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Dry Friction and Wear of Graphite-Filled PTFE Composites using Taguchi Approach

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Composite plain-bearing specimens with a porous structure were produced from spherical bronze powders (100–200 µm) using sintering technology. Pure Polytetrafluoroethylene (PTFE) and PTFE composites were then impregnated into the porous bronze structure and coated onto the surface. The PTFE mixtures were reinforced with graphite particles, with the graphite powder (average particle size: 200 µm) incorporated into the PTFE solution at varying ratios. This process was applied using the spray coating technique. Wear experiments were conducted based on a design created using the Taguchi method. The experimental parameters were optimized using the L27 Taguchi orthogonal array to achieve optimal friction coefficient and wear loss. The results showed that the experimental and verification test results were highly consistent. The material type/graphite content had the most significant impact on the friction coefficient and wear loss (71.6% and 30.88%, respectively). Sliding speed had the greatest effect (55.06%) on bearing temperature. Elemental analysis and chemical characterization of the composite plain bearing specimens were conducted using Energy Dispersive Spectroscopy (EDS). The wear surfaces were examined via Scanning Electron Microscope (SEM).The study concluded that the most significant factor affecting bearing wear is the material type. The 10% graphite additive, which reduces friction in the material, yielded optimal results in the study. An increase in sliding speed leads to a rise in bearing temperature, which in turn accelerates wear. Compared to industrially used bearings, the study found that more graphite lubricant was impregnated into the pores of bronze, and the optimal 10% additive provided a positive advantage in wear performance.

Keywords: Composite plain-bearing specimens, Graphite impregnate, Self-lubricated bearing, Taguchi method, Wear loss

Introduction

Self-lubricating composite structures are used in tribological industrial applications where lubrication is not possible. This structure can be produced using the powder method.[1,2] The bronze and polymer materials are generally used together in these composite structures. Tribological properties of the bronze and polymer composites are improved by adding to the matrix structure of the reinforcement components such as graphite, molybdenum disulfide (MoS_2), polytetrafluoroethylene (PTFE), carbon, glass fiber etc.[3–6] Because these structures benefit from low friction coefficient of the solid lubricating polymer material and the wear resistance of bronze. The combination of hard and soft phases such as graphite and bronze in the PTFE composite matrices enhances the tribological properties of PTFE such as self-lubrication and load-bearing. The solid lubricants are both impregnated into the pores and coated as the film layer on the material surface. This method has advantages in many ways. Primarily, it enables the friction pair to perform under self-lubricating operating conditions. The self-lubricating surface which is in order to improve the tribological condition between two moving surfaces in proximity is provided the load transmission from the bearing surface to the shaft surface for the transport of forces in bearing systems.[7] The impregnate of the oil or solid lubricants into the pores of the produced bronze by the powder metallurgy method provides high load carrying capacity and improved tribological properties.[8,9] Graphite and PTFE can use as a solid lubricating material by coating or impregnation in porous bronze structures. These composites which have a structure of the porous bronze + PTFE can acquire an anti-friction and wear-resistance property with the PTFE and Graphite additives.[9,10] Solid lubricant particles which are released and spread on the wear surface are acted as a lubricating interface between the sliding surfaces. PTFE has the lowest average coefficient of friction and can form a very thin transfer film due to its smooth molecular profile.

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Formation and breakdown of this film can occur to varying degrees, resulting in low wear resistance.[11] In these structures, alone use of the PTFE for a strong lubricating layer may be insufficient to improve their tribological properties. Because, the increase of dynamic load may be occur an increases wear loss on PTFE. At the same time, a durable transfer film layer of PTFE may not form onto work surface. Consequently, wear life may be shortened.[12,13] Graphite's carbonaceous nature and layered crystal structure contribute to excellent self-lubricating properties, reducing friction and wear between sliding surfaces.[14] In literature, dry sliding experiments indicate that the presence of graphite in composite structures leads to bringing about a film of graphite on their contact surface. The wear life of a PTFE-based composite transfer film is extended with additives such as graphite, MoS_2, aluminum, bronze.[12–16] The favorable tribological effects of graphite particles in the composite structure (polymer + bronze) were studied under dry sliding conditions.[10,12,13] In the matrix, while graphite is acted as a solid lubricant, the bronze has enhanced the wear resistance of its soft structure.[12,13] Hence, the bronze and graphite is a good pair for tribology applications. Effective wear resistance and friction reduction are achieved with graphite, which acts as a lubricant, providing a practical balance of performance and feasibility for industrial applications.[17] It has also been observed that these reinforcements have usually been used in producing machine components because of the superior wear resistance that they are gained to composite materials. For instance, electric motors, food machines, automobiles, printers, sewing machines packaging, and labeling machines.[13–18]

Tribological behavior of composite structures is affected by factors such as material type, amount, and reinforcement content, as well as test parameters like sliding speed and distance, load case and whether the test environment condition is dry or lubricated.[13–19] The amount of graphite particles is affected positively tribological behavior of the composite structure.[20,21] The superior tribological performance of composite materials used as plain bearing materials can only be achieved with the use of correct amount and compatible additives.[22] But the experimentation with traditional methods causes both more time and more cost. Furthermore, these methods which were omitted the effect on the test result of the interaction between the test parameters were unable to optimize.[14,23–26] However, it is possible to optimize these composites by means of the ANOVA and Taguchi technique.[27–29] The purpose of this study is to produce a distinctive composite structure using a different production technique.[30,32] In addition, it is to improve their optimum working conditions[33–35] and tribological properties with the Taguchi analysis approach and to obtain detailed and up-to-date information.[35–37]

Materials and Methods

Materials

The plain bearing matrix material was produced from copper-based Cu89Sn11 bronze powder (average grain size 100–200 µm) to produce a porous structure by powder metallurgy. Laboratory equipment for the production of the porous matrix structure consists of mixing, compression and sintering units. The preparation of the material consists of (1) mixing the main matrix bronze powder by adding zinc stearate powder (at the rate of 0.5%) as a natural dry lubricant (100 rpm and 60 minutes) via a mechanical blending machine, (2) compacting of this powder mixture by its pouring into a bushing mold on the hydraulic press (under 100 MPa pressure) and (3) sintering via a sintering furnace (under 780 °C temperature). Later, the coating process of the produced porous bronze bearing samples was carried out by the spray coating method, as shown in Fig. 1. Three different mixtures that pure PTFE, PTFE with 10% Graphite and PTFE with 20% Graphite have

