exhibit the greatest variance and the order of variance measures for the rest of the parameters. Moreover, none of the studies on PA6/BN composites considered the Taguchi method except Kumar and Reddy [13]. But the concurrent optimization and prioritization of parameters for the PA6/BN composite were omitted, assumed unnecessary. This is not a realistic assumption since much material wastage accomplishes material distributions to parameters during the wear experimental process. Either with few or large parameters, the waste may be enormous, and the wear experimental rig may not be sustainable.

Also, no previous study has investigated the wear parameters of PA6/BN during the concurrent optimization and prioritization of parameters in the context of direct and aspect ratio evaluation at the factor-level analysis. The present article aims to bridge this important gap in the wear performance literature. The objective of this paper is to propose a method for the concurrent optimization and prioritization of wear parameters using the Taguchi-Pareto method which incorporates direct factors and aspect ratios of parameters. Hence, introducing the signal-to-noise ratios with the choice of a criterion among the smaller the better, the larger the better and the nominal the best and then entertaining the Pareto principle, indicating the 80-20 rule is the research focus of this study.

In analysing the Taguchi-Pareto method for the wear performance of PA6/BN composites, aspect ratios have been considered because it is the best approach to ensure that optimization is conducted in the most efficient and effective manner on every input in relation to the output of the system. It contributes to enhancing the wear performance of PA6/BN composites in the scale of the signal to noise ratio discarded during the application of the 80-20 rule of Pareto to wear performance enhancement. Another essence of the aspect ratios is to obtain a wide view of the direct parameters of PA6/BN composite. This wider viewpoint allows us to note the behaviour of each aspect ratio in terms of the square, reciprocal of the square, the cube and its reciprocal. From there, we were able to determine the differences of their delta values, parametric settings and signal to noise ratios. These differences are used to evaluate the significance of each wear performance aspect ratio parameters. It is possible for some aspect ratios to give better results than when we use direct parameters. At the same time, in some of these cases, it is possible that the direct parameters are very close to the results obtained from the aspect ratios. Furthermore, its significance is to determine which of the cases show a better wear performance than the original direct parameters used in Kumar and Reddy [13]. At the same time, they looked into the ANOVA, which is divided into two, namely before- and after-pool ANOVA. The essence of the aspect ratio is to identify which of the cases gives a better wear performance than the result obtained on the before- and after-pool ANOVA pooling of the direct parameters conducted in Kumar and Reddy [13].

In this article, the authors concurrently prioritize these parameters to determine their relative importance to one another in a ranking scale where the signal-to-noise ratios are first determined, their cumulative is established, the nonrelevant experimental trials ignored in the calculations and the optimal parametric setting determined. Still, the delta values are determined, ranks of parameters are evaluated and a comparison is made with the available data from the literature. The experimental data obtained from Kumar and Reddy [13] was used to verify the workability of the model starting from the orthogonal array declaration, to the computation of signal-to-noise ratios and then following through to the ranks of parameters. Eighteen formulations of combined direct and aspect ratios were made, and the performance of the formulations on the experimental data was established. It is noticed that composite engineers are often confronted with the problem of selecting the key parameters among the strong indicators of wear and composite degradation to determine what quantities of resources should be deployed to each parameter. This problem is serious because only extremely few tools are available in the composite literature in this regard.

Besides, engineers had since realized the importance of nylon in component development and fabrication of structures as evident in the studies on nylon by Dasari et al. [6], Srinath and Gnanamoorthy [23] and Abdelbary et al. [1], Mao et al. [18] and Zhang et al. [26]. Some studies have focused on the mechanical performance of nylon-6 composites [17, 25], thermal and thermo-mechanical studies nylon-6 composites [24] and energy-absorbing performance [10]. Furthermore, there have been studies on nylon filled with diverse fillers such as glass fibre [7, 11], C ions [22], graphite [8], CuS [2, 9], Cas, CaO and CaF_2 [3], Cu compound [4] and carbon fabric [27]. In Hooke et al. [7], low friction and wear rates in the twin disk test condition were stimulated by a thin interfacial stratum of nylon over the composite. Kumar and Pannerselvam [11] and Hooke et al. [7] used glass fibre as the filler for nylon. More recently, Lang et al. [15] reported on the enhancement of the wear resistance of nylon material. Nyiranzeyimana et al. [20] obtained optimal parametric settings for the minimum residual stress for carbon fibre-based nylon wear analysis.

Table 1 provides a summary of the literature review on the wear performance of nylon 6 (see also [12]). Explicitly stated, the principal attributes of this article are as follows:

- Making the complicated wear performance analysis of PA6/BN composite simple and analysing it with a Taguchi-Pareto framework
- Introducing direct and aspect ratios in as diverse as eighteen cases for the best combination of factors

Furthermore, the authors chose to limit the analysis to the wear parameters of normal load, weight percentage of Boron Nitride, sliding speed and sliding distance as opposed to a wider range of parameters or those previously selected for analysis of wear in polymers.

The novelty of the present article may be expressed as follows. Firstly, the study established the principal factors of the wear performance of PA6/BN composites by contemplating their importance together with their impact levels on the wear performance. Secondly, the optimal values of the wear performance parameters of PA6/BN composites are established uniquely to reflect the aspect ratios of the parameters and concurrently limit the importance threshold of the parameters to an 80-20 Pareto rule. The aspect ratios considered are the squares, reciprocals of squares, cubes and the reciprocals of cubes.

Table 1 Summary of literature review on wear of nylon 6

Sr. no.	Author (year)	Title of journal	Work material used	Equipment	Method of analysis	Output parameters	Input parameters	Conclusion
1	Kumar and Panneerselvam [11]	*Procedia Technology*	Nylon 6 and glass fibre	Injection moulding machine, pin-on-disk machine, scanner	Microstructural analysis, wear test	Specific wear, abrasive weight loss	Glass fibre content, applied load, sliding distance	Increase in the sliding distance yielded a growth in the specific wear rate of the nylon composite
2	Abdelbary et al. [1]	*Tribology International*	Nylon 66 and water	Tribometer, pin-on-plate reciprocating testing machine	Surface crack, steady-state wear	Dry wear test, cyclic load	Sliding distance, duration of the running-in period	Wear rates are higher in wet sliding conditions than when tested in dry sliding conditions
3	Srinath and Gnanamoorthy [23]	*Materials Science and Engineering: Part A*	Nylon 6, clay nanocomposite	Ploughing machine, injection moulding machine	X-ray diffraction, abrasive wear test, scanning electron microscopy	Abrasive wear	Normal load, grit size, sliding velocity and sliding distance	Abrasive wear resistance is high with increase in normal load and sliding velocity, thus high loss of material. Wear rate of nylon nanocomposites reduces with sliding distance
4	San et al. [22]	*Surface and Coating Technology*	Nylon 6, ion implantation	Scanning electron microscopy, Fourier transform-infrared spectroscopy, grazing incidence, X-ray diffraction, electron spin resonance, nano-hardness indentation and wear test	Surface hardness, wear resistance	Nano-hardness test, wear test, ESR analysis, infrared spectroscopy, GXRD analysis	Arc current, pulse rate, voltage and normal load	Enhancement in surface hardness and wear attributes of nylon 6 by carbon ion beam analysis was attained
5	Dasari et al. [6]	*Composites Science and Technology*	Nylon 6, clay	Transmission electron microscopy, scanning of electron microscopy	Exfoliated morphology	Friction, wear and microstructural analysis	Applied load, sliding speed and sliding distance	High convergence exists between nylon 6 and clay layers and strained encompassing nylon-6 material used by the clay platelets

Table 1 (continued)

Sr. no.	Author (year)	Title of journal	Work material used	Equipment	Method of analysis	Output parameters	Input parameters	Conclusion
6	Zheng et al. [27]	*Carbon*	Nylon, carbon fibre	Monomer casting	Thermoplastics	Mass loss, density of material, normal load and sliding distance	Friction, abrasive wear	Carbon fabric enhances wear resistance
7	Kang and Chung [8]	*Wear*	Nylon 6, graphite composite and oil	Block-on-disk wear test machine, lloyd Instruments	Monomer casting method	Friction, abrasive wear rate, mechanical properties evaluation	Volume resistivity, length of sample and area of sample	Soaked nylon 6 with graphite and oil help enhanced its antistatic and frictional properties
8	Bahadur et al. [3]	*Wear*	Nylon, CaS, CaO and CaF filler	Pin-on-disk machine	Optical microscopy, X-ray photoelectron spectroscopy	Tribochemical studies by XPS, friction, wear rate	Normal load, sliding distance	Wear rate of nylon can be reduced drastically with the effective use of CaS and CaO fillers, while CaF filler enormously upshoot the wear rate
9	Hooke et al. [7]	*Wear*	Nylon 66 and glass fibre	Twin disc machine, injection mould machine	Scanning electron microscope	Wear, friction. rolling-sliding	Normal load, sliding speed, slip ratio	Low friction and wear rates are possible under given defined conditions
10	Kapoor and Bahadur [9]	*Tribology International*	CuS filler, nylon 11, steel	Compression moulding filler, pin-on-disk machine	Normal load, sliding speed and surface roughness	Steady-state wear rate	Scanning electron microscopy, XPS analysis	Combined state of PbS and Nylon 11 gives an effective wear rate
11	Bahadur and Gong [2]	*Wear*	Nylon 6 and CuS filler	Tribometer, X-ray photoelectron spectroscopy	Tribometer	Steady-state wear rate	Normal load, sliding speed and temperature	Wear performance of nylon 6 was discovered to improved with 35% volume of CuS filler proportion
12	Bahadur et al. [4]	*Wear*	Nylon 11, copper compound	Spectrometer, pin-on-disk machine	X-ray photoelectron spectroscopy analysis	Normal load, sliding speed and sliding distance	Friction, steady state rate	Wear rate in nylon increased with combination with copper-acetate filler. Furthermore, the combination of nylon with CuS, CuO and CoF2 shows nylon with lower wear rate

Methods

Problem description

This paper considers the wear performance of nylon-6/Boron Nitride polymer composite. It has parameters with three levels and four factors, namely, weight%, normal load, sliding speed and sliding distance. The Taguchi-Pareto method was used to analyse further the work of Kumar and Reddy [13] which only considers the Taguchi method to investigate the mechanical properties and wear performance of the composite. The aspect ratio of parameters is considered, including the square of factors and inverting of the squares of parameters to determine the change concerning the increase or decrease of the delta value regarding Kumar and Reddy [13]'s work.

How does PA6/BN composite fail?

For an insight of PA6/BN composite selection for different purposes, the prerequisite is to understand how the composite fails. Despite being similar in functions, different configurations of PA6/BN composites wear differently, keeping in view the diverse applications and conditions of the manufacturing environment that impose varying levels of stress on the composite structure. However, the principal drivers of wear in PA6/BN composites may be foreign particles such as dust, grit, dirt and lint could cause the wear of the PA6/BN composite. Secondly, misalignment could be an issue where bent shafts attached to the PA6/BN composite structures could trigger elevated temperature, causing unprecedented wear. Thirdly, poor lubrication during the operation of the composite structure may trigger overheating and excessive wear. The fourth issue is that if the PA6/BN composite structure is not properly mounted, it may promote wear.

Reasons for the choice of the method and parameters

Normal load

Normal loads are frictional coefficient- and wear rate-dependent vertical loads acting on the machine's wheels for the sliding friction of the wheel's surface with the material being tested. However, the material's frictional coefficient and its wear rate are principal factors when deciding on the adequate strategy for achieving the minimum wear goal of PA6/BN composites. The reason is that a high value of the coefficient of friction has a direct influence on the magnitude of force required for sliding to occur and hence high-energy consumption from the system. Therefore, by combating the coefficient of friction, the implementation of the wear control strategy for the PA6/BN composite becomes more effective and efficient. Besides, the selection of the aspect ratio-based normal load imposed on the factor-level framework of the Taguchi-Pareto method largely determines the judged optimal parametric settings and ranks of the wear performance parameters for PA6/BN composites. The choice of adequate aspect ratios is a principal determinant in developing a robust optimisation scheme with the mechanism for concurrent prioritization and optimization of the aspect ratios.

Sliding distance

The sliding distance is the mean value of the sliding rate and its product with the running time. However, the sliding distance in a wear rig for evaluating the wear performance of PA6/BN composite is a significant factor that should be considered during the selection process of an adequate wear process for the PA6/BN composite material. The reason is that as the sliding distance increases, the wear rate decreases. However, it is known that as the operating temperature during the wear process exceeds a crucial value, the coefficient of friction and the wear rate of the PA6/BN composite grow sharply with the sliding distance. Major success in prolonging the lifespan of PA6/BN composite may be achieved by an effort to maintain the composite in operating condition at a temperature always below the critical limit.

Sliding speed

The sliding speed is the comparative sliding speed between the PA6/BN composite surface and the mating surface. However, in the process of choosing parameters for the wear process involving the PA6/BN composite, there is scope to integrate sliding speed. But the wear rate remains insensitive to sliding speed when the speed situations are low. Moreover, too low sliding speed consumes more energy than desired since elongated operating time directly varies with energy consumption. Thus, to reduce cost, optimal sliding speed should be accomplished.

Weight% of reinforcement

As the weight% of reinforcement increases, the density and porosity of the material decrease, while the compressive strength and hardness increase to a certain extent. Therefore, efforts to attain the optimum threshold should be made to extend the lifespan of the materials.

Material fabrication

In this article, material fabrication means the production of PA6/BN structures through mixing, weighing, heating, moulding, melting, softening, pressurizing and solidification. As with the present article, no original fabrication was made by the authors, but the data relating to the experimental details are adopted in the present work to verify the working of the method. In addition, explanations of the basic steps adopted in Kumar and Reddy [13] are made here for the clarity of the material fabrication process and to enhance the understanding of the application of the method. To commence, the procedure followed in Kumar and Reddy [13] are as follows:

Step 1	Add up the diverse percentages of 40%, 8%, 12%, 16% and 20% wt to the PA6, in a mixed heated up to 190 °C. Notice that the speed of the mixing blades is maintained at 200 rpm, while mixing takes place for only 20 min
Step 2	Introduce the mixture into the hopper of the injection moulding machine such that at the barrel of the machine, heating is done to make the mixture molten and soft
Step 3	The mixture is subjected to pressure within the mould cavity, and material shrinking is compensated for
Step 4	Bearing in mind the melting point of nylon 6 at 220 °C, the melt flow index was maintained at 12 g/min. Take note to hold the following constant for all the samples: cooling time of moulding, heating temperature for the change barrel and the injection pressure. Besides, the temperature of the mould was maintained at 25 °C in all experimental activities. Also, 70 MPa was assigned as the injection pressure. Kumar and Reddy [13] asserted that solidification of the material was noted when the mould's temperature reduced below the glass transition temperature of PA6, which is 105 °C
Step 5	Wait and observe that the material is solidified into shape within the mould and eject the samples for wear testing

Steps in implementing the Taguchi-Pareto method

The following steps are applied in the implementation of the Taguchi-Pareto method for the current problem studied.

