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# EXPERIMENTAL INVESTIGATION OF THE TRIBOLOGICAL BEHAVIOR OF CARBON-CARBON COMPOSITES UNDER VARIOUS OPERATING CONDITIONS

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## ABSTRACT
**Aircraft brakes are very critical for its safe operation. During landing, the brakes takes 40% of the energy while aerodynamic brakes, reverses thrust and rolling friction takes the rest of energy, [1]. Thus superior tribological behavior at high temperatures is required to carry out this mission. Carbon fiber reinforced Carbon(C/C) composites have outstanding low density and high thermomecanical properties, [2]. For these reasons, more aircraft manufacturers convert to C/C brakes. The tribological behavior of C/C composites is examined in this paper by exploring the parameters that affect weight loss. The Taguchi method is used to conduct a design of experiment (DOE) to optimize the experiments size. The response surface methodology is utilized to ascertain the most favorable blend of process operating parameters. The Carbon/Carbon composite's wear and friction characteristics were evaluated using a dry sliding wear test, employing the disc-on-disc method. The findings revealed that the duration of contact between the stator and rotor discs was the most significant contributor to weight loss, followed by the applied load and rotational speed. The most predominant factor was the braking pressure then the time and vehicle speed.**

## KEYWORDS
**Carbon/carbon composites, taguchi method, analysis of variances, carbon/carbon tribology.**

## INTRODUCTION
**Carbon/carbon composites offer numerous benefits for braking systems in aircraft. these composites generate friction, transmit mechanical loads, and transform kinetic energy into thermal energy. additionally, they are lightweight, possess favorable frictional properties, exhibit low thermal conductivity, demonstrate resistance to thermal shocks, exhibit self-lubricating behavior, and have a high capacity for energy absorption, [3, 4, 5]. carbon/carbon composites are utilized in hypercars and**

**aircraft due to their exorbitant cost, which is attributed to their complex manufacturing process, [6, 7].**

**The tribological performance of Carbon/Carbon composites is impacted by a multitude of factors, including the laminate configuration, production technique, applied load, sliding speed, ambient temperature, humidity, and time of contact. These factors influence the friction coefficient; wear rate, surface morphology, and microstructure of the composites, [8, 5, 9, 10, 11].**

**This study applies the Taguchi approach to identify the key operating factors that influence the wear and friction characteristics of C/C composite disc brakes, with the aim of extending their lifespan. The Taguchi method was used to conduct experiments, taking into account three variables: sliding velocity, exerted force, and test duration. The Analysis of Variance (ANOVA) is employed to analysis the interplay of design parameters and their significance.**

**The Taguchi method is a powerful design tool used in engineering analysis. It is highly effective in reducing the number of experiments required by utilizing an orthogonal array, and it also minimizes the impact of uncontrollable factors, [12, 13].**

**The Taguchi approach offers a statistical performance metric called the signal-to-noise ratio (S/N), which is a non linear representation of the required. In this research, the S/N objective is to minimize wear and prolong service life, thus "the smaller is better" type is chosen. Then, (ANOVA) method is employed to investigate the interplay of design parameters and to determine the most influential factors affecting brake discs wear rate and their service life, [12, 14].**

## EXPERIMENTAL PROCEEDURE

### Material

**Carbon/carbon disc brakes are a composite material that has several advantages for aircraft applications. They are made of carbon fibers in a carbon matrix, which gives them high strength, low weight, and excellent thermal conductivity. The manufacturing process involves using a modified natural gas as the source of carbon and a combination of chemical vapor infiltration (CVI) and pressure impregnation carbonization (PIC) to create a dense and uniform structure.**
**The material used in this experiment is samples cut by water jet machine from an F-16 Falcon fighter jet manufactured by BFGoodrich Aerospace (USA). Although only wear properties were characterized, the other mechanical and thermal properties are reused from [15] stated in Table 1.**

**Table 1. (Carbon/Carbon composite properties)**

| | | |
|---|---|---|
| Density | gm/cm$^3$ | 1.72-1.79 |
| Flexural strength | MPa | 60-90 |
| Compressive strength | MPa | 120-140 |
| Specific heat | J/Kg | 1.2-1.5 |
| Thermal conductivity | W/m°K | 75-110 |

**Design of experiment**

**For the experiment, an L9 orthogonal array was selected, which comprises nine rows and four columns. The L9 array can accommodate either three factors with three levels each or four factors with two level each. The L9 array was deemed appropriate for this investigation because only three significant factors - pressure, speed, and time - have dominant impacts on the wear response.**