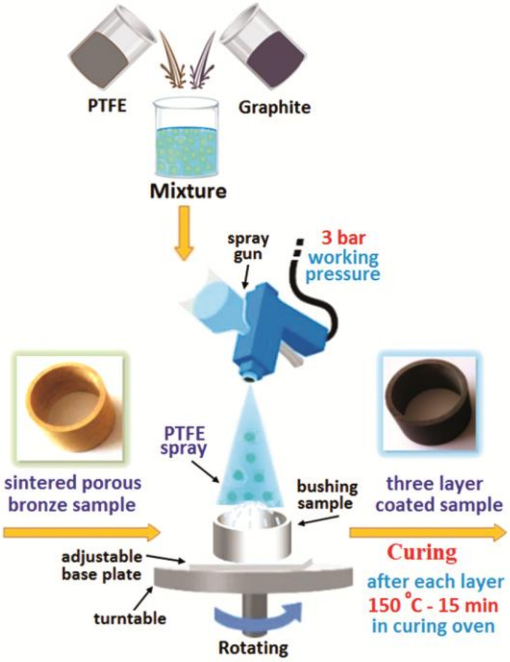

Fig. 1 — Coating process of specimens by spray coating method

been made for the spray coating operations. Samples were respectively placed on the turntable with objective to generate identical pulverizing on their surfaces and then subjected to coat processing. Turntable speed is approximately 40 rpm. The coating thickness was obtained as ~50 µm by applying the spray coating process. The developments of tribological properties of the composite structure were attained by the application of PTFE and graphite particles as solid lubricating reinforcement. Graphite particles were used as a lubricant additive and their particle sizes are around the average of 200 µm. The plain bearing samples having three different composite structures were produced by using the prepared mixtures. Test bushing sample which PTFE impregnated and coated was given surface cross-section and technical drawing in Fig. 2.

Experimental Design of Wear Tests

The experiment device consists of the following components: plain bearing test rig, loadcell, measuring booster, data gathering unit and computer. AISI 4140 steel shaft was preferred as counter-part in the plain bearing testing apparatus, a schematic representation of which is given in Fig. 3. The shaft has Ra (µm) <0.23 surface roughness and 423 HB hardness. Sample cleaning was done with acetone in the ultrasonic bath. This process was repeated before and after each experiment. The experiments were conducted with various sliding speeds and loads under dry conditions (ambient temperature: 23 °C, humidity: 55 ± 5% RH).

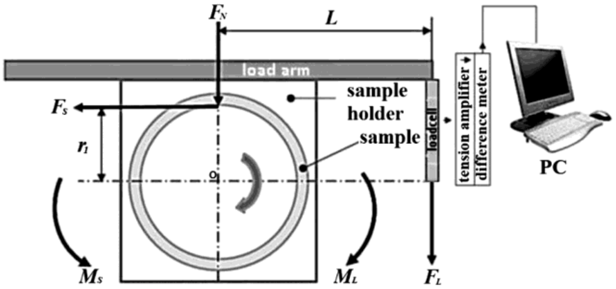

Fig. 3 — Schematically drawing of the plain bearing test apparatus[13]

Wear loss of the bushing samples was ascertained as a result of tests under three different values of the sliding speeds 0.5, 1 and 1.5 (m/s) with applied loads 30, 50, 70 (N), over a sliding time of 2.5 hours. All factors affecting wear loss and levels are demonstrated in Table 1. Experimental design method of Taguchi is an approach used to optimize experiment parameters. In this research, the orthogonal array L27 (3)(13) was formed to Statistical tool Minitab 27 of the Taguchi method and the experimental design was generated as in Table 2, because orthogonal arrays are contributed to less experimentation in this method. Due to this feature, it has been used in many scientific and engineering fields. In the data analysis phase, the experimental raw dates are transformed to signal / noise (S/N) ratios. Expected value is Signal (S) and unexpected values is Noise (N) S/N ratios refers to the distribution around the expected value. Analysis shows the " smaller, better" property of the S/N ratio. Corresponding equality is indicated from equality (1):

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} yi^2\right) \quad \ldots (1)$$

The terms are given in the equation show that signal-to-noise ratios : S/N, number of repetitions in each trial : n, experimental observation value of ith experiment: yi, expressed in terms of concepts.[25,36] Table 2 shows experimental plan created according to Taguchi L27 (3)(13) array.

Table 1 — Test parameters and levels

Test Parameters	Levels 1	2	3
A: Material Type	PTFE without Graphite	PTFE with 10% Graphite	PTFE with 20% Graphite
B: Applied Load (N)	30	50	70
C: Sliding Speed (m/s)	0.5	1.0	1.5

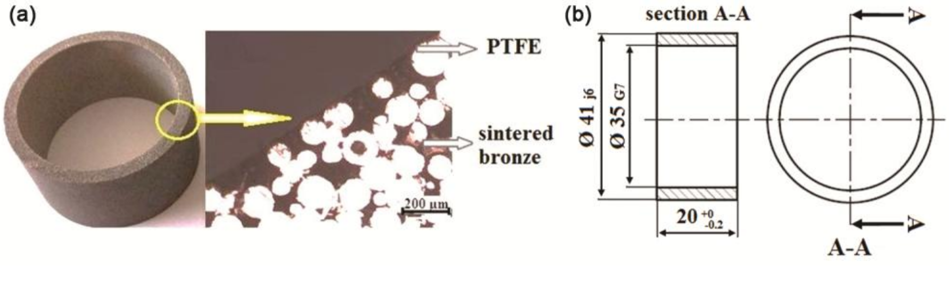

Fig. 2 — Coated/impregnated bushing specimen, (a) surface cross-section and (b) technical drawing