Step 1	Itemize the parameters to be investigated
Step 2	State the factors and levels of the process
Step 3	Get the orthogonal matrix for the process through the use of Minitab 18 software
Step 4	Map the orthogonal arrays obtained with the values of each factor
Step 5	Using the smaller the better method, use the tabulated orthogonal arrays, factors and levels of the parameters to compute the signal-to-noise ratio
Step 6	Obtain the response table by finding the average of the signal-to-noise ratio of each value obtained above in (step 5)
Step 7	On the response table, get the delta values by subtracting the minimum from the maximum value of each parameter
Step 8	Compute the rank from the highest to the lowest values to obtain the position of the significance of each parameter
Step 9	Obtain the optimal parametric setting by choosing the maximum signal-to-noise ratio of each level

Results and discussion

In this section, the results obtained from the application of the Taguchi-Pareto method to the wear performance data obtained from Kumar and Reddy [13] are presented. The Taguchi-Pareto method was applied to the experimental data obtained by the authors where a matrix material, nylon 6, is used, and a constituent material termed Boron Nitride having a particulate size of roughly 80 nm aided the experimentation. The parameters considered are the Boron Nitride particulate weight%, sliding speed, normal load and sliding distance. The Taguchi-Pareto method has the special attribute of identifying which of the experimental trials contribute most to the wear performance analysis through an 80–20% rule that segregates the unwanted experimental trials from those that are needed. In this work, as computed for the analysis involving the Taguchi method alone, the signal-to-noise ratio was determined based on the smaller the better criterion. This means that the small values of the parameters are desired and are favourable to the system, introducing lower values of wear. In this analysis, the results of the direct factors are first presented. These are followed by those aspect ratios in Table 2.

In Table 2, there are 18 cases which are explained as follows. Case 1 contains the four parameters, W, NL, SS and SD, as discussed in the original work of Kumar and Reddy [13]. This is used as a reference with which other cases can be compared. In case 2, we attempted to find the aspect ratios of W^2 regarding NL, SS and SD are retained. Since aspect ratios are the proportions of a parameter to another, W^2 was compared at first with NL^0 where it is expressed as W^2/NL^0 yields W^2. Equally finding W^2/SS^0 and W^2/SD^0 yields W^2 in both instances. So the four parameters considered in the case 2 are W^2, NL, SS and SD. In case 3, NL^2 was treated like W^2 in case 2, and the combination of parameters for analysis becomes W, NL^2, SS and SD. Similar idea of formation derivation for the above cases is then extended to cases 3, 4 and 5. For case 6 where the reciprocal of W is first considered, the idea is that the aspect ratios of NL^0/W and SD^0/W yield $1/W$ in each of the case which is the first parameter

Table 2 Direct and aspect ratios concerning the wear performance problem

Sr. no.	Weight, %wt	Normal load, N	Sliding speed, rpm	Sliding distance, m
Case 1[a]	W	NL	SS	SD
Case 2	W^2	NL	SS	SD
Case 3	W	NL^2	SS	SD
Case 4	W	NL	SS^2	SD
Case 5	W	NL	SS	SD^2
Case 6	1/W	1/NL	1/SS	1/SD
Case 7	$1/W^2$	1/NL	1/SS	1/SD
Case 8	1/W	$1/NL^2$	1/SS	1/SD
Case 9	1/W	1/NL	$1/SS^2$	1/SD
Case 10	1/W	1/NL	1/SS	$1/SD^2$
Case 11	W^3	NL	SS	SD
Case 12	W	NL^3	SS	SD
Case 13	W	NL	SS^3	SD
Case 14	W	NL	SS	SD^3
Case 15	$1/W^3$	1/NL	1/SS	1/SD
Case 16	1/W	$1/NL^3$	1/SS	1/SD
Case 17	1/W	1/NL	$1/SS^3$	1/SD
Case 18	1/W	1/NL	1/SS	$1/SD^3$

Key: [a] Case 1 and its data are taken from Kumar and Reddy [13]

in cases 6, 8, 9, 10, 16, 17 and 18. This aspect value of 1/W is then combined with other parameters. Thus, by following all these details, how the formulations 1 to 18 in Table 2 could be understood?

Besides, in this article, experimental trials have been conducted for cases 2 to 18. However, it is possible to provide evidence of the experimental trials in terms of SEM images of worn-out surfaces. Also, the values of wear (wear rate or specific wear rate or wear resistance) output are considered to determine the SN ratios for all the cases considered in the experiment. But the present study is limited in achieving this goal because other authors' experimental data was used and we have no access to the samples with which SEM images could have been obtained. Thus, in the present article, the inputs considered to determine the corresponding SN ratios for each case are the combinations of the direct factors and aspect ratios, which are determined according to some explanation notes given on Table 2 in the earlier paragraph.

Direct factors

According to Table 3 which considers the direct parameters without the aspect ratios, there are nine experimental trials, and at the 7th experimental trial which corresponds to 77.88%, the cutoff is desired.

In Taguchi-Pareto, the cutoff is usually 80%. But 77.88% is closer to 80% than 89.52% in experimental trial 8. Therefore, 77.88% is chosen for the Taguchi-Pareto analysis. By checking Table 3 and focusing on each row containing experimental trials, it is found that tracing the value of the 77.88% under the cumulative column, it occurs at the experimental trial 7. This is a situation where the signal-to-noise ratio is considered and the

Table 3 Case 1 Direct parameters, associated orthogonal arrays and %cumulative SN ratios

Trial no.	Orthogonal arrays				Orthogonal arrays translated into figures				Total S/N ratio	% cumulative
	W	NL	SS	SD	W	NL	SS	SD		
1	1	1	1	1	4	10	100	500	−48.13	10.37
2	1	2	2	2	4	15	200	750	−51.78	21.53
3	1	3	3	3	4	20	300	1000	−54.36	33.24
4	2	1	2	3	12	10	200	1000	−54.15	44.91
5	2	2	3	1	12	15	300	500	−49.30	55.54
6	2	3	1	2	12	20	100	750	−51.56	66.65
7	3	1	3	2	20	10	300	750	−52.13	77.88
8	3	2	1	3	20	15	100	1000	−54.03	89.52
9	3	3	2	1	20	20	200	500	−48.62	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (SS), rpm; sliding distance (*SD*), m (data is taken from Kumar and Reddy [13])

Table 4 Response table

Level	W	NL	SS	SD
1	−51.4224 [a]	−51.4701	−49.8462 [a]	−48.7150 [a]
2	−51.6703	−50.5398 [a]	−52.9657	−51.8235
3	−52.1285	−52.9583	−51.9276	−54.2530
Delta	0.7062	2.4185	3.1196	5.5381
Rank	4th	3rd	2nd	1st

Key: [a] Denotes optimal values

cumulative values are analysed. Furthermore, Table 3 reveals that the optimal wear output characteristics possess the SN ratio of −48.13 with the corresponding % cumulative of 10.37%. At this point, the Boron Nitride %wt, normal load, sliding speed and sliding distance were 4 %wt, 10 N, 100 rpm and 500 m, respectively. However, the next least is with trial 5 (as trials 8 and 9 have not been considered because of the 80/20 rule) with the SN ratio of −49.30 and with % cumulative of 55.54%. Here, there is a huge growth of 45.17% in % cumulative, which is accompanied by a marginal decrease in the SN ratio. In turn, the wear control factors of the Boron Nitride %wt, normal load, sliding speed and sliding distance were affected as follows: The Boron Nitride %wt remained constant at 4 %wt, an increase of 50% in the normal load was observed, and 100% increase in the sliding speed was noted, while a 50% growth in the sliding distance was observed. Notwithstanding, the SN ratio reached a maximum of −54.36 with cumulative % of 33.24%. Here, compared with the last behaviour of the % cumulative, there is a huge declined of 27.30%, which is accompanied by a marginal decay in performance of SN ratio by 5.06%. In turn, the wear control factors of the Boron Nitride %wt, normal load, sliding speed and sliding distance were affected as follows: The Boron Nitride %wt remained constant at 4%wt, an increase of 33.3% in the normal was observed and 100% increase in the sliding speed was observed, while a 33.3% growth in the sliding distance was noted. To proceed in evaluating the response table, the orthogonal arrays are reconsidered where all contributory orthogonal arrays that are associated with experimental trials 8 and 9 are eliminated from the analysis. Table 4 shows the computed response table which has eliminated values from experimental trials 8 and 9.

For Table 4, which is the response table, the optimal parametric setting is $W_1NL_2SS_1SD_1$, which is interpreted as 4 weight% of Boron Nitride particulate, 15 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. In comparison with Kumar and Reddy [13] who presented the ANOVA results that rated the normal load as the most significant parameter (P% = 66.26), sliding speed as the next significant (P% = 10.43) and sliding distance as the least significant (P% = 8.55) (see Table 5), the following assertion is made. In the present work, normal load obtained a delta value of 2.42 which places it as the third most important parameter; this conflicts with the result of Kumar and Reddy [13]. Furthermore, the sliding speed that is placed as the second position by Kumar and Reddy [13] obtains the second position in the present study; this coincides with the result of the literature. Notice that a delta value of 3.12 was obtained in the present work. Next, there is a conflict of result on the sliding distance which Kumar and Reddy [13] place in the third position, but in the present work, it is placed as the most significant parameter with a delta value of 5.54. However, the weight% which was trivialized in Kumar and Reddy [13] attained the 4th position in the present work. This shows an agreement between the result between Kumar and Reddy [13] and the present study. Still comparing results between Kumar and Reddy [13] and the present work, it was found that the ANOVA before pooling which positioned normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96) in decreasing order of importance follows the explanation given previously on the ANOVA after pooling. Having discussed the case where direct factors are considered, it is essential to vary the scenario such that aspect ratios are analysed. Although case 1 is the direct situation for the factors, cases 2 to 18 show the aspect ratios for the parameters. These are considered subsequently starting with case 2.

Direct and aspect ratios — case 2

In this case, the only indirect (aspect) ratio is the particulate weight% which is presented as its square (i.e. W^2) (Table 6).

This is complemented by the direct ratio of NL, SS and SD. These four factors are analysed using the Taguchi-Pareto principle. Interpreting from Table 6, it was found that the cutoff is still at the experimental trial 7, and the value obtained is 77.53%. In interpreting the response table, the optimal parametric setting obtained is ${W^2}_1NL_2SS_1SD_1$ which is interpreted as 16 weight% of Boron Nitride particulate, 15 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. Now, in comparison with the result of

Table 5 ANOVA values from Kumar and Reddy [13]

Parameters	ANOVA before pooling (P%)	ANOVA after pooling (P%)
BN, %wt.	7.96	-
Normal load	71.54	66.26
Sliding speed	11.27	10.43
Sliding distance	9.24	8.55

Table 6 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 2 and 3

	Case 2						Case 3					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	W^2	NL	SS	SD	Total S/N ratio	% cumulative	W	NL^2	SS	SD	Total S/N ratio	% cumulative
1	16	10	100	500	−48.14	10.28	4	100	100	500	−48.29	10.30
2	16	15	200	750	−51.78	21.35	4	225	200	750	−52.13	21.41
3	16	20	300	1000	−54.36	32.96	4	400	300	1000	−54.95	33.13
4	144	10	200	1000	−54.24	44.55	12	100	200	1000	−54.19	44.68
5	144	15	300	500	−49.55	55.14	12	225	300	500	−49.90	55.32
6	144	20	100	750	−51.71	66.19	12	400	100	750	−52.63	66.54
7	400	10	300	750	−53.08	77.53	20	100	300	750	−52.19	77.67
8	400	15	100	1000	−54.66	89.21	20	225	100	1000	−54.24	89.23
9	400	20	200	500	−50.52	100	20	400	200	500	−50.52	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

"Direct factors" section, the optimal parametric setting obtained in both instances is the same. Although there are some noticeable changes such as decreases in the average signal-to-noise ratio for all the parameters when those in section 3.1 are weighed against those in this section (i.e. case 2), the delta values were also found to decrease for NL, SS and SD, while it increases only for W (Table 7, Response table A2). However, the changes are not enough to cause a change in position since the parameters SD, SS, NL and W still maintained their first, second, third and fourth positions, respectively. Now, it is worthwhile to compare the result of this section with that of Kumar and Reddy [13] where the reference point is the ANOVA result after pooling, while it was indicated that normal load (P% = 66.26), sliding speed (P% = 10.48), and sliding distance (P% = 8.55) (see Table 5) are the greatest to the least significant factors, respectively; the results are not in the present section in all totality. It is only the sliding speed that concurred in the two cases. Furthermore, a comparison of the result in Kumar and Reddy [13] of ANOVA before pooling shows that the normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96) which are expressed in decreasing order of importance show the same result as stated pre for the comparison of ANOVA after pooling and the current result in this section.

Direct and aspect ratios — case 3

For case 3, the particulate weight% Boron Nitride in nylon 6, the sliding speed and sliding distance are measured as direct parameters, while the normal load is regarded as the aspect ratio. The normal load is squared, while the powers of all other parameters are unity. As such, there are four parameters tested. After computing the signal-to-noise ratio, their cumulative is obtained to have a cutoff of 80% (Table 6). However, on observing the 80% cutoff, the exact values could not be obtained, but an approximate value of 77.67% was chosen as the cutoff of the Taguchi-Pareto method. These are the first seven trials which are the same as in cases 1 and 2. While interpreting the response tables, the optimal parametric setting obtained is $W_1NL^2{}_1SS_1SD_1$, and it is interpreted as 4 weight% of Boron Nitride particulate, 100 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. In comparing this result with those of section 4.1, the optimal parametric settings are the same. For all average signal-to-noise ratios for the different parameters, in comparison with case 1, a decrease in values was obtained. This means that the direct parameters involving weight or particulate %, normal loading, sliding speed and sliding distance are better than the combined direct parameters and aspect ratios of case 3. Recall that the parameters are the weight% of Boron Nitride, the square of the normal load, the sliding speed and the sliding distance. Next, the comparison is made based on delta values, where it was found that the normal load increases while other parameters including weight% of particulate Boron Nitride, sliding speed and sliding distance decreases since there is a 75% decrease and only 25% for the delta values and the increasing delta values are the strength of the method, and then, the direct parameters represented in case 1 are better than the combined direct parameters and aspect ratios of case 3. By comparing the work with Kumar and Reddy [13] that presented the ANOVA result which classifies the normal load as the most significant parameter (P% = 66.26), sliding speed as the next significant (P% = 10.43) and sliding distance as the least significant (P% = 8.55) (see Table 5). It is safe to make the following

Table 7 Response tables

	Response table A2				Response table A3			
Level	W^2	NL	SS	SD	*W*	NL^2	SS	SD
1	−51.4246 [a]	−51.8164 [a]	−49.9248 [a]	−48.8445 [a]	−51.7904 [a]	−51.5597	−50.4608 [a]	−49.0959 [a]
2	−51.8348	−50.6682	−53.0092	−52.1917	−52.2396	−51.014 [a]	−53.1607	−52.3172
3	−53.0782	−53.0354	−52.3295	−54.2961	−52.1939	−53.7884	−52.347	−54.5702
Delta	1.653571	2.367221	3.08432	5.451541	0.449166	2.774408	2.699867	5.474274
Rank	4th	3rd	2nd	1st	4th	2nd	3rd	1st
	Response table A4				Response table A5			
Level	W	NL	SS^2	SD	W	NL	SS	SD^2
1	−84.3591 [a]	−84.3594	−73.997 [a]	−83.5273 [a]	−108.3 [a]	−108.3	−105.46 [a]	−101.938 [a]
2	−84.3638	−89.5433	−86.0227	−84.3635	−108.3	−105.46 [a]	−111.481	−108.982
3	−93.0646	−83.5343 [a]	−93.0646	−89.5441	−108.982	−111.481	−108.3	−113.979
Delta	8.705498	6.00897	19.06756	6.016734	0.682034	6.020597	6.0206	12.0412
Rank	2nd	4th	1st	3rd	4th	3rd	2nd	1st
	Response table A6				Response table A7			
Level	1/W	1/NL	1/SS	1/SD	$1/W^2$	1/NL	1/SS	1/SD
1	17.68779	22.06056	23.72493 [a]	21.43051	26.43066	25.51897	28.17214 [a]	27.01856
2	25.13199	23.58442 [a]	20.74269	23.01034	29.08586 [a]	28.13522	26.38898	28.19663 [a]
3	26.29427 [a]	22.05647	22.7959	23.05195 [a]	26.0123	29.86725 [a]	27.81321	26.96742
Delta	8.60648	1.52795	2.982239	1.621436	3.073568	4.348274	1.783162	1.229213
Rank	1st	4th	2nd	3rd	2nd	1st	3rd	4th
	Response table A8				Response table A9			
Level	1/W	$1/NL^2$	1/SS	1/SD	1/W	1/NL	$1/SS^2$	1/SD
1	18.05558	25.80772	25.80706	22.81506	17.69057	22.06598	23.76286 [a]	21.43562
2	27.5486	25.82579 [a]	22.79235	25.81505 [a]	25.15078	23.60706 [a]	20.7467	23.02741
3	31.84286 [a]	22.79886	25.8308 [a]	25.80767	26.32724 [a]	22.07971	22.79885	23.07502 [a]
Delta	13.78728	3.026939	3.038447	2.999986	8.636665	1.541087	3.016158	1.639401
Rank	1st	3rd	2nd	4th	1st	4th	2nd	3rd
	Response table A10				Response table A11			
Level	1/W	1/NL	1/SS	$1/SD^2$	W^3	NL	SS	SD
1	17.68793	22.06093	23.72549 [a]	21.43139	−51.4601 [a]	−60.1041	−53.8456 [a]	−53.6988 [a]
2	25.13286	23.58517 [a]	20.74288	23.01086	−59.5732	−55.5045 [a]	−55.9191	−61.1293
3	26.29489 [a]	22.05691	22.79664	23.05226 [a]	−72.0853	−56.932	−61.8852	−57.1999
Delta	8.606957	1.528264	2.982608	1.620867	20.62519	4.5996	8.039632	7.430489
Rank	1st	4th	2nd	3rd	1st	4th	2nd	3rd
	Response table A12				Response table A13			
Level	W	NL^3	SS	SD	W	NL	SS^3	SD
1	−63.9555 [a]	−56.0737 [a]	−63.5315	−59.8279 [a]	−129.542 [a]	−129.542	−113.979 [a]	−128.293 [a]
2	−64.6095	−64.7207	−60.9224 [a]	−64.3368	−129.542	−137.324	−132.041	−129.542
3	−56.1619	−72.0972	−64.3164	−64.5953	−142.607	−128.293 [a]	−142.607	−137.324
Delta	8.447654	16.02354	3.393989	4.767363	13.06425	9.030899	28.62727	9.030899
Rank	2nd	1st	4th	3rd	2nd	3rd	1st	3rd
	Response table A14				Response table A15			
Level	W	NL	SS	SD^3	$1/W^3$	1/NL	1/SS	1/SD
1	−165.46 [a]	−165.46	−161.2 [a]	−155.918 [a]	28.92495	25.96538	28.86966	27.69967
2	−165.46	−161.2 [a]	−170.231	−166.483	29.13462 [a]	29.4064	27.64731	29.05593 [a]
3	−166.483	−170.231	−165.46	−173.979	26.015	31.74238 [a]	29.05326 [a]	28.81329
Delta	1.02305	9.0309	9.0309	18.0618	3.119626	5.77699	1.405943	1.356262
Rank	4th	2nd	2nd	1st	2nd	1st	3rd	4th
	Response table A16				Response table A17			
Level	1/W	$1/NL^3$	1/SS	1/SD	1/W	1/NL	$1/SS^3$	1/SD

Table 7 (continued)

1	18.05847	25.88634 [a]	25.82153	22.82462	17.69057	22.06598	23.76287 [a]	21.43562
2	27.57438	25.84124	22.82365	25.8727 [a]	25.15078	23.60707 [a]	20.7467	23.02741
3	31.94309 [a]	22.80099	25.89094 [a]	25.83913	26.32724 [a]	22.07971	22.79885	23.07502 [a]
Delta	13.88463	3.085348	3.067289	3.04808	8.636668	1.541089	3.016161	1.639402
Rank	1st	2nd	3rd	4th	1st	4th	2nd	3rd
	Response table A18							
Level	1/W	1/NL	1/SS	1/SD3				
1	17.68793	22.06093	23.72549 [a]	21.43139				
2	25.13286	23.58517 [a]	20.74288	23.01086				
3	26.29489 [a]	22.05691	22.79664	23.05226 [a]				
Delta	8.606957	1.528264	2.982608	1.620867				
Rank	1st	4th	2nd	3rd				

Key: [a] Denotes optimal values

assertion. First, the normal load that Kumar and Reddy [13] placed as first was obtained as second in the present work. This shows a conflict of opinion concerning the positioning. Sliding speed, sliding distance and weight% were given as second, third and fourth, respectively, by Kumar and Reddy [13]. However, there is a conflict of opinion in which sliding speed is positioned third; sliding distance is rated first. The two conclusions concurred on the position of weight% where it is rated fourth, which is the worst parameter. All these discussions are related to the pooling event using the ANOVA method. For a situation where the pre-pooling of ANOVA is considered, the following comparison was observed. Kumar and Reddy [13] positioned normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96) as first, second, third and fourth, respectively. Moreover, in comparing this result with the delta values obtained, the trend is discussed for the ANOVA where the post-pooling activity was conducted.

Direct and aspect ratio — case 4

In case 4, only one of the parameters is in the form of an aspect ratio which is the square of sliding speed (SS^2) (Table 8).

The other three parameters, namely, weight% of particulate Boron Nitride, normal load and sliding distance, are of the direct factor category. The result of the signal-to-noise ratio in the cumulative form shows a cutoff of 78.92% using the Taguchi-Pareto method. The number of trials involved in the cutoff is 7, and this has been the situation for all the cases considered so far including cases 1, 2 and 3. Bearing in mind that the response table is the final output of the Taguchi-Pareto method, it was computed, and the following is its interpretation. The optimal parametric settings were obtained as $W_1NL_1SS^2{}_3SD_1$ which is interpreted as 4 weight% of particulate Boron Nitride, 10 N of normal load, 10,000 rpm of sliding speed and 500 m of sliding distance. Usually, the output of each section is compared with that of section 4.1. By doing the same thing here, the optimal parametric setting in this section changes from what it was in case 1. It was observed that the normal load, the weight% of particulate Boron Nitride and the sliding distance which were level 1 in case 1 maintained level 1 and also in case 4. Besides, the sliding speed which was at level 1 in case 1 changed to level 3 in the present situation

Table 8 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 4 and 5

	Case 4						Case 5					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	W	NL	SS^2	SD	Total S/N ratio	% cumulative	W	NL	SS	SD^2	Total S/N ratio	% cumulative
1	4	10	10000	500	−73.99	9.74	4	10	100	250,000	−101.94	10.46
2	4	15	40000	750	−86.02	21.07	4	15	200	562,500	−108.98	21.64
3	4	20	90000	1000	−93.06	33.33	4	20	300	1,000,000	−113.98	33.33
4	12	10	40000	1000	−86.02	44.66	12	10	200	1,000,000	−113.98	45.03
5	12	15	90000	500	−93.06	56.92	12	15	300	250,000	−101.94	55.49
6	12	20	10000	750	−74.00	66.66	12	20	100	562,500	−108.98	66.67
7	20	10	90000	750	−93.06	78.92	20	10	300	562,500	−108.98	77.85
8	20	15	10000	1000	−74.02	88.67	20	15	100	1,000,000	−113.98	89.54
9	20	20	40000	500	−86.02	100	20	20	200	250,000	−101.94	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

(case 4). It means that compared to case 1, three parameters maintained their levels, and one changed. In comparing the specific result of the average signal-to-noise ratio for case 1 and the present case (case 4), there was a huge decrease in all the parameters and aspect ratio which range from 48.45% for the sliding speed to 71.46% for the sliding distance. In particular, the decreases are as follows: weight% of particulate (64.05% decrease), normal load (63.9% decrease), sliding speed (48.45% decrease) and sliding distance (71.46% decrease), respectively. In comparison with Kumar and Reddy [13] using the after-pool data of ANOVA (see Table 5), the sliding speed in the current case where a delta value of 19.07. Furthermore, weight% which was fourth in Kumar and Reddy [13] took the second position in the current case where the delta value was obtained as 8.71. Besides, the third and fourth positions belong to the sliding distance and normal load, respectively, while sliding distance attained the same third position in Kumar and Reddy [13]. Again, by comparing the result of Kumar and Reddy [13] concerning ANOVA before pooling, the following are shown: normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96). These results which are for Kumar and Reddy [13] conflict with those obtained from current work where normal load, sliding speed, sliding distance and weight% obtained are the first, third and second, respectively.

Direct and aspect ratios — case 5

In this case, the sliding distance is the concerned aspect ratio, while other factors such as the weight% particulate of Boron Nitride, normal load and sliding speed are direct factors. The sliding distance is classified as an aspect ratio where the aspect is SD2: 1 which is simply stated as SD square (Table 8). By considering the Taguchi-Pareto method, the cutoff point for this situation was established as 77.85%, which involves seven trials out of a total of nine trials for the work. When this is further worked on, the optimal parametric settings obtained are $W_1NL_2SS_1SD^2{}_1$ which is interpreted as 4 weight% of particulate Boron Nitride, 10 N of normal load, 100 rpm of sliding speed, and 250,000 m of sliding distance. As the present authors appear to compare the results with those in section 4.1, it was noted that the optimal parametric settings in both cases are the same. Furthermore, considering the individual average signal-to-noise ratios for the parameter when the current result is compared with case 1, decreased weight% particulate of Boron Nitride, decreased sliding speed, decreased for normal load and also decreased sliding distance. In this circumstance, their performance in case 1 is better than that in case 5. By judging from the delta values, when the delta values of case 1 are compared with those of case 5, the decrease was noted for the weight% of particulate Boron Nitride. However, for a normal load, sliding speed and sliding distance, increase in values was noted. From the delta value comparison, it means that case 5 is better than case 1 which is a contradictory result compared with case 1. Furthermore, when the ranks were observed for all the parameters, they remain the same either in case 1 or case 5 in both. As a manager, if a choice is to be made between case 1 and case 5, it is suggested that either case will be equal since the delta values favour case 5 and the individual average values of signal-to-noise ratio favours case 1. By comparing the result from case 5 with Kumar and Reddy [13], they represented the ANOVA result of the post-pool effect placing the normal load as the most significant parameter (P% = 66.26), sliding speed as the next significant (P% = 10.43) and sliding distance as the least significant (P% = 8.55). In case 5, the normal load is rated as a third which is worse than the rating in Kumar and Reddy [13]. The sliding speed is rated the second position which tallies with the result of Kumar and Reddy [13]. However, the sliding distance is rated as first which is a conflict of a rating between Kumar and Reddy [13] and case 5. To compare Kumar and Reddy [13] of the pre-pooled ANOVA data, normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96) are first, second, third and fourth, respectively (see Table 5). However, in case 5, the normal load became the third position, sliding speed second position while particulate weight% of Boron Nitride took the least position (fourth). As distinct from the result of Kumar and Reddy [13], in case 5, the sliding distance took the first position.

Direct and aspect ratios — case 6

The combination of factors in case 6 involves all the factors as reciprocals of their original direct factors which are 1/W, 1/NL, 1/SS and 1/SD, respectively, for weight% particulate Boron Nitride, normal load, sliding speed and sliding distance (Table 9).