Table 2 — Experimental plan created according to Taguchi L27 array

Samples	Applied Load (N)	Sliding Speed (m/s)	Friction Coefficient (μ)	Wear Loss (mg)	Bearing Temperature (ºC)
PTFE without Graphite	30	0.5	0.345	1.60	32.73
		1.0	0.404	10.52	42.39
		1.5	0.433	91.70	46.61
	50	0.5	0.316	2.80	37.68
		1.0	0.367	72.58	47.82
		1.5	0.397	296.80	60.05
	70	0.5	0.29	5.70	41.17
		1.0	0.344	172.43	56.89
		1.5	0.365	431.10	72.89
PTFE with 10% Graphite	30	0.5	0.266	1.10	30.42
		1.0	0.276	1.87	39.03
		1.5	0.284	2.63	44
	50	0.5	0.248	1.60	32.42
		1.0	0.263	2.40	42.12
		1.5	0.275	3.15	47.45
	70	0.5	0.242	2.25	33.48
		1.0	0.25	2.80	46.8
		1.5	0.263	3.96	55.34
PTFE with 20% Graphite	30	0.5	0.283	1.13	30.98
		1.0	0.293	2.25	37.58
		1.5	0.304	2.87	39.67
	50	0.5	0.257	1.80	32.74
		1.0	0.27	3.67	42.52
		1.5	0.29	4.17	45.94
	70	0.5	0.236	2.20	35.23
		1.0	0.254	3.90	48.52
		1.5	0.271	4.73	58.49

Results and Discussions

S/N Analyses

S/N ratios were analyzed to the purpose of confirming the effect of investigated (material type, sliding speed and applied load) test factors. Combination of highest S/N ratios among effect parameters gives optimum value. The control parameter has the strongest effect, which is defined as the variation between max. and min. values of the S/N ratios average.[27,37] Therefore, higher difference between the S/N ratios average, the better the control parameter effect. Its effectiveness on the coefficient of friction is indicated in Table 3. Most dominant parameter affecting to friction coefficient was found the type of material. Sliding speed and applied load have smaller effectiveness and at values close to each other on the coefficient of friction. The effectiveness of the control parameter on the wear loss is given in Table 4. Thses responses were clearly given in Table 4 that the ranking of parameters brings out the material type and sliding speed values as respectively the most dominant parameters affecting the wear loss. The control parameters' effectiveness in bearing temperature is given Table 5.

Table 3 — Response table for S/N ratios of friction coefficient

Level	Material Type (A)	Applied Load (B)	Sliding speed (C)
1	8.878	9.997	11.250
2	11.612	10.621	10.512
3	11.298	11.170	10.026
Delta	2.734	1.173	1.224
Rank	1	3	2

Table 4 — Response table for S/N ratios of wear loss

Level	Material Type (A)	Applied Load (B)	Sliding speed (C)
1	−30.213	−10.633	−5.901
2	−7.140	−16.229	−17.170
3	−8.692	−19.183	−22.974
Delta	23.074	8.550	17.073
Rank	1	3	2

Table 5 — Response table for S/N ratios of temperature

Level	Material Type (A)	Applied Load (B)	Sliding speed (C)
1	−33.50	−31.54	−30.62
2	−32.15	−32.56	−32.97
3	−32.16	−33.71	−34.22
Delta	1.35	2.17	3.61
Rank	3	2	1

bearing temperature. Parameters ranking was brought out sliding speed as the most dominant parameter affecting the bearing temperature and then was respectively followed by applied load and material type. Main effect graphs showing the effects on coefficient of friction, wear loss and bearing temperature are given in Fig. 4. Also, their interactions among factors and mutual effects were given in Fig. 5. S/N plots and interactions were utilized to decide optimum test parameters. The optimum levels obtained from the S/N ratios were marked on the plots with a red circle.

The optimum value of the friction coefficient was determined with its affecting parameters. These are A_2 level of material type, B_3 level of applied load and C_1 level of sliding speed. It has been clearly demonstrated that the addition of graphite additive to the composite structure reduces the friction coefficient. However, increases in sliding speed or applied load have affected the coefficient of friction. Rises in the applied load caused a decrease in friction coefficient. Clearly, material type has the greatest effect on friction coefficient, while the applied load and sliding speed have slightly less effect in comparison to the material type. In summary, the minimum friction coefficient was achieved with the PTFE with 10% Graphite material type, at 0.5 m/s speed and 70 N load. The optimum value of wear loss was determined with its affecting parameters. These are level 2 of material type, level 1 of applied load and level 1 of sliding speed. It was determined that the wear loss was decreased thanks to the graphite added to the porous composite structure. It has been found out that the wear loss is diminished thanks to the graphite added to the porous composite structure. Applied load and sliding speed increase caused to rising in wear loss.[20–23] Consequently, PTFE with 10% Graphite material type should be used under 30 N with 0.5 m/s operating parameter combinations in order to minimize wear loss. Similarly, the optimum value of bearing temperature was determined by the effect parameter levels A_2 level of material type, B_1 level of applied load, C_1 level of sliding speed. Because, the temperature increase was caused both wear increase and transfer volume increase.[22] It is clear that the minimum bearing temperature has been achieved in PTFE with 10% Graphite material type, 30 N with 0.5 m / s conditions.

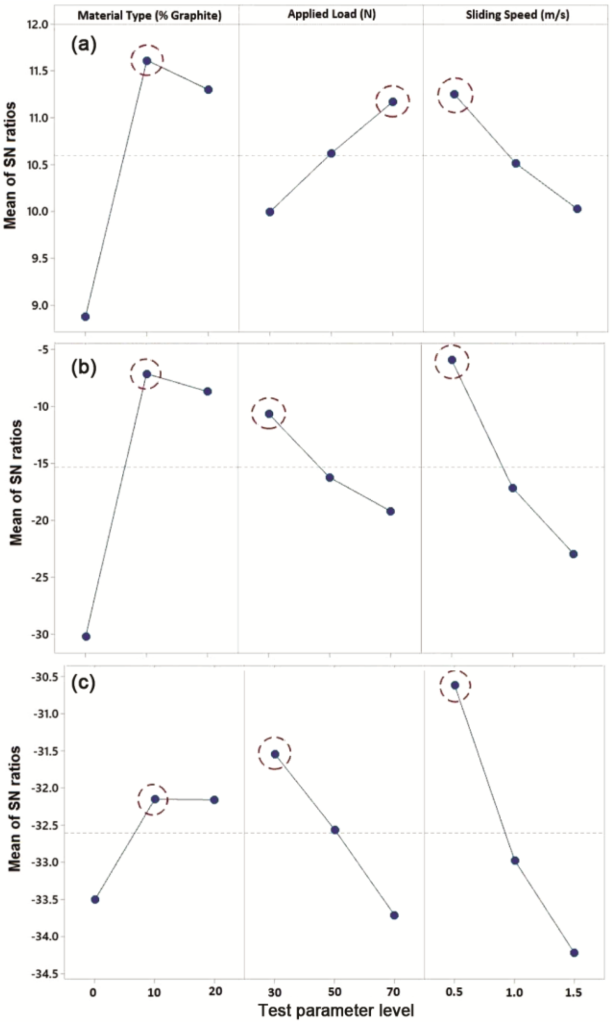

Fig. 4 — Main effects plot for S/N ratio data means on (a) friction coefficient, (b) wear loss, and (c) bearing temperature