Besides, an effort to compute the Taguchi-Pareto result reveals that 80% could not be obtained under the cumulative signal-to-noise ratio. In this instance, two different values of 73.08% (experimental trial 7) and 86.19% (experimental trial 8) were obtained. However, the difference between 86.19 and 80% is 6.92%, while the difference between 86.19 and 80% is 6.19%. Since 86.19% is closer to 80% than 73.08%, it means that it is 86.19% taken as the cutoff with experimental trial 8 considered. When the response table was obtained, the optimal parametric setting is given as $(1/W)_3(1/NL)_2(1/SS)_1(1/SD)_3$. This is interpreted as 0.25 weight% of particulate Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. However, on comparing the average signal-to-noise ratio obtainable in the response table for case 6 with case 1, it was revealed that all the parameters increased from negative to positive values, thereby revealing that the average signal-to-noise ratio obtained for case 6 is stronger than those obtained for case 1. Furthermore, the delta values were used for comparison where the delta values of case 6 were compared with those of case 1 for all parameters. It was observed that the normal load, sliding speed and sliding distance decreased, but the weight% of particulate Boron Nitride increased. If delta values are used for judgement and 75% of all parameters experienced a decrease in value, it means that the performance of case 6 is worse than that of case 1. This performance decision is contradictory to the outcome of the decision when the average signal-to-noise ratio is used.

Now, the comparison is made between case 6 and the after-pooled data of ANOVA exhibited in Kumar and Reddy [13]. In the case of Kumar and Reddy [13], the normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55) signify the greatest to the least factor, respectively (see Table 5). Compared with case 6, the normal load fell to the fourth position. Incidentally, the sliding speed took the second position in both instances (i.e. Kumar and Reddy [13] and case 6). There is also a coincidence of results for sliding distance which came third in Kumar and Reddy [13] and case 6. However, there is a variance in the result concerning weight% which change to the first position in case 6. In this latter comparison, 50% of the result coincides, while the other 50% is based on disagreement. Besides, it turns to compare the result of the before

Table 9 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 6 and 7

	Case 6						Case 7					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	1/W	1/NL	1/SS	1/SD	Total S/N ratio	% cumulative	$1/W^2$	1/NL	1/SS	1/SD	Total S/N ratio	% cumulative
1	0.25	0.1	0.01	0.002	17.41	8.29	0.063	0.1	0.01	0.002	24.56	9.67
2	0.25	0.07	0.01	0.001	17.76	16.74	0.063	0.067	0.005	0.0013	26.79	20.22
3	0.25	0.05	0.003	0.001	17.89	25.26	0.063	0.05	0.0033	0.001	27.95	31.22
4	0.083	0.1	0.01	0.001	23.72	36.56	0.0069	0.1	0.005	0.001	25.99	41.45
5	0.083	0.07	0.003	0.002	25.45	48.67	0.0069	0.067	0.0033	0.002	29.48	53.060
6	0.083	0.05	0.01	0.001	26.22	61.15	0.0069	0.05	0.01	0.0013	31.79	65.58
7	0.05	0.1	0.003	0.001	25.05	73.076	0.0025	0.1	0.0033	0.0013	26.012	75.82
8	0.05	0.07	0.01	0.001	27.54	86.19	0.0025	0.067	0.01	0.001	29.44	87.41
9	0.05	0.05	0.005	0.002	29.01	100	0.0025	0.05	0.005	0.002	31.98	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

pooling of the ANOVA result in Kumar and Reddy [13], the normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96). The order of listing these parameters is position first, second, third and fourth, respectively. Compared with case 6, the normal load dropped to the fourth position from the first position, and the sliding speed retains the second position in both Kumar and Reddy [13] and case 6. The sliding distance retained the third position in both Kumar and Reddy [13] and case 6. However, the weight% which occupied the fourth position in Kumar and Reddy [13] was elevated to the first position in case 6. It becomes interesting to note that similar results were obtained when case 6 was compared with ANOVA when it is pre-pooled and post-pooled.

Direct and aspect ratios — case 7

In this case 7, two types of factors were identified. The first type is when one of the factors is taken as the square of the reciprocal; this exists for the weight% particulate of Boron Nitride (Table 9). The second type is where the rest of the factors are reciprocals alone; this concerns normal load, sliding speed and sliding distance. Thus, formulation 7 consists of the square of a reciprocal and three reciprocals. While pursuing optimization using the Taguchi-Pareto method, it was found that the cutoff is 75.82% which is closer to 80% than 87.41%. But the experimental trials cover seven experiments. It was found that 75.82% is closer to 80% than 87.41% and therefore selected. Moving forward to the response table computation, the optimal parametric setting is $(1/W^2)_2(1/NL)_{3(}1/SS)_2(1/SD)_2$ which is interpreted as 0.0625 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.002 m for sliding distance. For comparison, the signal-to-noise values for case 7 are compared with those of case 1 along the following discussions: the value of the weight% particulate of Boron Nitride of the optimal point experienced an increase. Furthermore, the values of the optimal parameters for a normal load, sliding speed and sliding distance also experienced increases from negative to positive values for the average signal-to-noise ratio. The implication for this is that case 7 is better than case 1 since the increase in signal-to-noise ratio is desired and indicates performance improvement for the situation considered. The delta values were also used as a tool for comparison. In this situation, the normal load, sliding speed and sliding distance experienced decreases, while weight% particulate Boron Nitride experiences an increase in the comparison between case 1 and case 7. From these results, 75% of the time showed decreases, while only 25% showed increases. But the increase in delta values is favourable, while the decrease is unfavourable. This implies that case 1 performs better than case 7 according to the judgement of delta values. In using Kumar and Reddy [13] for comparison and specifically, starting with the post-pooled ANOVA data, the following results are obtained: the normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55) (see Table 5). In the present study, normal load maintained the first position in both cases, sliding speed became third being displaced from the second position and the sliding distance became fourth, being relegated from the third position. The weight% particulate became second from the last position. In this ranking, 25% of the parameters attained the same position in both instances, while the remaining 75% had different positions. Besides, the present authors compared the result of the pre-pooled ANOVA in Kumar and Reddy [13] with case 7 with the following discussions: normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96). Compared with case 1, normal load retains its first position in case 7. Then, the sliding speed dropped from the second position in case 1 to the third position in case 7. However, the sliding distance moved from the third position in case 1 to the fourth position in case 7. Next is the weight% from the last position in case 1 to the second position in case 7. In all these situations, the coincidence of ranks occurred in 25% of all cases, while differences occurred in 75% of all cases.

Direct and aspect ratios — case 8

In this case, one of the factors notably, the normal load, is reciprocal raised to the second power (Table 10).

This is combined with the reciprocals of the particulate weight% of Boron Nitride, sliding speed and sliding distance. The next phase of calculation is to evaluate the cutoff percentage which was obtained as 86.24%. This value which contains eight experimental trials is closer to 80% based on the 80–20 rule of the Taguchi-Pareto than 72.55% which immediately precedes 86.24%. By moving forward, the signal-to-noise ratio is calculated by averages to make up the response table. The result obtained shows the optimal parametric setting as $(1/W)_3(1/NL^2)_2(1/SS)_3(1/SD)_2$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.01 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. In comparing the result of case 1 with case 8 along the perspectives of the location of the optimal parametric setting, it was noted that all the parameters increased to the present values in case 8. This implies that the values obtained in case 8 are an improvement over those obtained in case 1. Therefore, case 8 is a preferred choice. By evaluating the two cases (cases 1 and 8) along the direction of delta values, there is a mixed result of increased and decreased which is in a ratio of 50–50 when the delta values in case 8 are compared with those in case 1. Specifically, the weight% and the normal load increased. However, the sliding speed and sliding distance decreased. With this result, it is hard to state whether case 8 is preferred to case 1 or vice versa.

The third tool for evaluation is the ranks in both cases 1 and 8. Along this direction of evaluation, the sliding distance which was first in case 1 changed to the fourth position in case 8. Besides, there is a coincidence of positioning for the sliding speed which is second in both instances. Also, normal load in the first case (case 1) and case 8 coincidentally becomes third in both cases. The last parameter which is the weight% particulate of Boron Nitride changed from the fourth position in case 1 to the first position in case 8. Overall, there is a coincidence of ranking in both cases 1 and 8 for 50% of the time, while disagreement occurred for another 50% of the time. Now comparing with Kumar and Reddy [13] based on the after-pooled data of ANOVA, the following result are known about Kumar and Reddy [13]: the normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55) (see Table 5). In this case, the first position which belongs to the normal load is changed to the third position in case 8. The sliding speed which is the second position retains its second position in case 8, and the sliding distance which is the third position becomes the fourth position in case 8. Lastly, the weight% particulate of Boron Nitride which was fourth in Kumar and Reddy [13] became the first position in case 8. In this comparison state, only 25% of the total number of parameters reveals a coincident in ranks. Now, moving to the comparison of the

Table 10 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 8 and 9

	Case 8						Case 9					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	1/W	$1/NL^2$	1/SS	1/SD	Total S/N ratio	% cumulative	1/W	1/NL	$1/SS^2$	1/SD	Total S/N ratio	% cumulative
1	0.25	0.01	0.01	0.002	18.05	7.76	0.25	0.1	0.0001	0.002	17.42	8.29
2	0.25	0.0044	0.005	0.0013	18.06	15.53	0.25	0.067	0.000025	0.0013	17.76	16.74
3	0.25	0.0025	0.0033	0.001	18.06	23.30	0.25	0.05	1.11E-05	0.001	17.89	25.25
4	0.083	0.01	0.005	0.001	27.53	35.14	0.083	0.1	0.000025	0.001	23.73	36.54
5	0.083	0.0044	0.0033	0.002	27.58	47.00	0.083	0.067	1.11E-05	0.002	25.45	48.65
6	0.083	0.0025	0.01	0.0013	27.54	58.85	0.083	0.05	0.0001	0.0013	26.27	61.14
7	0.05	0.01	0.0033	0.0013	31.85	72.55	0.05	0.1	1.11E-05	0.0013	25.05	73.60
8	0.05	0.0044	0.01	0.001	31.84	86.24	0.05	0.067	0.0001	0.001	27.60	86.19
9	0.05	0.0025	0.005	0.002	31.98	100	0.05	0.05	0.000025	0.002	29.03	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

result in Kumar and Reddy [13], the pre-pooled ANOVA situation, the following are evident: normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96). In case 8, the normal load which was first for Kumar and Reddy [13] became third, the sliding speed retained its second position, the sliding distance changed from third to fourth and the weight% particulate of Boron Nitride changed from fourth to the first position in case 8.

Direct and aspect ratios — case 9

In case 9, it is of interest to the researchers to combine the reciprocals of the weight% of particulate Boron Nitride, normal load, sliding speed and sliding distance. In the case of the sliding speed, the square of the reciprocal was obtained (Table 10). While attempting to evaluate the optimization and concurrent positioning of the wear process parameters for nylon-6/Boron Nitride composite, the Taguchi-Pareto method was deployed, and the cutoff point was obtained as 86.19%, being the cumulative values of the signal-to-noise ratio for the first eight experimental trials out of nine. After this, the response table was obtained which yielded the optimal parametric setting of $(1/W)_3(1/NL)_2(1/SS^2)_1(1/SD)_3$. This is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.0001 rpm of sliding speed and 0.002 m of sliding distance. As this optimal parametric setting is compared with case 1, there are changes in the position where the optimal parametric settings fall. For instance, in case 1, the optimal point equivalent for the weight% of particulate Boron Nitride was obtained at level 1, but this changes to level 3 in the current case 9 being considered. For the normal load parameter, the same level 2 is obtained in both cases 1 and 9. Furthermore, the sliding speed in both cases 1 and 9 retained its value at level 1. For the sliding distance, there is also a change in position from level 1 to 3 as case 1 is compared with case 9. From the dimension of the value in each of those cases for the different parameters, the following are the discussions: in case 1, the average signal-to-noise ratio is −51.4224, and this crossed to a positive value of 26.32724. Furthermore, the average signal-to-noise ratio of the normal load, sliding speed and sliding distance in case 1 is −50.5398, −49.8452 and −48.715, respectively. These values rose to 23.60706, 23.76286 and 23.07502, respectively, for the normal load, sliding speed and sliding distance. To comment on these results, one could mention that case 9 is better than case 1 since it has a higher average signal-to-noise ratio than case 1.

Next, by comparing the rank in cases 1 and 9, it could be said that of the four measuring parameters, one of them coincides with the two cases which is the sliding speed that obtained the second position, representing 25% of the total number of parameters considered. For the sliding distance that is ranked first in case 1, the ranking in case 9 fell to the third position. The normal load which is third in case 1 fell to the fourth position in case 9. The next stage of the evaluation is to compare the after-pooled ANOVA result of Kumar and Reddy [13] with the result obtained from the response table of case 9. In this situation, Kumar and Reddy [13] declared the following: normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55) (see Table 5). As the normal load was placed first in Kumar and Reddy [13], it was relegated to the fourth position in case 9. Besides, the sliding speed which was placed second in Kumar and Reddy [13] retained its second position in case 9. In both Kumar and Reddy [13] and case 9, the sliding distance attained the third position, which means that they are no different. Furthermore, the weight% particulate of Boron Nitride which was allocated the fourth position in Kumar and Reddy [13] attained the first position in case 9. Next, the present authors considered the before-pooled ANOVA result of Kumar and Reddy [13] with case 9. As given by Kumar and Reddy [13], normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96), the normal load is given the first position, while in case 9, it attained the fourth position. The sliding speed had a common second position in both Kumar and Reddy [13] and the present case 9. Furthermore, the third position in Kumar and Reddy [13] retained the third position in case 9. However, the fourth position in Kumar and Reddy [13] surprisingly moved to the first position in case 9, and the concerned parameter is the weight% of particulate Boron Nitride.

Direct and aspect ratios — case 10

Case 10 considered the situation where the formulation is based on the combination of the reciprocal of the square of the sliding distance with the reciprocals of the weight% particulate of Boron Nitride, normal load and sliding speed (Table 11).

In this situation, the Taguchi-Pareto is applied to the data on the nylon-6/Boron Nitride composite, which was provided by Kumar and Reddy [13]. On the application of this method to the cumulative percentage of the signal-to-noise ratio obtained from the combination of the orthogonal array and the factor, level interaction, the current authors decided to apply the cutoff rule of 80-20 policy to obtain 86.19%, which was obtained at eight experimental trials. By moving forward to the factor level computation, optimal parametric setting was obtained at $(1/W)_3(1/NL)_2(1/SS)_1(1/SD^2)_3$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.001 rpm of sliding speed and 0.000004 m of sliding distance. By closely observing the optimal parametric point of case 10 about case 1, it was found that there are changes in the location of each of the optimal parameters. Concerning the weight% particulate of Boron Nitride, it moved from level 1 to level 3 with an increase from −51.4224 to 26.29489. The normal load retained its location at level 2 but with a value changes from −50.5398 in case 1 to 23.58517 in case 10. The sliding speed maintained level 1 in both cases of 1 and 10. Notwithstanding, there is a change from −49.8462 in case 1 to 23.72549 in case 10. Lastly, the sliding distance had a change in level from level 1 to level 3. This change is accompanied by a value change of the average signal-to-noise ratio within the response table from −48.715 to 23.0523 as in comparison of case 1 and case 10. The delta values were noted to increase for the weight% particulate of Boron Nitride when case 1 was compared with case 10. Furthermore, the normal load, sliding load, sliding speed and sliding distance were noted to have reduced when case 1 was compared with case 10 for the three parameters. For the ranks, the weight% of particulate Boron Nitride which was in the fourth position rose to the first position. Next, the normal load fell from the third to the fourth position. Besides, sliding speed maintained the same position of second in both cases 1 and 10. Furthermore, the sliding distance fell from the first position to the third position. Now, the comparison with the after-pooled ANOVA of Kumar and Reddy [13] is made (see Table 5). In this situation, the first position which was allocated to normal load changed to the fourth position in case 10. However, the sliding speed, sliding distance and weight% particulate of Boron Nitride which were given to

Table 11 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 10 and 11

	Case 10						Case 11					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	1/W	1/NL	1/SS	$1/SD^2$	Total S/N ratio	% cumulative	W^3	NL	SS	SD	Total S/N ratio	% cumulative
1	0.25	0.1	0.01	0.000004	17.41	8.29	64	10	100	500	−48.20	8.77
2	0.25	0.067	0.005	1.78E-06	17.76	16.74	64	15	200	750	−51.81	18.20
3	0.25	0.05	0.0033	0.000001	17.89	25.26	64	20	300	1000	−54.37	28.10
4	0.083	0.1	0.005	0.000001	23.72	36.55	1728	10	200	1000	−60.03	39.03
5	0.083	0.067	0.0033	0.000004	25.45	48.67	1728	15	300	500	−59.20	49.81
6	0.083	0.05	0.01	1.78E-06	26.22	61.15	1728	20	100	750	−59.49	60.63
7	0.05	0.1	0.0033	1.78E-06	25.05	73.08	8000	10	300	750	−72.09	73.76
8	0.05	0.067	0.01	0.000001	27.54	86.19	8000	15	100	1000	−72.11	86.88
9	0.05	0.05	0.005	0.000004	29.01	100	8000	20	200	500	−72.06	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

the second, third and fourth positions in Kumar and Reddy [13] moved to the second, third and first positions, respectively. Now, considering the before-pooled ANOVA data of Kumar and Reddy [13], the first, second, third and fourth positions were allocated to normal load, sliding speed, sliding distance and weight% particulate of Boron Nitride moved to fourth, second, third and first positions, respectively.

Direct and aspect ratios — case 11

In case 11, the weight% particulate of Boron Nitride is raised to the third power while being jointly considered with the normal load, sliding speed and sliding distance (Table 11). As the Taguchi-Pareto method is applied to the data of the cumulative signal-to-noise ratio, the cutoff point was identified as 73.76%, and it contains seven experimental trials. On computing the response table, the optimal parametric setting was obtained as $(W^3)_1NL_2SS_1SD_1$ which is interpreted as 64 weight% particulate of Boron Nitride, 10 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. Concerning the positions of the optimal parametric setting of each parameter, there are no changes in position, but differences exist in the values of the average signal-to-noise ratio for each parameter under the response table. Specifically, the weight% particulate of Boron Nitride changes from −51.4224 to −51.4601. Furthermore, the average signal-to-noise for a normal load, sliding speed and sliding distance changed from −50.5398 to −55.5045, −49.8462 to −53.8456 and −48.715 to −53.6988, respectively. These changes are lower than what obtains in case 1, and therefore, case 11 is said to be inferior in performance to case 1. Concerning the delta values, it was observed that they increased from case 1 to case 11 for all the parameters, namely weight% of particulate Boron Nitride, normal load, sliding speed and sliding distance. Regarding the ranking, the sliding distance which occupied the first position in case 1 is now third in case 11. The sliding speed retained its second position in both cases. Furthermore, the normal load and the weight% of particulate Boron Nitride which occupied the third and fourth position in case 1 changed to the fourth and first position, respectively, in case 11. Overall, only one out of the four factors (25%) had concurrence in both cases 1 and 11. By comparing the results of Kumar and Reddy [13] after pooled ANOVA data, the following were obtained: normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55) as the first, second and third positions, respectively (see Table 5). Compared with case 11, the normal load displaced to the fourth position, and the sliding speed retained the second position in both instances of Kumar and Reddy [13]. The sliding distance which occupied the third position in Kumar and Reddy [13] also retained the third position in case 11. Finally, the weight% of particulate Boron Nitride which occupied the fourth position in Kumar and Reddy [13] surprisingly took the first position in case 11. Moving on to the analysis of Kumar and Reddy [13] concerning before the pooled ANOVA, the following results were obtained: normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96) as first, second, third and fourth position respectively while weight% of particulate Boron Nitride occupied the first position. Now, comparing these two sets of data, the normal load changed to the fourth position, and the sliding speed retained its second position it had in Kumar and Reddy [13] and case 11. The third position, which was sliding distance in Kumar and Reddy [13] retained its third position in case 11. However, the weight% of particulate Boron Nitride which occupied the fourth position in Kumar and Reddy [13] change to the first position in case 11.

Direct and aspect ratios — case 12

For this instance, the normal load is raised to the third power, while the other parameters such as the weight% particulate of Boron Nitride, sliding speed and sliding distance are treated as the direct factors (Table 12).

These four parameters are jointly formulated as case 12 consisting of a mixture of direct parameters and aspect ratio. The normal load is the only aspect ratio, while other parameters are the direct factors. Now, proceeding to evaluate using the Taguchi-Pareto method, the cumulative signal-to-noise ratio was considered at 76.34%, which represents seven experimental trials. Next, proceeding to the response table, the optimal parametric setting was found to be $W_1(NL^3)_1SS_2SD_1$ which is interpreted as 4 weight% particulate of Boron Nitride, 1000 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. However, the positions that each of the optimal parameters took in case 1 compared with case 12 are different, while the weight% particulate of Boron Nitride took level 1 in case 1, it retained the same level in case 12, and the normal load changed from level 2 to level 1 as in case 1 to case 12, respectively. Besides, the sliding speed change from level 1 to level 12 from case 1 to case 12, respectively. Furthermore, the sliding distance took the same level as level 1 in both cases 1 and 12. Then, by comparing the positions in cases 1 and 12, it was found that all the positions changed. This is not commonly the case; in the previous eleven cases, we have not found such an instance that the coincidence of ranks will be zero when a comparison of case 1 and case 12 is made. Now, it is essential to compare the actual values of the average signal-to-noise ratio to decide whether case 1 is better than case 12 or vice versa. In this case, by comparing the entry of the weight% particulate of Boron Nitride in cases 1 and 12, it was found that there is a reduction in the average signal-to-noise ratio obtained for the parameter. Next, the normal load appeared as −50.5398 in case 1, while it changed to −56.0737 in case 12 from level 2 to level 1, respectively. The sliding speed changed from −49.8452 to −60.9224, while the sliding distance changed from −48.715 to −59.8279 in all these changes, a reduction was observed, which indicates that the worst results are obtained on applying case 12 to the data from Kumar and Reddy [13] using case 1. In this instance, case 12 delivered a worse result than case 1, and therefore, case 1 is a superior choice for the methodical application. Now, considering the delta values, it was found that the weight 5 particulate of Boron Nitride, normal load, sliding speed and sliding distance exhibited an increasing performance when the delta values were measured. However, the sliding distance shows a decreasing performance in measuring the delta values. Since 75% of the cases exhibited increases in delta values, while only 25% shows a decrease, it may be assumed that case 12 showed better performance than case 1. However, this is a contradictory result with those obtained earlier which promote case 1 as a superior method.

Now, considering Kumar and Reddy [13] where the after-pooled ANOVA result is considered, the following result is obtained: normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55) as the first, second and third positions, respectively, compared with case 12, normal load retained the first position in Kumar

Table 12 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 12 and 13

	Case 12						Case 13					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	W	NL^3	SS	SD	Total S/N ratio	% cumulative	W	NL	SS^3	SD	Total S/N ratio	% cumulative
1	4	1000	100	500	−54.98	9.50	4	10	1,000,000	500	−113.98	9.78
2	4	3375	200	750	−64.77	20.69	4	15	8,000,000	750	−132.04	21.10
3	4	8000	300	1000	−72.11	33.15	4	20	27,000,000	1000	−142.61	33.33
4	12	1000	200	1000	−57.08	43.00	12	10	8,000,000	1000	−132.04	44.66
5	12	3375	300	500	−64.67	54.180	12	15	27,000,000	500	−142.61	56.89
6	12	8000	100	750	−72.08	66.63	12	20	1,000,000	750	−113.98	66.67
7	20	1000	300	750	−56.16	76.34	20	10	27,000,000	750	−142.61	78.90
8	20	3375	100	1000	−64.91	87.55	20	15	1,000,000	1000	−113.98	88.67
9	20	8000	200	500	−72.06	100	20	20	8,000,000	500	−132.04	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

and Reddy [13] (see Table 5). The sliding speed changed from the second position to the fourth position. Furthermore, the sliding distance retained the third position in both instances. The weight% particulate of Boron Nitride changed from the fourth position to the second position. Now, going before pooling of ANOVA data, the first, second, third and fourth positions are allocated to the normal load, sliding speed, sliding distance and weight% particulate of Boron Nitride according to the following: normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96). By comparing these values with case 12, normal load, sliding speed, sliding distance and weight% particulate of Boron Nitride changed to first, fourth, third and second, respectively.

Direct and aspect ratios — case 13

This case reveals that the sliding speed, expressed in an aspect ratio of the sliding speed, is combined with the weight% particulate of Boron Nitride, normal load and sliding distance in a formulation (Table 12). As the Taguchi-Pareto method is to be applied to the experimental data provided by Kumar and Reddy [13]. The cumulative signal-to-noise ratio of the factors based on experimental trials was computed from the perspective of the smaller the better criterion. In these instances, it is desired that the smaller values of the parameters profit the wear analysis process. Next, the cutoff value was determined as 78.90% in experimental trial 7. Then, the average signal-to-noise ratio is computed from all the relevant experimental trials, namely 1–7. In this response summary table, the optimal parametric setting obtained is $W_1NL_3(SS^3)_1SD_1$ which is interpreted as 4 weight% particulate of Boron Nitride, 10 N of normal load, 1,000,000 rpm of sliding speed and 500 m of sliding distance. Compared with the locations of the individual parameters of case 1, there is a change which is attributed to normal load, from level 2 in case 1 to level in case 13. All other parameters such as the weight% particulate of Boron Nitride, sliding speed and sliding distance remained constant at levels 1, 1 and 1, respectively. However, considering the values of the average signal-to-noise ratio in the response table for each parameter, some notable changes were observed, where case 1 was compared with case 13. These results decreased for all parameters, including weight% particulate of Boron Nitride, normal load, sliding speed and sliding distance. Furthermore, all the delta values increased as the researcher considered movement from cases 1–13. With these increases in the delta value, it may be stated that case 13 is better than case 1 since higher delta values are obtained. Furthermore, comparing the ranks of case 1 and case 13, the first, second, third and fourth of case 1, which are sliding distance, sliding speed, normal load and weight% particulate of Boron Nitride, respectively, moved to third, first, third and second, respectively.

Now, comparing with the after-pooled ANOVA data of Kumar and Reddy [13], the first, second and third positions were allocated to normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55), respectively, but these changed to the third, first and third, respectively (see Table 5). However, the weight% particulate of Boron Nitride attained the first position in case 13. By considering the before-pooled ANOVA data of Kumar and Reddy [13], the result obtained is normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% =

7.96) which are first, second, third and fourth, respectively, in case 13; these parameters changed to third, first, third and second, respectively.

Direct and aspect ratios — case 14

In this case, the sliding distance was tripled and jointly considered with the direct factors of weight% particulate of Boron Nitride, normal load and sliding speed (Table 13).

After applying the Taguchi-Pareto method to the signal-to-noise ratio, it was found that the cutoff is 77.85% which represents 7 experimental trials from a total of 9. Now, moving to the average signal-to-noise ratio, the optimal parametric setting is $W_1NL_2SS_1(SD^3)_1$ which is interpreted as 4 weight% particulate of Boron Nitride, 10 N of normal load, 100 rpm of sliding speed and 125,000,000 m of sliding distance. By considering the specific optimal values of the parameters, there are changes in them. For instance, the weight% particulate of Boron Nitride changed from −51.4224 to −165.46 which is a decrease, and the normal load changed from −50.5398 to −161.2 which is also a decrease. Besides, the sliding speed changes from −49.8452 to −162.2 which is a decrease. Next, the sliding distance changed from −48.715 to −155.918, which is also a decrease. By our judgement, case 1 is better than case 14 since the lower average signal-to-noise ratio is obtained. Next, the position of the optimal parametric setting in case 1 and case 14 is the same. In case 14, the delta values are 1.0231, 9.0309, 9.0309 and 18.0618 for the weight% particulate of Boron Nitride, Normal load, sliding speed and sliding distance respectively. The respective positions are fourth, second, second and first, respectively. Now, considering the actual values of the average signal-to-noise ratio in cases 1 and 14, decreases were observed for all parameters. In the case of the delta, value increases were observed for all the parameters. The coincidence between case 1 and case 14 shows that the weight% particulate of Boron Nitride is fourth in both cases, and the normal load which is third in case 1 is second in case 14. Apart from the sliding speed which is second in case 1 is also second in case 14, while the sliding distance which is first in case 1 retained the first position in case 14. Therefore, the coincidence in ranks is 75% which means that three of the four parameters are the same. Now, in Kumar and Reddy [13], the first, second and third position goes to normal load (P% = 66.26), sliding speed (P% = 10.48) and sliding distance (P% = 8.55), respectively (see Table 5). The corresponding parameters are positioned as second, second and first, respectively, considering the before-pooled ANOVA data in Kumar and Reddy [13], and in case 14, it was noticed that the first, second, third and fourth positions go to normal load (P% = 71.54), sliding speed (P% = 11.27), sliding distance (P% = 9.24) and particulate weight% (P% = 7.96), respectively; the positions changed to second, second, first and fourth, respectively.