ANOVA Analyses

Test results including the effectiveness of test factors on coefficient of friction, wear loss and bearing temperature analyzed by the help of ANOVA (Analysis of Variance) method. ANOVA identified the dominant factors and percentage contributions of the test results.[25,32] ANOVA for the friction coefficient, wear loss, bearing temperature is shown in Table 6. ANOVA analyze was accomplished at $\alpha = 0.045$ significance level, namely at 95.5% confidence level. Analyze results in Table 6 indicates that, material type has a maximal effect on friction coefficient (71.61%). A smaller effect was determined in terms of sliding speed (11.92%) and applied load (10.32%) parameters. The interaction material type*sliding speed has the greatest effect (4.54%), followed by the interactions material type*applied load (1.41%), while the effect of interaction applied load*sliding speed may neglect (0.03%). Table 7 indicates that material type has the greatest effect in

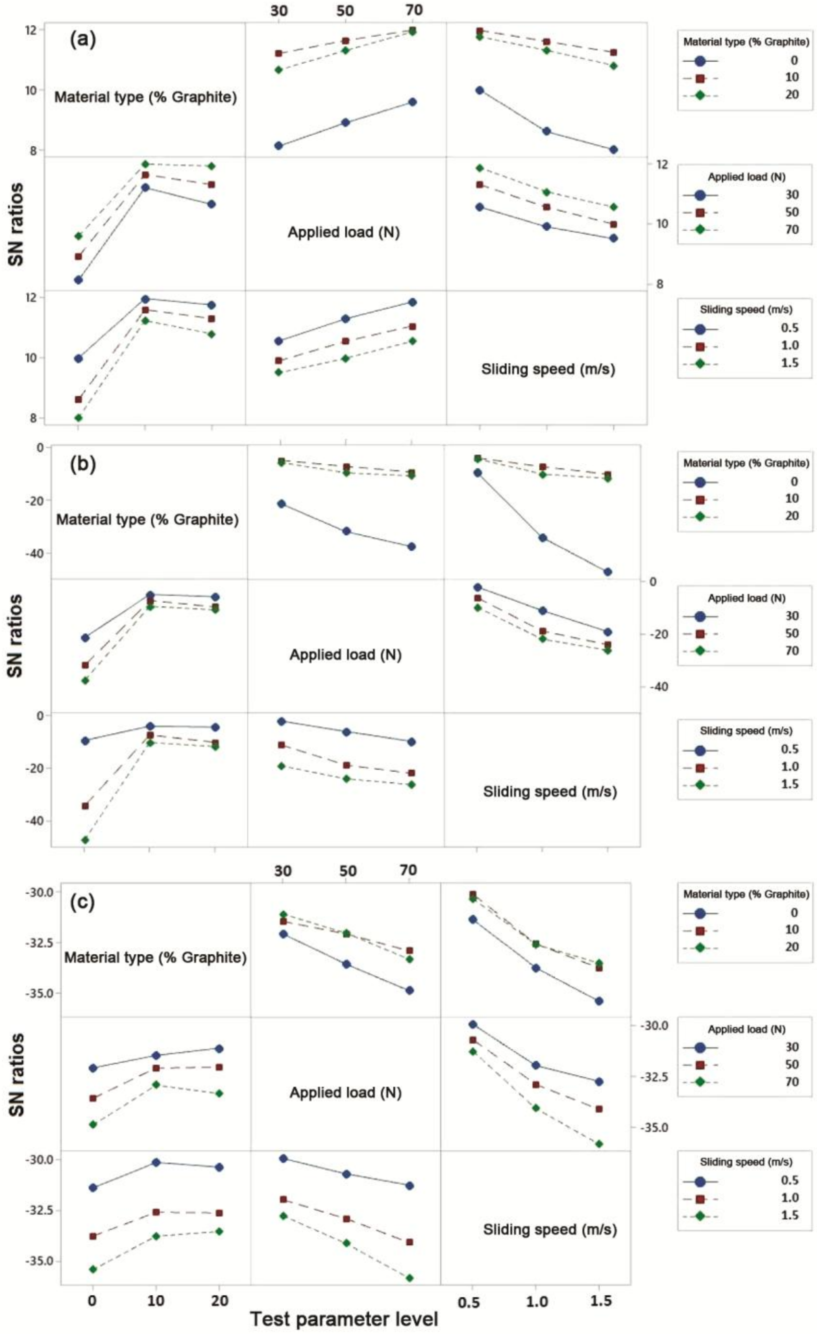

Fig. 5 — Interaction plot for S/N ratios data means on the (a) friction coefficient, (b) wear loss, and (c) bearing temperature

Table 6 — ANOVA for different parameters

Parameters	*DF*	*Adj SS*	*Adj MS*	F_{Factor}	F_{Table}	*P(%)*
Friction coefficient						
A	2	0.0537899	0.0268949	1762.53	11.04[a]	71.61
B	2	0.0077547	0.0038774	254.1	11.04[a]	10.32
C	2	0.0089543	0.0044771	293.41	11.04[a]	11.92
A*B	4	0.0010588	0.0002647	17.35	8.81[a]	1.41

(*Contd.*)

Table 6 — ANOVA for different parameters (*Contd.*)