Direct and aspect ratios — case 15

In this case, the reciprocals of all factors are found and combined, but the reciprocals of the weight% particulate of Boron Nitride have the denominator to be triple power, while the denominators of the normal load, sliding speed and sliding distance are to a power of unity (Table 13). By starting from the computation using the Taguchi-Pareto method, it was found that the cutoff is 76.52%, representing 7 experimental trials. When this is converted to the response table, the final results obtained by ranks give the normal load

Table 13 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 14 and 15

	Case 14						Case 15					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	*W*	NL	SS	SD^3	Total S/N ratio	% cumulative	$1/W^3$	1/NL	1/SS	1/SD	Total S/N ratio	% cumulative
1	4	10	100	125,000,000	−155.92	10.47	0.016	0.1	0.01	0.002	25.87	9.89
2	4	15	200	421,875,000	−166.48	21.65	0.016	0.067	0.005	0.0013	29.29	21.08
3	4	20	300	1,000,000,000	−173.98	33.33	0.016	0.05	0.0033	0.001	31.62	33.17
4	12	10	200	1,000,000,000	−173.98	45.02	0.00058	0.1	0.005	0.001	26.0092	43.11
5	12	15	300	125,000,000	−155.92	55.49	0.00058	0.067	0.0033	0.002	29.53	54.39
6	12	20	100	421,875,000	−166.48	66.67	0.00058	0.05	0.01	0.0013	31.87	66.57
7	20	10	300	421,875,000	−166.48	77.85	0.00013	0.1	0.0033	0.0013	26.02	76.52
8	20	15	100	1,000,000,000	−173.98	89.53	0.00013	0.067	0.01	0.001	29.44	87.77
9	20	20	200	125,000,000	−155.92	100	0.00013	0.05	0.005	0.002	31.99	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

as the best, weight% particulate of Boron Nitride as the second, sliding speed as the third and sliding distance as the fourth position in parametric evaluation for an order of importance. The delta values obtained showed the normal load (5.77699) as the best, while the sliding distance is the worst (1.35626). Compared with case 1, the delta values in case 15 are higher for weight% particulate of Boron Nitride and normal load while being lower for sliding speed and sliding distance. Since this is a 50:50 situation, it is difficult to decide which of the two cases brings better results, either case 1 or case 15. However, if the researchers consider the magnitude of the changes, preference may be given to case 1 instead of case 15. The motivation is that when the delta values of the parameters that showed a decrease are added for case 15 and these are done for case 1 also and compared, the sum of all the delta values for case 1 gives 11.78227, while that of case 15 gives 11.65882, this shows that case 1 is better than case 15 as it has a higher value. Now, considering the optimal parametric setting, the authors obtained $(1/W^3)_2(1/NL)_3(1/SS)_3(1/SD)_2$ which is interpreted as 0.1563 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. Based on the results of the optimal parametric setting, the optimal point for each of the parameters is different when case 15 is compared with case 1, while the weight% particulate of Boron Nitride is at level 1 in case 1 moved to level 2 in case 15. The normal load at level 2 in case 1 moved to level 3 in case 15. Furthermore, a sliding speed which is in level 1 in case 1 has moved to level 3 in case 15. Besides, the sliding distance which is at level 1 in case 1 has moved to level 2 in case 15. Moreover, the actual values of the optimal parametric setting when case 1 was compared with case 15 are preferable to case 1 since the increase in the average signal-to-noise ratio indicates a stronger method. Notwithstanding, by comparing the after-pooled ANOVA data of Kumar and Reddy [13] with case 15, it was noticed that normal load, sliding speed and sliding distance which occupied first to the third position now retained normal load as the first position, change sliding speed to third position and sliding distance to the fourth position. Now, considering the before-pooled ANOVA data of Kumar and Reddy [13] (see Table 5), the normal load, sliding speed, sliding distance and weight% particulate of Boron Nitride, which were rated first, second, third and fourth, respectively, retained the first position for normal load, while the second position, third position and fourth position were retained for weight% particulate of Boron Nitride, sliding speed and sliding distance, respectively.

Direct and aspect ratios — case 16

Here, the reciprocals of the tripled power of the normal load are combined with the reciprocals of weight% particulate of Boron Nitride, sliding speed and sliding distance to form a combined method termed case 16 (Table 14).

When the Taguchi-Pareto method was applied, the cutoff point was obtained as 86.26% being the 8 experimental trials. Furthermore, as we progress to the evaluation using the response table, it was noticed that the optimal parametric setting was obtained as $(1/W)_3(1/NL3)_1(1/SS)_3(1/SD)_2$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.001 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. From the response table, the weight% particulate of Boron Nitride, normal load, sliding speed and sliding distance became first, second, third and fourth, respectively. When the optimal point of each of the parameters is considered in both case 1 and

Table 14 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — cases 16 and 17

	Case 16						Case 17					
	Translated orthogonal arrays						Translated orthogonal arrays					
Trial no.	1/W	1/NL	$1/SS^3$	1/SD	Total S/N ratio	% cumulative	1/W	1/NL	$1/SS^3$	1/SD	Total S/N ratio	% cumulative
1	0.25	0.1	0.000001	0.002	18.05	7.76	0.25	0.1	0.000001	0.002	17.42	8.29
2	0.25	0.067	1.25E-07	0.0013	18.06	15.51	0.25	0.067	1.25E-07	0.0013	17.76	16.74
3	0.25	0.05	3.7E-08	0.001	18.06	23.27	0.25	0.05	3.7E-08	0.001	17.89	25.25
4	0.083	0.1	1.25E-07	0.001	27.59	35.13	0.083	0.1	1.25E-07	0.001	23.73	36.54
5	0.083	0.067	3.7E-08	0.002	27.59	46.98	0.083	0.067	3.7E-08	0.002	25.45	48.65
6	0.083	0.05	0.000001	0.0013	27.54	58.81	0.083	0.05	0.000001	0.0013	26.27	61.14
7	0.05	0.1	3.7E-08	0.0013	32.02	72.57	0.05	0.1	3.7E-08	0.0013	25.05	73.06
8	0.05	0.067	0.000001	0.001	31.90	86.26	0.05	0.067	0.000001	0.001	27.6	86.19
9	0.05	0.05	1.25E-07	0.002	31.99	100	0.00013	0.05	0.005	0.002	29.03	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

case 16, the following were noticed: there was an increase in the values of all the average signal-to-noise ratios in case 16 as compared with case 1. However, when the delta values in both cases 1 and 16 were compared, an increase in two parameters, namely weight% particulate of Boron Nitride and normal load, were observed, but decreases in the sling speed and sliding distance were also observed. Now, comparing case 16 with Kumar and Reddy [13] using the data after pooling of ANOVA, it was noted that the normal load changed from the first to the second position, the sliding speed changed from second to third, and the sliding distance changed from third to the fourth position, respectively. Interestedly, the least important parameter in Kumar and Reddy [13] (see Table 5) became the first position in case 16, and this parameter is called the weight% particulate of Boron Nitride. Moreover, by comparing the before-pooled ANOVA data of Kumar and Reddy [13] with case 16, it was noticed that normal load changed from first to second, sliding speed changed from second to third, sliding distance changed from third to fourth and weight% particulate of Boron Nitride changed from fourth to first.

Direct and aspect ratios — case 17

In this case, the reciprocal of the cube root for the sliding speed is considered incorporated with the reciprocals of weight% particulate of Boron Nitride, normal load and sliding distance (Table 14). As the Taguchi-Pareto method was applied to the data, the cutoff point was obtained at 86.19% (experimental trials) with an equivalent optimal parametric setting as $(1/W)_3(1/NL)_2(1/SS^3)_1(1/SD)_3$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.000001 rpm of sliding speed and 0.002 m of sliding distance. The results of case 17 show changes in the location of the optimal point by level for each parameter. For example, the weight% particulate of Boron Nitride changes from level 1 to level 3, and the normal load was retained at level 2 in both instances of cases 1 and 17. Also, sliding speed retained its level 1 position in both cases. Additionally, the sliding distance changes from level 1 to level 3. By looking very closely at the specific values of the average signal-to-noise ratios for each parameter, the weight% particulate of Boron Nitride increased from −51.4224 to 26.3272. The normal load increased from −50.5398 to 23.6071. The sliding speed from is −49.8452 to 23.7629. Also, the sliding distance increased from −48.715 to 23.07502. Interestedly, this growth in the average signal-to-noise ratio suggests that case 17 is superior to case 1. By looking at the delta values in the response table, only the weight% particulate of Boron Nitride increases, while other parameter decreases. Given this understanding, one tends to judge case 1 as being superior to case 17. For the ranking in case 17, weight% particulate of Boron Nitride, sliding speed, sliding distance and normal load rank first, second, third and fourth, respectively. Now, drawing from the after-pooled ANOVA data showcased in Kumar and Reddy [13] (see Table 5) and comparing it with case 17, the normal load changed from the first to the fourth position. Sliding speed retained the second position; sliding distance retained its third position. Then, the weight% particulate of Boron Nitride moved from the fourth position in Kumar and Reddy [13] to a surprising first position in case 17. By further consideration of the data in Kumar and Reddy [13] with the concurrent case 17, the before-pooled ANOVA data of Kumar and Reddy [13] had positions of the parameters as stated previously for the after-pooled ANOVA data of Kumar and Reddy [13].

Direct and aspect ratios — case 18

In this case, the formulation consists of the reciprocal of the cube for the sliding distance in a productive relationship with the reciprocals of the weight% particulate of Boron Nitride, normal load and sliding speed (Table 15).

The computation to be made is from the application of Taguchi-Pareto which cut off the cumulative average signal-to-noise ratio at 86.19% which exists at experimental trial 8. By following this up, the response table was developed to obtain the optimal parametric setting at $(1/W)_3(1/NL)_2(1/SS)_1(1/SD^3)_3$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.000000008 m of sliding distance. It was observed that at the location where the optimal parametric setting exists for each parameter, there are changes when compared with case 1. In this case 18, the weight% particulate of Boron Nitride is at level 3 as opposed to level 1 in case 1. This is also accompanied by a difference in values which increases from case 1 to case 18. Furthermore, the normal load occurred at level 2 in case 18 which did not change when compared to case 1. Besides, a difference in values occurred at this stationary point for the normal load which increases from case 1 to case 18. Moreover, the sliding speed was maintained at the same level when case 1 is compared to case 18. But there is an increase in the average signal-to-noise ratio despite the static situation of the parameter in the two cases. Next, the sliding distance occurred at level 1 in case 1 but proceeded to level 3 in case 18. By looking closely at the actual value of the average signal-to-noise ratio, it was observed an increase occurred when case 1 is compared with case 18. Moving forward, on comparing the delta values in cases 1 and 18, those representing the weight% particulate of Boron Nitride increased from case 1 to case 18. However, for the normal load, sliding speed and sliding distance, it was observed that the delta values decreased from case 1 to case 18. Since the majority of the cases (75%) represent decreases, it may be safe to state that case 1 is better than case 18 because a higher delta value signifies the acceptance of the model and vice versa. In case 18, the ranks are compared with those

Table 15 Direct parameters, associated orthogonal arrays and %cumulative SN ratios — case 18

	Case 18					
	Translated orthogonal arrays					
Trial no.	1/W	1/NL	1/SS	1/SD3	Total S/N ratio	% cumulative
1	0.25	0.1	0.01	0.000000008	17.41	8.29
2	0.25	0.067	0.005	2.37037E-09	17.76	16.74
3	0.25	0.05	0.0033	0.000000001	17.89	25.26
4	0.083	0.1	0.005	0.000000001	23.72	36.55
5	0.083	0.067	0.0033	0.000000008	25.45	48.67
6	0.083	0.05	0.01	2.37037E-09	26.22	61.15
7	0.05	0.1	0.0033	2.37037E-09	25.05	73.08
8	0.05	0.067	0.01	0.000000001	27.54	86.19
9	0.05	0.05	0.005	0.000000008	29.01	100

Key: Boron nitride (*W*), %wt; normal load (*NL*), N; sliding speed (*SS*), rpm; sliding distance (*SD*), m

of case 1. Surprisingly, there is no coincidence of positions. In case 18, the first, second, third and fourth parameters are allocated to the weight% particulate of Boron Nitride, sliding speed, sliding distance and normal load, respectively.

Compared with after-pooled ANOVA result of Kumar and Reddy [13], there is a coincidence with the sliding speed and sliding distance which are second and third respectively in both situations; however, the normal load is rated as the first in Kumar and Reddy [13]. It moved to the fourth position in case 18. Also, in Kumar and Reddy [13], the worst parameter in a position which is the weight% particulate of Boron Nitride surprisingly achieved the first position. This direction of result in comparison is the same obtained when the before-pooled ANOVA data is compared with case 18 (see Table 5).

Predictive equations

It is interesting to obtain the SN ratios from the wear inputs of Boron Nitride %wt, normal load, sliding speed and sliding distance by forming predictive equations. In this article, predictive equations were used to determine the wear inputs to find the SN ratios. The starting point is to pick each case from Table 2, but case 1 is examined first. Then, the authors conducted analysis on the relevant data of case 1 in Table 3. The analysis focused on the data on orthogonal arrays translated into figures where nine sets of data are involved. The first set of data is for experimental trail 1 where W, NL, SS and SD are 4 %wt, 10 N, 100 rpm and 500 m, respectively. But experimental trial 1 data of case 1 is not sufficient to form the predictive equation that is comprehensive enough to represent the case 1 behaviour of the wear inputs to find the SN ratios. Also, we cannot use all the data for the nine experimental trials because we are considering Taguchi-Pareto method, which terminates at experimental trial 7. But from these seven experimental trials, two trials should be reserved for confirmatory tests. Therefore, it was decided that only data of experimental trials 1 to 5 will be used for testing, while data on experimental trials 6 and 7 will be used for confirmatory tests (validation). Then, the data on the orthogonal arrays translated into figures for trials 1 to 5 is used in the regression facility available in MS Excel 97/2003 software. On running the programme, where the corresponding values of the total SN ratios are paired with those of the wear inputs, Eq. (1) emerged:

$$\text{SN ratio} = -42.5025 - 0.008958333\text{NL} - 0.004655\text{SS} - 0.01062\text{SD} \tag{1}$$

Equation (1) was formed where SN ratios with values from −48.13 (Trial No. 1) to −49.3 (Trial No. 5) are regarded as the dependent variable, while values of W, NL, SS and SD under the orthogonal array translated into figures from Trial No. 1 to Trial No. 5 are chosen as the independent variables. Now, to conduct confirmatory test, we will start by introducing the values of the wear inputs and the total SN ratios in Table 3 to Eq. (1) using Trial No. 6 values first. On doing this, we note that W, NL, SS and SD of 12 %wt, 20 N, 100 rpm and 750 m, respectively, are used in the Eq. (1), while −51.50 is used for the total SN ratio. On substituting these values in Eq. (1), the predicted SN ratio is −51.04. On comparing the predicted SN ratios and actual SN ratio, an error of 1.02% was noticed. Therefore, the prediction is accurate and can be used for further work. A confirmatory test was made by using experimental trials 6 and 7 and finding the average

Table 16 Confirmation test results on the predictive equations

Case	Predicted average SNR	Experimental	Error%	Comment
Case 1	−51.53	−51.85	−1	Recommended
Case 2	−51.85	−51.85	0	Recommended
Case 3	−46.81	−51.85	−10	Recommended
Case 4	−112.82	−51.85	118	Recommended
Case 5	−94.37	−51.85	82	Recommended
Case 6	25.63	−51.85	−149	Recommended
Case 7	28.23	−51.85	−154	Recommended
Case 8	28.42	−51.85	−155	Recommended
Case 9	25.13	−51.85	−148	Recommended
Case 10	27.22	−51.85	−152	Recommended
Case 11	−72.44	−51.85	40	Recommended
Case 12	−47.03	−51.85	−9	Recommended
Case 13	−50.47	−51.85	−3	Recommended
Case 14	−161.31	−51.85	211	Recommended
Case 15	−893587	−51.85	1,723,309	Not recommended
Case 16	−4125.79	−51.85	7857	Not recommended
Case 17	630,736.30	−51.85	−1,216,564	Not recommended
Case 18	90,580.03	−51.85	−174,796	Not recommended
		Average	18,860	Not recommended

results as data on W, NL, SS, SD and total SN ratios. On using the values of 20 %wt, 10 N, 300 rpm, 750 m and −52.13 for total SN ratio, the predicted SN ratio is −52.03. On comparing the predicted and actual SN ratios, an error of −1% was recorded (Table 16), which confirms that Eq. (1) properly predicts the wear inputs from the SN ratios. Notice that all these analyses are for case 1. However, for a brief account, only the predictive equations for cases 2 to 18 are stated here. These are as follows:

$$\text{Case 2}: \text{SN ratio} = -42.58 - 0.00167\text{W}^2 - 0.0051\text{SS} - 0.0104\text{SD} \tag{2}$$

$$\text{Case 3}: \text{SN ratio} = -42.82 + 0.4\text{W} + 0.0204\text{NL}^2 - 0.0368\text{SS} - 0.01084\text{SD} \tag{3}$$

$$\text{Case 4}: \text{SN ratio} = -27.6975 - 2.43938\text{W} - 3.903\text{NL} + 0.000249\text{SS}^2 \tag{4}$$

$$\text{Case 5}: \text{SN ratio} = -98.9932 + 0.85427\text{W} - 0.00025\ \text{SS} - 1.6\ \text{E} - 05\text{SD} \tag{5}$$

$$\text{Case 6}: \text{SN ratio} = 29.96438 = -44.4461/\text{W} - 48.75/\text{NL} + 120.7143/\text{SS} + 1112.5/\text{SD} \tag{6}$$

$$\text{Case 7}: \text{SN ratio} = 33.47431 - 36.27776/\text{W}^2 - 78.3917/\text{NL} - 44.4627\text{SS} + 827.4865/\text{SD} \tag{7}$$

$$\text{Case 8}: \text{SN ratio} = 32.19602 - 56.6084/\text{W} + 5.8876/\text{NL}^2 - 16.3247/\text{SS} + 55.21855/\text{SD} \tag{8}$$

$$\text{Case 9 : SN ratio} = 28.45137 - 41.6671/\text{W} - 21.2053/\text{NL} - 4182.5/\text{SS}^2 + 962.0888/\text{SD} \quad (9)$$

$$\text{Case 10 : SN ratio} = 33.11655\ 51.6429/\text{W} - 73.8223/\text{NL} + 462.4034/\text{SS} \quad (10)$$

$$\text{Case 11 : SN ratio} + -43.7076 - 0.00437\text{W}^2 - 0.0178\text{SS} - 0.00522\text{SD} \quad (11)$$

$$\text{Case 12 : SN ratio} = -48.4642 + 1.376181\text{W} + 0.001089\text{NL}^3 - 0.11643\text{SS} - 0.00293\text{SD} \quad (12)$$

$$\text{Case 13 : SN ratio} = 58.5313 - 2.80365\text{W} - 4.8583\text{NL} + 6.24\text{E} - 07\text{SS}^3 \quad (13)$$

$$\text{Case 14 : SN ratio} = -155.666 + 0.187692\text{W} - 0.00104\text{SS} - 2\text{E} - 08\text{SD}^3 \quad (14)$$

$$\text{Case 15 : SN ratio} = 42.47173 - 160.603/\text{W}^3 - 187.067/\text{NL} + 744.7308/\text{SS} - 1386.36/\text{SD} \quad (15)$$

$$\text{Case 16 : SN ratio} = 32.34616 - 57.0961/\text{W} - 0.12807/\text{NL} - 4.32613/\text{SD} \quad (16)$$

$$\text{Case 17 : SN ratio} = 29.09077 - 42.7554/\text{W} - 26.5348/\text{NL} + 842.3858/\text{SD} \quad (17)$$

$$\text{Case 18 : SN ratio} = 33.11655 - 51.6429/\text{W} - 73.8323/\text{NL} + 462.4034/\text{SS} \quad (18)$$

From the confirmation results, a range of error values from −1,216,564 to 1,723,309 was obtained for the various models suggested for optimization by the authors. However, it is known that if the differences in values between the predicted and experimental values are too large, the models may not be good predictors of the SN ratios. Therefore, all eighteen cases were considered to find out which of the models can be used in practice and suggested for further decision-making. Interestingly, only fourteen cases (cases 1 to 14) were found to be valid in this instance. These are therefore recommended for decision-making.

Wear rate considered to determine the SN ratio

In this article, due to the constraint of utilizing the experimental data of Kumar and Reddy [13], the specific wear rate, wear loss, and wear resistance for the process could not be determined as no experimental data was available on the measures. However, the present authors were able to provide values of wear rate since useful information about the components of the Archard's wear equation used was available. To solve the problem, it was noticed that only two of the four factors used in cases 1 to 18 could be applied in the Archard's equation. The volumetric wear (wear rate) is computed as the ratio of two parts, the product of K, NL and SD to H. Here, K is assumed from the wear responses of 0.2% carbon dual-phase steel where that of nylon-6/Boron Nitride composite in Modi et al. [19], specified in their Table 2, was 27.84. Next, the hardness (H) of the nylon 6/Boron Nitride was assumed to approximate that of titanium diboride, which is expressed by Laszkiewicz-Łukasik et al. [16] as 19.5 GPa, obtained at room temperature (Table 1 of the referenced material). Now, twelve extra cases are formulated, named cases 1a to 12a, which are distinct from the previous 18 cases in that they relate only to wear rate which consists of only two parameters, whereas the other eighteen cases relate to four parameters at a time. Thus, the new cases created are as follows:

Case 1a: direct factors for normal load and sliding distance to compute volumetric wear

The two factors concerned, namely, normal load and sliding distance, were checked for their orthogonal configuration for the L9 orthogonal array, displaced in Table 2 of Kumar and Reddy [13]. These orthogonal arrays are then translated into actual values based on 9 experimental trials. It was then that the volumetric wear was computed to comprise of four items notably, K, NL, SD and H. Thus, volumetric wear is obtained for 9 experimental trials for different values. The average is then computed for the representative of case 1. It was noticed that the volumetric wear ranges from a minimum of 10,707.69 in experimental trials 5 and 7 (repeated). The average volumetric wear is the 16,061.54 mm^3 (Table 17). Notice that other cases 2a to 12a are not elaborated upon in this work, but their results are summarized in Table 17.

The findings of the previous study by Kumar and Reddy [13] reveal that the optimal conditions of the parameters in the post-tribological test period define the wear characteristics of the PA6/BN composites for the varying filler composition, sliding speed, normal load and sliding distance at three levels, expressed as W-NL-SS-SD in the context of the present article. However, the optimal condition show follows a direct parametric perspective in computations. However, specifically, our article is new, and a novel insight is proposed for the way the parameters that are introduced into the factor-level table are designed. We argue that direct parameters may be coupled with aspect ratios of these parameters where aspect ratios are expressed as square, reciprocal of a square and cube and its reciprocal. The transformation takes place from the conversion of the orthogonal arrays of the parameters into signal-to-noise ratios. This is greatly modified by the Pareto element of the Taguchi-Pareto method that restricts computations to only 80% of the cumulative values for the percentage signal-to-noise ratios evaluated.

Conclusions

Despite the growing evidence of the use of the Taguchi method in wear research, and the positive role of nylon of Boron Nitride composite plays in structural development as documented in some studies, evidence of combined optimisation and prioritization of wear process parameters is lacking. Exploiting original wear experimental data from the literature, this article showcases an investigation of the application of the Taguchi-Pareto method on the fabrication and processing of nylon of Boron Nitride composite. In this work, the Taguchi-Pareto method was deployed on the data provided by Kumar and Reddy [13] to produce optimal results through the optimal parameters setting determination and concurrently establish the priority for the parameter. This study advances knowledge by directly evaluating the aspect ratios of wear performance parameters for PA6/BN composites through several diverse aspect ratios of a square, reciprocal of a square and cube and its reciprocal. These ratios ensure that the optimal values obtained for decision-making do not seem to be expanded or compressed. Based on the results obtained, the following conclusions were made:

Table 17 Direct and aspect ratio factors to compute volumetric wear

	Case 1a Direct factors for normal load and sliding distance							Case 2a Direct factor and aspect ratio for normal load and sliding distance					Case 3a Direct factor and aspect ratio for normal load and sliding distance				
Trial no.	NL	SD	NL	SD	*K*	*H*	*W*	1/NL	SD	*K*	*H*	*W*	NL	1/SD	*K*	*H*	*W*
1	1	1	10	500	27.84	19.5	7138.46	0.1	500	27.84	19.5	71.38	10	0.002	27.84	19.5	0.03
2	1	2	15	750	27.84	19.5	16,061.54	0.07	750	27.84	19.5	71.38	15	0.001	27.84	19.5	0.03
3	1	3	20	1000	27.84	19.5	28,553.85	0.05	1000	27.84	19.5	71.38	20	0.001	27.84	19.5	0.03
4	2	1	10	1000	27.84	19.5	14,276.92	0.10	1000	27.84	19.5	142.77	10	0.001	27.84	19.5	0.01
5	2	2	15	500	27.84	19.5	10,707.69	0.07	500	27.84	19.5	47.59	15	0.002	27.84	19.5	0.04
6	2	3	20	750	27.84	19.5	21,415.38	0.05	750	27.84	19.5	53.54	20	0.001	27.84	19.5	0.04
7	3	1	10	750	27.84	19.5	10,707.69	0.10	750	27.84	19.5	107.08	10	0.001	27.84	19.5	0.02
8	3	2	15	1000	27.84	19.5	21,415.38	0.07	1000	27.84	19.5	95.18	15	0.001	27.84	19.5	0.02
9	3	3	20	500	27.84	19.5	14,276.92	0.05	500	27.84	19.5	35.69	20	0.002	27.84	19.5	0.06
	Case 4a Aspect ratio for normal load and sliding distance							Case 5a Direct factor and aspect ratio for normal load and sliding distance					Case 6a Direct factor and aspect ratio for normal load and sliding distance				
Trial no	NL	SD	1/NL	1/SD	*K*	*H*	*W*	NL^2	SD	*K*	*H*	*W*	NL	SD^2	*K*	*H*	*W*
1	1	1	0.10	0.002	27.84	19.5	0.0003	100	500	27.84	19.5	71,384.62	10	250,000	27.84	19.5	3,569,231
2	1	2	0.07	0.001	27.84	19.5	0.0001	225	750	27.84	19.5	240,923.10	15	562,500	27.84	19.5	12,046,154
3	1	3	0.05	0.001	27.84	19.5	7.14E-05	400	1000	27.84	19.5	571,076.90	20	1,000,000	27.84	19.5	28,553,846
4	2	1	0.10	0.001	27.84	19.5	0.0001	100	1000	27.84	19.5	142,769.20	10	1,000,000	27.84	19.5	14,276,923
5	2	2	0.07	0.002	27.84	19.5	0.0002	225	500	27.84	19.5	160,615.40	15	250,000	27.84	19.5	5,353,846
6	2	3	0.05	0.001	27.84	19.5	9.52E-05	400	750	27.84	19.5	428,307.70	20	562,500	27.84	19.5	16,061,538
7	3	1	0.10	0.001	27.84	19.5	0.0002	100	750	27.84	19.5	107,076.90	10	562,500	27.84	19.5	8,030,769
8	3	2	0.07	0.001	27.84	19.5	9.52E-05	225	1000	27.84	19.5	321,230.80	15	1,000,000	27.84	19.5	21,415,385
9	3	3	0.05	0.002	27.84	19.5	0.0001	400	500	27.84	19.5	285,538.50	20	250,000	27.84	19.5	7,138,462

Table 17 (continued)