Parameters	*DF*	*Adj SS*	*Adj MS*	F_{Factor}	F_{Table}	*P(%)*
Friction coefficient						
A*C	4	0.0034093	0.0008523	55.86	8.81[a]	4.54
B*C	4	0.0000237	0.0000059	0.39	—	0.03
Error	8	0.0001221	0.0000153	—	—	—
Total	26	0.0751127	—	—	—	100
Wear loss						
A	2	83387	41693	17.20	11.04[a]	30.88
B	2	14664	7332	3.03		5.43
C	2	39295	19647	8.11	11.04[a]	14.55
A*B	4	27970	6992	2.89		10.36
A*C	4	75572	18893	7.80	8.81[a]	27.98
B*C	4	9770	2442	1.01	—	3.62
Error	8	19389	2424	—	—	—
Total	26	270046	—	—	—	100
Plain bearing temperature						
A	2	331.2	165.6	73.83	11.04[a]	12.13
B	2	621.2	310.6	138.48	11.04[a]	22.75
C	2	1503.48	751.74	335.15	11.04[a]	55.06
A*B	4	62.46	15.615	6.96	8.81[a]	2.29
A*C	4	51.59	12.8975	5.75	8.81[a]	1.89
B*C	4	142.92	35.73	15.93	8.81[a]	5.23
Error	8	17.94	2.2425	—	—	—
Total	26	230.8	—	—	—	100

[a] 99.5% confidence level

Table 7 — Verification test results

Level	Optimum Wear Test Conditions		
	Estimation Results	Experimental Results	C.L (dB)
	For friction coefficient	$A_2B_3C_1$	
	For wear loss and bearing temp.	$A_2B_1C_1$	
S/N ratio for friction coefficient (dB)	12.832	12.323	±0.00767
S/N ratio for wear loss (dB)	−7.026	−0.8279	±9.608
S/N ratio for temperature (dB)	−33.1024	−29.6632	±2.92

wear loss (30.88%). Sliding speed (14.55%) and applied load (5.43%) parameters have a minimal effect. The interaction material type*sliding speed has the greatest effect (27.98%), followed by the interactions material type*applied load (10.36%) and applied load*sliding speed (3.62%). It is understood from Table 8 that, sliding speed has a higher effect in the wear loss (55.06%). Other parameters have smaller effect: the applied load (22.75%) and material type (12.13%). While the interaction of the applied load*sliding speed was found 5.23% effect value, the interactions of the (material type) A*B (applied load) = 2.29% and A (material type)* C (sliding speed) = 1.89% found to be a smaller effect value.

The Confirmation test method is used to verify the optimum test conditions obtained from the analysis performed. Verification test was carried out according to the optimum test conditions and estimated calculations were made with the following equations:[24,25,27,28,34,36]

$$\hat{\mu}_{frictioncoefficient} = \overline{A_2} + \overline{B_3} + \overline{C_1} - 2.\bar{T} \quad \dots (2)$$

$$\hat{\mu}_{wearloss} = \overline{A_2} + \overline{B_1} + \overline{C_1} - 2.\bar{T} \quad \dots (3)$$

$$\hat{\mu}_{bearingtemperature} = \overline{A_2} + \overline{B_1} + \overline{C_1} - 2.\bar{T} \quad \dots (4)$$

Here, the estimated mean S /N ratio was given as $-\hat{\mu}$, mean S/N ratio of tests was given as $\bar{T}$. The C.L is the confidence level. $F_{(1,m)}$ is the F Table value. m is the degrees of freedom of error. V_e is given as the variance of the error. N_e is given as the replications number. The verification test and the estimated test results performed according to the optimum test conditions were shown in Table 7. F_{Table} values were taken according to 99.5% confidence interval.

$$C.L = \left[\frac{F(1,m).V_e}{N_e}\right]^{0.5} \quad \dots (5)$$

$$N_e = \frac{Total number of experiments}{average of degrees of freedoom \quad (=1) + degrees of freedom of all parameters} \quad \ldots (6)$$

$$\hat{\mu} - C.L \leq \eta \leq \hat{\mu} + C.L \quad \ldots (7)$$

ANOVA analysis map was generated to examine together the changes in the composite structure test outputs according to different test parameters.[25,27] Analysis maps were shown together the changes to the parameters affecting the experimental results. ANOVA maps of the composites are shown in Fig. 6. The effect of the sliding speed and applied load test parameters on the friction coefficient is shown in Fig. 6a. Minimum friction coefficient was observed at low level of the sliding speed and at high level of the applied load. In general, rises in applied load and sliding speed led to an increase in the surface temperature during the wear test. Risen the surface temperature softens the interface. The PTFE polymer and graphite debris were spread over the surface between the friction pairs since it has a solid lubrication property that softens the surface. This cause reduces the coefficient of friction.[22,32,35]

Test parameter effects in wear loss are shown in Fig. 6b. The increased load and sliding speed conclude a raised wear loss. In short, these increases were caused the bronze layer to be seen. Because the coating layer of the sample working surface was worn. The main matrix bronze came into contact directly with the counter-part AISI 4140 steel and caused to increase of the wear loss. Prasad[19] determined similar findings in his study. Also, when Fig. 6a and 6b evaluated together, It has been determined that the wear loss is affected by the increase in temperature. But, the reinforced solid lubricants between the friction surfaces have decreased the friction and wear as result of optimal load and sliding speed. As a result, this process enabled to decrease in friction coefficient and weight loss.[13,25] Fig. 6c exhibits the effect of wear test factors, like applied load and sliding speed on bearing temperature. PTFE and graphite additive composites were demonstrated perfect wear resistance under dry environment. However, the rising effect of both load and speed increased the bearing temperature. Consequently, PTFE with Graphite coating material on the surface decreases and the bronze structure comes into direct contact with the AISI 4140 shaft. This causes to more increase the bearing temperature during the test process.[22] The minimum bearing temperature was observed at 0.5 m/s speed and 30 N load conditions.

SEM and EDS Analysis of Wear Surfaces

Wear surfaces of graphite-reinforced PTFE coated bronze bearing structure were examined using an SEM. SEM images of samples under optimum test conditions are given in Fig. 7. After wear experiments, the examination of microstructure of the sample surfaces contributes to understanding of tribological properties of bronze + polymer composite structures. Because, these structures are used from wear resistance of the bronze and self-lubricating property of the solid lubricating polymer materials.

In general, the sliding wear of the composite structure is characterized by the wear of the solid lubricant coating layer between the friction pair. As seen in SEM images of Fig. 7, wear marks were occurs similar to scratches and debris. In addition, peeling and peeling films were observed. Multiple debris and scratches were shown the existence of abrasive wear on worn surfaces. This situation (Fig. 7a) is especially more evident on the surface of the PTFE without graphite additives. Because multiple and large sizes of wear debris contributed to the oxide layer breakdown. But, as seen Fig. 7b and 7c, wear resistance of the composite structure which tested in dry

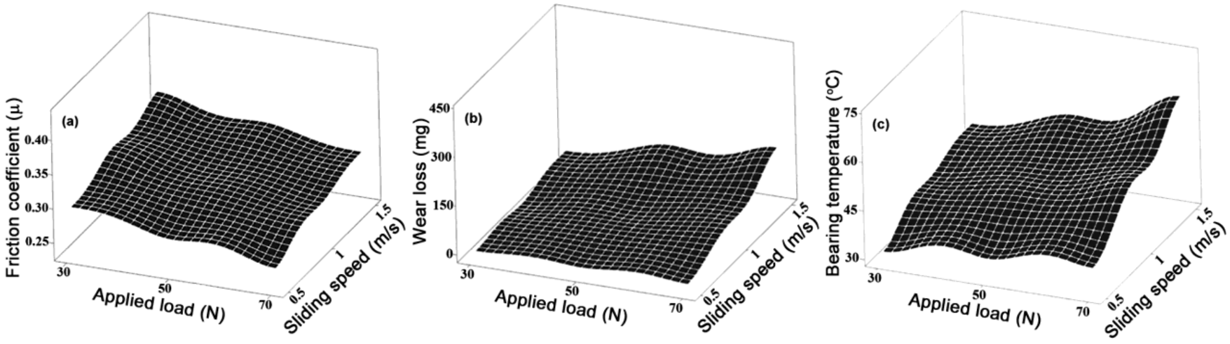

Fig. 6 — Analysis map of parameters affecting on the (a) friction coefficient, (b) wear loss, and (c) bearing temperature

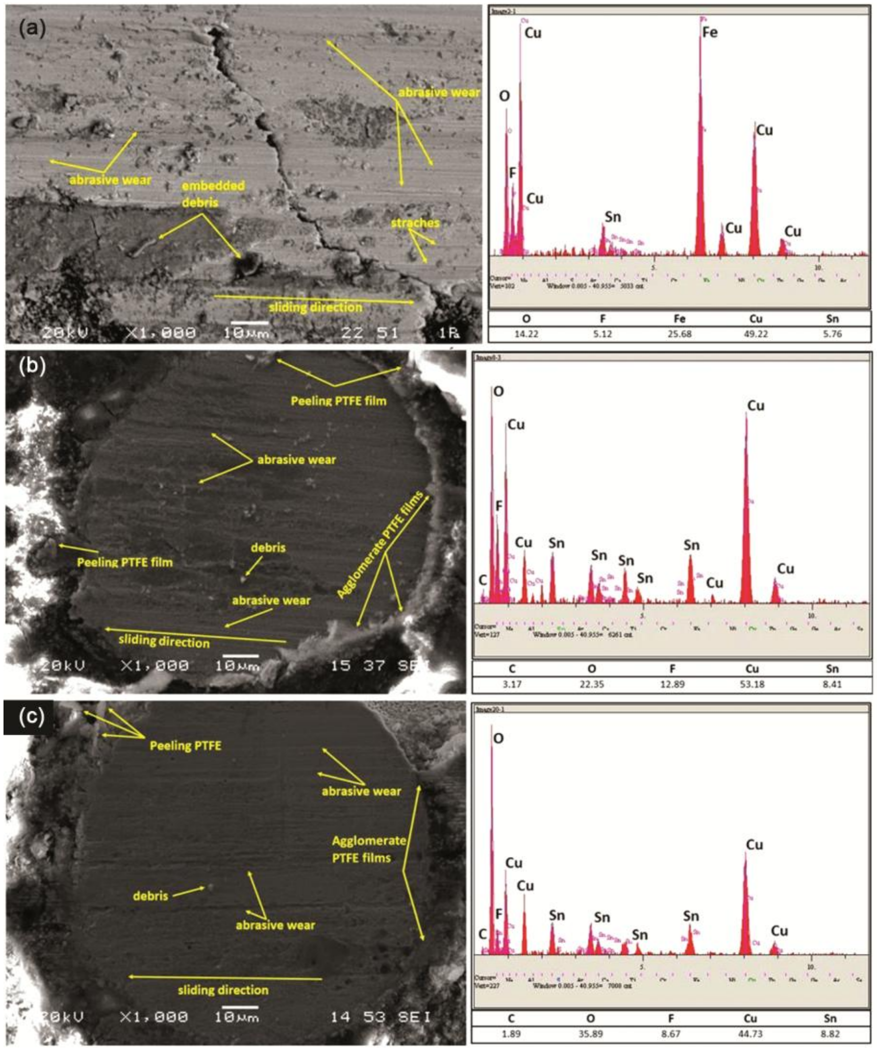

Fig. 7 — Analyses SEM and EDS of specimens after wear tests at 0.5 m/s sliding speed and 30 N applied load: (a) sample of PTFE without Graphite, (b) sample of PTFE with 10% Graphite, and (c) sample of PTFE with 20% Graphite

sliding conditions is developed with adding of the graphite to PTFE. The between of sliding surfaces was supported by self-lubricating film layers which are formed with graphite. The disintegration of the solid lubricant film between the surfaces of the friction pair, which an undesirable situation was led to sudden contact. This situation is more pronounced with PTFE coated samples. Because PTFE has poor wear resistance. The solid lubricant additives were impregnated into the matrix pores and consisted lubricating layer on the surface. Thus, a strong structure having a film layer was obtained. Tribological improvement was achieved between contacting surfaces. In this consideration, the presence of graphite additive and the sliding speed with applied load were become significant from the point of low coefficient of friction compared to pure PTFE. Because PTFE with graphite has lower friction coefficient, the solid lubricant graphite increases wear resistance by establishing a lubricant layer over the sliding counterparts.[26] Graphite strengthened the surface structure of the matrix.[13,15] The impregnation and coating of graphite (~50 µm) that was increased the surface energy. Therefore, there is a notable reduction in wear losses and friction coefficients for composites.[20] Fig. 7b and 7c show that, solid lubricant debris contributed to a continuation of lubrication by continuing one's existence between friction pairs and piling up into the surface gaps. Additionally, the debris protected the surface of the spindle from scratches. Abrasion debris can break off from bronze structure as a result of an increase in sliding speed and load during sliding under dry conditions. This situation was generally detected as embedded and larger in the PTFE samples (Fig. 7a) that were caused by inadequacy of PTFE against wear. Fe debris was detected by EDS analysis, which was performed after wear experiments.[36] Analyses of the composite structure were performed using EDS on the specific mark points of the sample surface.EDS analysis was acknowledged the presence of component elements such as Graphite (C), F, Cu, Sn.