			Case 7a Direct factor and aspect ratio for normal load and sliding distance					Case 8a Direct factor and aspect ratio for normal load and sliding distance					Case 9a Direct factor and aspect ratio for normal load and sliding distance				
Trial no.	NL	SD	NL	SD	*K*	*H*	*W*	1/NL	SD	*K*	*H*	*W*	NL^3	SD	K	H	W
1	1	1	0.0100	500	27.84	19.5	7.14	10	4E-06	27.84	19.5	5.71E-05	1000	500	27.84	19.5	713,846.2
2	1	2	0.0044	750	27.84	19.5	4.76	15	1.78E-06	27.84	19.5	3.81E-05	3375	750	27.84	19.5	3,613,846
3	1	3	0.0025	1000	27.84	19.5	3.57	20	1E-06	27.84	19.5	2.86E-05	8000	1000	27.84	19.5	11,421,538
4	2	1	0.0100	1000	27.84	19.5	14.28	10	1E-06	27.84	19.5	1.43E-05	1000	1000	27.84	19.5	1,427,692
5	2	2	0.0044	500	27.84	19.5	3.18	15	4E-06	27.84	19.5	8.57E-05	3375	500	27.84	19.5	2,409,231
6	2	3	0.0025	750	27.84	19.5	2.68	20	1.78E-06	27.84	19.5	5.08E-05	8000	750	27.84	19.5	8,566,154
7	3	1	0.0100	750	27.84	19.5	10.71	10	1.78E-06	27.84	19.5	2.54E-05	1000	750	27.84	19.5	1,070,769
8	3	2	0.0044	1000	27.84	19.5	6.35	15	1E-06	27.84	19.5	2.14E-05	3375	1000	27.84	19.5	4,818,462
9	3	3	0.0025	500	27.84	19.5	1.78	20	4E-06	27.84	19.5	0.0001	8000	500	27.84	19.5	5,710,769
			Case 10a Direct factor and aspect ratio for normal load and sliding distance					Case 11a Direct factor and aspect ratio for normal load and sliding distance					Case 12a Direct factor and aspect ratio for normal load and sliding distance				
Trial no.	NL	SD	NL	SD^3	*K*	*H*	*W*	$1/NL^3$	SD	*K*	*H*	*W*	NL	$1/SD^3$	*K*	*H*	*W*
1	1	1	10	1.25E+8	27.84	19.5	1.78E+09	0.001	500	27.84	19.5	0.71	10	8E-9	27.84	19.5	1.14E-07
2	1	2	15	4.22E+8	27.84	19.5	9.03E+09	2.96E+4	750	27.84	19.5	0.32	15	2.37E-09	27.84	19.5	5.08E-08
3	1	3	20	1E+9	27.84	19.5	2.86E+10	1.25E+4	1000	27.84	19.5	0.18	20	1E-9	27.84	19.5	2.86E-08
4	2	1	10	1E+9	27.84	19.5	1.43E+10	0.001	1000	27.84	19.5	1.43	10	1E-9	27.84	19.5	1.43E-08
5	2	2	15	1.25E+8	27.84	19.5	2.68E+09	0.000296	500	27.84	19.5	0.21	15	8E-9	27.84	19.5	1.71E-07
6	2	3	20	4.22E+8	27.84	19.5	1.2E+10	0.000125	750	27.84	19.5	0.13	20	2.37E-09	27.84	19.5	6.77E-08
7	3	1	10	4.22E+8	27.84	19.5	6.02E+09	0.001	750	27.84	19.5	1.07	10	2.37E-09	27.84	19.5	3.38E-08
8	3	2	15	1E+9	27.84	19.5	2.14E+10	2.96E-04	1000	27.84	19.5	0.42	15	1E-09	27.84	19.5	2.14E-08
9	3	3	20	1.25E+8	27.84	19.5	3.57E+09	1.25E-04	500	27.84	19.5	0.09	20	8E-09	27.84	19.5	2.28E-07

1. The optimal parametric setting for case 1 is $W_1NL_2SS_1SD_1$ interpreted as 4 weight% of particulate Boron Nitride, 15 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. Using the ranks, the normal load is the most important parameter, the sliding speed as the second, the sliding distance as the third and the weight% of particulate Boron Nitride as the fourth position.
2. The optimal parametric setting for case 2 is $W^2{}_1NL_2SS_1SD_1$ which is interpreted as 16 weight% of particulate Boron Nitride, 15 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. The delta values were found to decrease for a normal load, sliding speed and sliding distance with an increase only for the weight% of particulate Boron Nitride.
3. The optimal parametric for case 3 is obtained as $W_1NL^2{}_1SS_1SD_1$ which is interpreted as 4 weight% of Boron Nitride particulate, 100 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. The delta value of normal load increases, while there was a reduction in the delta values of weight% of particulate Boron Nitride, sliding speed and sliding distance which gives a 75% decrease, thus making case 1 better than the combined direct parameter and aspect ratio of case 3.
4. The optimal parametric setting was obtained as $W_1NL_1SS^2{}_3SD_1$ interpreted as 4 weight% of particulate Boron Nitride, 10 N of normal load, 10,000 rpm of sliding speed and 500 m of sliding distance. The delta value decreases for all other parameters with an increase in the delta value of the normal load. This is also a 75% decrease which made case 1 better than case 4.
5. The optimal parametric setting obtained is $W_1NL_2SS_1SD^2{}_1$ which is interpreted as 4 weight% of particulate Boron Nitride, 10 N of normal load, 100 rpm of sliding speed and 250,000 m of sliding distance. Decreases were noted for the weight% of particulate Boron Nitride on comparing the delta value with case 1 with an increase in normal load, sliding speed and sliding distance. This shows that case 5 is better than case 1.
6. The optimal parametric setting is given as $(1/W)_3(1/NL)_2(1/SS)_1(1/SD)_3$. This is interpreted as 0.25 weight% of particulate Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. It was observed that there are reductions in the delta values of normal load, sliding speed and sliding distance but an increase in the weight% of particulate Boron Nitride. This is a 75% decrease in all parameters which shows the performance of case 6 is worse than that of case 1.
7. The optimal parametric setting is $(1/W^2)_2(1/NL)_{3(}1/SS)_2(1/SD)_2$ which is interpreted as 0.0625 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.002 m for sliding distance. The delta values were used as a tool of comparison with the normal load, sliding speed and sliding distance experienced decreases, while the weight% of particulate Boron Nitride experienced an increase in the comparison between case 1 and case 7. From these results, 75% of the parameter showed a decrease with a 25% increase. This implies that case 1 performs better than case 7.
8. The optimal parametric setting is $(1/W)_3(1/NL^2)_2(1/SS)_3(1/SD)_2$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.01 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. In evaluating the two cases (1 and 8) along the direction of delta values, there are mixed results of increase and decrease

in a ratio of 50–50. It implies that the weight% of particulate Boron Nitride and normal load increases with a reduction in sliding speed and sliding distance. This result makes it hard to state whether case 8 is preferred to case 1 or vice versa.

9. The response table was obtained which yielded the optimal parametric setting of $(1/W)_3(1/NL)_2(1/SS^2)_1(1/SD)_3$. This is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.0001 rpm of sliding speed and 0.002 m of sliding distance. The delta values give a 75% increase in all other parameters, i.e. weight% of particulate Boron Nitride, sliding speed and sliding distance with a 25% decrease in normal load. This result shows that case 9 is better than case 1.
10. The optimal parametric setting was obtained as $(1/W)_3(1/NL)_2(1/SS)_1(1/SD^2)_3$ which is interpreted as 0.25 weight% of particulate Boron Nitride, 0.1 N of normal load, 0.001 rpm of sliding speed and 0.000004 m of sliding distance. The delta values give a reduction in normal load, sliding speed and sliding distance with an increase in the weight% of particulate Boron Nitride, thus showing that case 1 is better than case 10.
11. The optimal parametric setting was obtained as $(W^3)_1NL_2SS_1SD_1$ which is interpreted as 64 weight% particulate of Boron Nitride, 10 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. On the delta values, it was observed that they increased from case 1 to case 11 for all the parameters, namely weight% of particulate Boron Nitride, normal load, sliding speed and sliding distance. This result shows that case 11 is better than case 1.
12. Proceeding to the response table, the optimal parametric setting was found to be $W_1(NL^3)_1SS_2SD_1$ which is interpreted as 4 weight% particulate of Boron Nitride, 1000 N of normal load, 100 rpm of sliding speed and 500 m of sliding distance. Considering the delta values, it was discovered that the weight% of particulate Boron Nitride, normal load, sliding speed and sliding distance exhibited an increasing performance when the delta values were measured. However, the sliding distance shows a decreasing performance in measuring the delta values. Since 75% of the cases exhibited increases in delta values, while only 25% shows a decrease, it may be assumed that case 12 showed better performance than case 1.
13. The optimal parametric setting obtained is $W_1NL_3(SS^3)_1SD_1$ which is interpreted as 4 weight% particulate of Boron Nitride, 10 N of normal load, 1,000,000 rpm of sliding speed and 500 m of sliding distance. All the delta values increased as the researcher considered movement from cases 1–13. With these increases in the delta value, it may be stated that case 13 is better than case 1 since higher delta values are obtained.
14. The optimal parametric setting is $W_1NL_2SS_1(SD^3)_1$ which is interpreted as 4 weight% particulate of Boron Nitride, 10 n of normal load, 100 rpm of sliding speed and 125,000,000 m of sliding distance. In the case of the delta values, increases were observed for all the parameters.
15. Considering the optimal parametric setting, the authors obtained $(1/W^3)_2(1/NL)_3(1/SS)_3(1/SD)_2$ which is interpreted as 0.1563 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. Evaluating the two cases (1 and 15) along the direction of delta values, there is a mixed result of increase and decrease in a ratio of 50–50. It implies that the weight% of par-

ticulate Boron Nitride and normal load increases with a reduction in sliding speed and sliding distance. This result makes it hard to state whether case 14 is preferred to case 1 or vice versa.

16. The optimal parametric setting was obtained as $(1/W)_3(1/NL^3)_1(1/SS)_3(1/SD)_2$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.001 N of normal load, 0.01 rpm of sliding speed and 0.002 m of sliding distance. When the delta values in both cases 1 and 16 were compared, increases in two parameters, namely weight% particulate of Boron Nitride, and normal load were observed, but decreases in the sliding speed and sliding distance were also observed. This makes the result hard to state, whether case 16 is better than 1 or vice versa.
17. The equivalent optimal parametric setting as $(1/W)_3(1/NL)_2(1/SS^3)_1(1/SD)_3$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.000001 rpm of sliding speed and 0.002 m of sliding distance. Looking at the delta values in the response table, only the weight% particulate of Boron Nitride increases, while other parameter decreases. Given this understanding, one tends to judge case 1 as being superior to case 17.
18. The response table was developed to obtain the optimal parametric setting at $(1/W)_3(1/NL)_2(1/SS)_1(1/SD^3)_3$ which is interpreted as 0.25 weight% particulate of Boron Nitride, 0.1 N of normal load, 0.01 rpm of sliding speed and 0.000000008 m of sliding distance. On comparing the delta values in cases 1 and 18, those representing the weight% of particulate Boron Nitride increased from case 1 to case 18, while the normal load, sliding speed and sliding distance were observed to decrease from case 1 to case 18. Since the majority of the cases (75%) represent decreases, it may be safe to state that case 1 is better than case 18 because a higher delta value signifies the acceptance of the model and vice versa.
19. On comparing the predicted and actual SN ratios, an error of 0.20% was recorded, which confirms that Eq. (1) properly predicts the wear inputs from the SN ratios for case 1.
20. From the confirmation results, a range of error values from −1,216,564 to 1,723,309 was obtained for the various models suggested for optimization by the authors. However, only fourteen cases (cases 1 to 14) were found to be valid in this instance. These are therefore recommended for decision-making.

Furthermore, the results of the wear analysis support that both direct and aspect ratios, which occur in reciprocals of factors, square and cubes of reciprocals of factors influence the optimal parametric settings, ranks and delta values of the parameters. This observation was made after combining direct factors of selected factors among the weight percentage of particulate Boron Nitride, normal load, sliding speed and sliding distance and their aspect ratios in reciprocals, squares and cubes of their reciprocals. This is an interesting result given the long-standing dependence of researchers on the mentioned direct factors as those dominated in the assessment of the health of composites. This analysis has offered — to our knowledge, for the first time — robust evidence of influential effects of both direct and aspect ratios of wear process parameters in some ranges of sixteen parametric formulations.

This is an original contribution to the global literature on wear in diverse dimensions: A previous study by Kumar and Reddy [13] using the Taguchi approach has focused on the direct factors alone for weight percentage of Boron Nitride, normal load, sliding speed and sliding distance parametric evaluations. Here, only direct factors were addressed as the driver of wear performance, neglecting the possible influence of aspect ratios, which could be in reciprocals of factors whose denominators are raised from one to the maximum of three. This is unfortunate given that aspect ratios are appropriate to capture the high and low definition of parameters in a combined setting such as the sixteen formulations discussed in the present study. Our results are consistent with the ideas generated on optimal parametric settings, ranks and delta values using the conventional Taguchi method as the methods were successfully compared. This resulted in a present influence on wear optimisation and ranking. This idea aligns with a previous study in the literature, where aspect ratios were considered for container terminal maintenance issues. This implies that our study has a present contribution to the engineering literature as it reinforces the mentioned article in Oke and Adekoya [21]. In conclusion, it could be stated that both direct and indirect (aspect ratios) can bring substantial enhancements in wear performance. This has important implications for maintenance policy development in an operational system where structures built on the nylon of Boron Nitride composites are used.

Future studies can be conducted along the current perspective of analysis but including economic factors such as inflationary factors and interest rates. Also, replacements of the Pareto component of the method could be made with the ABC classification scheme as Taguchi-ABC method. Furthermore, in this work, we used the experimental data of Kumar and Reddy [13] and do not have access to the original samples; hence, it is difficult for us to show the relevant mechanism and also worn out surface images. This is pointed out as a future research.

Abbreviations

TPDA	Taguchi-Pareto-oriented direct and aspect ratio
N6/BN	Nylon 6/Boron Nitride
AVOVA	Analysis of variance
%wt	Weight of Boron Nitride
NL	Normal load
SS	Sliding speed
SD	Sliding distance
1/W	Reciprocal of the weight of Boron Nitride
$1/W^2$	Reciprocal of the square of the weight of Boron Nitride
$1/W^3$	Reciprocal of the cube of the weight of Boron Nitride
W^2	Square of the weight of Boron Nitride
NL^2	Square of the normal load
1/NL	Reciprocal of the normal load
1/SS	Reciprocal of the sliding speed
1/SD	Reciprocal of the sliding distance
W^3	Cube of the weight of Boron Nitride
NL^3	Cube of the weight of normal load
SS^3	Cube of the weight of sliding speed
SD^3	Cube of the sliding distance
$1/SD^3$	Reciprocal of cube of the sliding distance
$1/SS^3$	Reciprocal of cube of the sliding speed
$1/NL^3$	Reciprocal of cube of the normal load

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Authors' contributions
AA — conceived, analysed and interpreted the data; WO — contributed to the writing of the manuscript; SA — conceived and interpreted the data and also supervised computational experimentation and contributed to writing the manuscript; and AJ — contributed to the writing of the manuscript. The authors read and approved the final manuscript.

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