The friction heat (bearing temperature) emerges because of the influence of sliding speed.[22,25] Because the sliding speed rise was increased the bearing temperature. In particular, Fig. 7b and 7c show that the presence of oxide on the surface contributed positively to the reduction of wear marks. Because the oxide layer was acted as a solid lubricant that reduced wear and friction.[13,25]

Conclusions

The wear tests of alternative plain bearing, developed using powder metallurgy and spray coating methods was carried out with Taguchi experimental optimization. The optimal parameters for the coefficient of friction were achieved using PTFE with 10% graphite additive, 70 N load, and 0.5 m/s sliding speed. Similarly, the optimal test parameters for wear loss and temperature were obtained with 10% graphite, 30 N load, and 0.5 m/s sliding speed. It was found that the material type had the greatest effect on the coefficient of friction (71.61%), followed by sliding speed (11.92%) and applied load (10.32%). For wear loss, the most significant factors were material type (30.88%), material type & bearing temperature interaction (27.98%), and sliding speed (14.55%). The parameters with the highest influence on bearing temperature were sliding speed (55.06%) and applied load (22.75%). A confidence level of 99.5% was found between the predicted and actual values for the coefficient of friction, wear loss, and bearing temperature. Such bearings are recommended for use in shaft-hub connections in dry environments where high speed is not required. In future studies, the lubricating properties of nano-particulate graphite in PTFE will be a topic of investigation.

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References

1 Sander D E, Allmaier H & Priebsch H H, Friction and wear in automotive journal bearings operating in today's severe conditions, *Adv Tribol, IntechOpen*, (2016) 143–172, http //dx.doi.org/Chapter DOI: 10.5772/64247.

2 Ouyang J H, Li Y F, Zhang Y Z, Wang Y M & Wang Y J, High-temperature solid lubricants and self-lubricating composites a critical review, *Lubricants*, **10(8)** (2022) 177, https://doi.org/10.3390/lubricants10080177.

3 Shaji S & Radhakrishnan V, Application of solid lubricants in grinding: Investigations on graphite sandwiched grinding wheels, *Mach Sci Technol*, **7(1)** (2003) 137–155, https://doi.org/10.1081/MST-120018959.

4 Trabelsi M, Kharrat M & Dammak M, On the friction and wear behaviors of PTFE based composites filled with MoS_2 and/or bronze particles, *Trans Indian Inst Met*, **69(5)** (2016) 1119–1128, https://doi.org/10.1007/s12666-015-0666-x.

5 Omrani E, Rohatgi P K & Menezes P L, Tribology and applications of self-lubricating materials, *CRC Press*, (2017), https://doi.org/10.1201/9781315154077.

6 Patare P M, Palekar S, Asolekar U, Patare S P & Suryawanshi V, Effect of molybdenum disulfide and bronze on tribological behaviors of polytetrafluoroethylene composites, *Mater Today Proc*, (2023), https://doi.org/10.1016/j.matpr.2023.10.118.

7 Lewis R, Friction in a hydraulic motor piston/cam roller contact lined with PTFE impregnated cloth, *Wear*, **266(7–8)** (2009) 888–892, https://doi.org/10.1016/j.wear.2008.12.009.

8 Ren S, Xu H, Chen J & Qu X, Effects of sintering process on microstructure and properties of flake graphite-diamond/copper composites, *Mater Manuf Process*, **31(10)** (2016) 1377–1383, https://doi.org/10.1080/10426914. 2015. 1103865.

9 Lince J R, Effective application of solid lubricants in spacecraft mechanisms, *Lubricants*, **8(7)** 74 (2020), https://doi.org/10.3390/lubricants8070074.

10 Kornopol'tsev V N, Kornopol'tsev N V & Mognonov D M, Metal-PTFE material for dry friction bearings, *J Frict Wear*, **28** (2007) 187–192, https://doi.org/10.3103/S1068366607020092.

11 Fidan S, Korkusuz O B, Toker P Ö, Gültürk E, Ateş B H & Sınmazçelik T, Effect of filling materials on the tribological performance of polytetrafluoroethylene in different wear modes, *Polym Compos*, (2024) 1–17, https://doi.org/10.1002/pc.28718.

12 Valente C A G S, Boutin F F, Rocha L P C, do Vale J L & da Silva C H, Effect of graphite and bronze fillers on PTFE tribological behavior a commercial materials evaluation, *Tribol Trans*, **63(2)** (2020) 356–370, https://doi.org/10.1080/10402004.2019.1695032.

13 Güngör K & Demirer A, Investigation of dry sliding friction wear behavior of CuSn11 bronze plain bearing applying impregnated graphite-filled PTFE, *Tribol Trans*, **65(5)** (2022) 880–891, https://doi.org/10.1080/10402004. 2022. 2099496.

14 Jagannath G R R, Basawaraj, Naik Narayana C K, Hulikere Mallaradhya M, Majdi A, Alkahtani M Q & Islam S, Enhancing wear resistance of UHMWPE composites with micro MoS_2 and nano graphite a Taguchi–DOE approach, *ACS omega*, **9(14)** (2024) 16743–16758, https://doi.org/10.1021/acsomega.4c00864.

15 Wang Z, Fu Q &Wu S, Effect of solid lubricant particles on the tribological properties of PTFE composites lubricated with natural seawater, *J Dispers Sci Technol*, **40(2)** (2019) 239–249, https://doi.org/10.1080/01932691.2018.1467774.

16 Mazur K, Gądek-Moszczak A, Liber-Kneć A & Kuciel S, Mechanical behavior and morphological study of polytetrafluoroethylene (PTFE) composites under static and cyclic loading condition, *Materials*, **14(7)** (2021) 1712, https://doi.org/10.3390/ma14071712.

17 Gudipalli K R V, Chapke Y, Guddhur H & Doddamani S, Effects of addition of graphite on the tribological behaviour of Al7075-SiC hybrid composites using design of experiments, *J Bio- Tribo-Corros*, **10(3)** (2024) 1–11, https://doi.org/10.1007/s40735-024-00880-y.

18 Muterlle P V, Cristofolini I, Pilla M, Pahl W & Molinari A, Surface durability and design criteria for graphite–bronze sintered composites in dry sliding applications, *Mater Des*, **32(7)** (2011) 3756–3764, https://doi.org/10.1016/j.matdes.2011.03.048.

19 Prasad B K, Sliding wear behaviour of bronzes under varying material composition microstructure and test conditions, *Wear*, **257(1–2)** (2004) 110–123, https://doi.org/10.1016/j.wear.2003.10.021.

20 Goyal R K & Yadav M, Study on wear and friction behavior of graphite flake-filled PTFE composites, *J Appl Polym Sci*, **127(4)** (2013) 3186–3191, https://doi.org/10.1002/app. 37707.

21 Khan M J, Wani M F & Gupta R, Friction and wear characterization of graphite/polytetrafluoroethylene composites against stainless steel a comparative investigation under different environments, *J Phys Conf Ser*, *IOP Publishing*, **1240(1)** (2019) 012107, https://doi.org/10.1088/1742-6596/1240/1/012107.

22 Güngör K & Demirer A, Effects of impregnating PTFE filled with added graphite on wear behavior of sintered bronze plain bearings, *Int J Mater Res*, **112(8)** (2021) 623–635, https://doi.org/10.1515/ijmr-2020-8067.

23 Pavani P N L, Pola Rao R, Prasad C L V R S V & Srikiran S, Performance assessment and study of tribological properties of self-lubricating materials for dry lubrication, *J Mech Eng Res Dev*, **39(3)** (2016) 670–680.

24 Güngör K, Ozsert I, Demirer A, Fiçici F & Demir A, Experimental optimization of wear parameters of sintered bronze based materials, *Indian J Eng Mater Sci*, **22(3)** (2015) 288–296.

25 Ficici F & Kurgun S, Analysis of weight loss in reciprocating wear test of cylinder liner and piston ring coated with molybdenum, *Arab J Sci Eng*, **46** (2021) 7801–7813, https://doi.org/10.1007/s13369-021-05566-y.

26 Veeranjaneyulu I, Haripriya V, Saminathan R, Naidu B V V, Hillary J J M, Prasad A S V & Subbiah R, Friction and wear optimization of SiC/graphite reinforced AZ31 hybrid composite using Taguchi method, *Int J Interact Des Manuf*, **18(3)** (2024) 1373–1386, https://doi.org/10.1007/s12008-023-01687-w.

27 Saravanakumar A, Rajeshkumar L, Balaji D & Jithin K M P, Prediction of wear characteristics of AA2219-Gr matrix composites using GRNN and Taguchi-based approach, *Arab J Sci Eng*, **45(11)** (2020) 9549–9557, https://doi.org/10.1007/s13369-020-04817-8.

28 Jebran M, Wani M F & Gupta R, Tribological performance evaluation of polytetrafluoroethylene composites under dry sliding and aqueous environments using Taguchi approach and grey relational analysis effect of material test environment and load, *Polym Compos*, **40(7)** (2019) 2863–2875, https://doi.org/10.1002/pc.25113.

29 Sabarish K V & Paul P, Optimizing the concrete materials by L9 orthogonal array, *Mater Today Proc*, **22** (2020) 460–464, https://doi.org/10.1016/j.matpr.2019.07.720.

30 Kuznetsov R V & Kuznetsov P A, A new way of manufacturing bimetal products on the basis of the technology of casting with crystallization under pressure, In *Advances in Mechanical Engineering Part of the Lecture Notes in Mechanical Engineering book series (LNME)* (Springer) (2020) 119–127, https://doi.org/10.1007/978-3-030-39500-1_13.

31 Zhengchuan Z, Tarelnyk V, Konoplianchenko I, Guanjun L, Xin D & Yao J, Characterization of tin bronze substrates coated by Ag+B83 through electro-spark deposition method, *Surf Eng Appl Electrochem*, **59(2)** (2023) 220–230, https://doi.org/10.3103/S1068375523020187.

32 Torabizadeh M A & Fereidoon A, Applying Taguchi approach to design optimized effective parameters of aluminum foam sandwich panels under low-velocity impact, *Iran J Sci Technol – Trans Mech Eng*, **46** (2022) 851–862, https://doi.org/10.1007/s40997-021-00441-5.

33 Saurabh A, Joshi K, Manoj A & Verma P C, Process optimization of automotive brake material in dry sliding using Taguchi and ANOVA techniques for wear control, *Lubricants*, **10(7)** (2022) 161, https://doi.org/10.3390/lubricants10070161.

34 Tyagi A, Pandey S M, Murtaza Q, Walia R S & Tyagi M, Tribological behavior of carbon coating for piston ring applications using Taguchi approach, *Mater Today Proc*, **25(4)** (2020) 759–764, https://doi.org/10.1016/j.matpr.2019.09.004.

35 Ritapure P P, Damale A V, Yadav R G & Kharde Y R, Optimization of dry sliding wear characteristics of Al–25Zn/SiC hybrid composites by graphite reinforcement using artificial neural network and Taguchi's method, *Tribol-Mater Surf Interfaces*, **16(1)** (2022) 76–89, https://doi.org/10.1080/17515831.2021.2002598.

36 Miloradović N, Vujanac R, Stojanović B & Pavlović A, Dry sliding wear behaviour of ZA27/SiC/Gr hybrid composites with Taguchi optimization, *Compos Struct*, **264** (2021) 113658, https://doi.org/10.1016/j.compstruct.2021.113658.

37 Ibrahim M A, Çamur H, Savaş M A *&* Sabo A K, Multi-response optimization of the tribological behaviour of PTFE-based composites via Taguchi grey relational analysis, *Stroj Vestn/J Mech Eng*, **68(5)** (2022) 359–367, https://doi.org/10.5545/sv-jme.2021.7466.