**Design factors**

**To analyze how response variables depend on operation variables, the design of experiments was implemented with guidelines proposed for mentions various parameters that influence the wear rate and service life of Carbon/Carbon composite, [6, 9]. Therefore, the selected operation variables are: time, rotational speed and applied load. These are the main design parameters (input variables) that affect the response variables. Each design parameter has three different levels. As shown in Table 2.**

**Table 2 Taguchi orthogonal array design of experiment**

| Parameters | Levels | | |
|---|---|---|---|
| | Load (N) | Speed (rpm) | Time (min) |
| 1 | 300 | 800 | 8 |
| 2 | 300 | 1200 | 10 |
| 3 | 300 | 1500 | 12 |
| 4 | 500 | 800 | 10 |
| 5 | 500 | 1200 | 12 |
| 6 | 500 | 1500 | 8 |
| 7 | 800 | 800 | 12 |
| 8 | 800 | 1200 | 8 |
| 9 | 800 | 1500 | 10 |

**Wear and friction experiments**

**A wear and friction test is a method to evaluate the performance of self-lubricated materials in rubbing contact under different operating conditions. The standard test methods for this purpose are in ASTM D3702, which uses a thrust washer testing machine to measure the wear rate and coefficient of friction of the test material. The test conditions include combinations of pressure and velocity. The test duration is usually long enough to produce at least 0.1 mm of wear depending on the material. The test method used to measure the Carbon/Carbon material friction coefficient and the wear rate (weight loss). The contact occurs between two discs (rotor and stator) with dimensions (in mm) shown in Table 3**

**Table 3 Wear Specimens Dimensions**

| | Diameter | | Thickness |
|---|---|---|---|
| | Outer | Inner | |
| Stator | 28 | 5 | 10 |
| Rotor | 31 | 8 | 15 |

**The testing machine uses load, speed, and time as inputs and outputs friction coefficient and temperature. The equation below shows how to compute the friction coefficient [8]. Where M is the measured moments; μ, coefficient of friction, and F, machine load.**

$$M = \mu \frac{(r_{outer}+r_{inner})}{2} F \quad M = \mu*(r1 + r2)*F/2 \qquad (1)$$

**Fig. 1 Uuniversal friction and wear testing machine.**

**Fig. 2 Balance $10^{-4}$ grams resolution.**

**Friction between two surfaces generates heat that alters the material's tribological behavior. To measure the specimen's temperature, a type (j) thermocouple from National Instruments was attached 3mm below the contact surface of the stator specimen. A $10^{-4\ grams}$ resolution weighing balance measured the weight of the stator and rotor test specimens before and after the experiment. The average weight in grams was calculated from three measurements for each specimen.**

**Response variables**

**The performance outputs of the two responses, coefficient of friction and weight loss (wear rate), were evaluated based on experiments performed using the Taguchi approach.**

## RESULTS AND DISCUSSION

**In this investigation, a range of sliding wear experiments were performed on C/C composites under varying conditions of test duration, load, and speed. The Taguchi Method, based on the L9 orthogonal array, was used to identify the optimal combination of factors for reducing wear and friction. The S/N ratio serves as a measure of two responses to select the most influential operational parameters that control performance and enhance service life.**

**The tribological behaviour of Carbon/Carbon composites**

**When employing Carbon/Carbon composite brake material, each braking operation progresses through three phases: A, B, and C, as depicted in Fig. (3). In phase A, the wear rate is reduced by the moisture absorbed by the material. In phase B, the surface temperature rises sufficiently to evaporate moisture and release carbon**

**wear particles. These particles are located between two surfaces: the stator and the rotor. They impact and damage both surfaces as the temperature remains below 150°C. In phase C, Disc material particles (debris) form a flake-like layer between the moving and stationary surfaces and thus serves as a lubricant to reduce wear, [16]. All of these steps were observed during all experiments.**

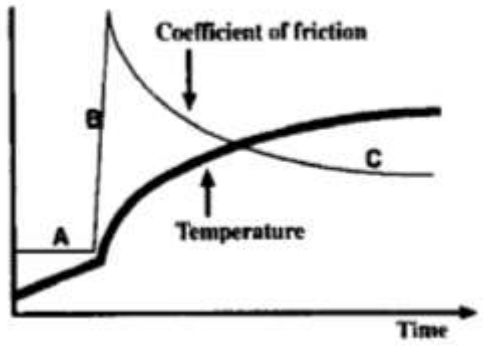


**Fig. 3 Carbon brakes wear regimes, [16].**

**Just prior to the aircraft coming to a halt, the highest operating conditions of elevated speed and pressure result in a low wear rate. This is due to the reduction in the duration allowed for the transformation of disc material debris from sharp particles that inflect damage on disc surface to lubricating smooth layer that dimenshies wear. As the speed and applied load increase, a transition occurs rapidly, and the temperature rises above 150 °C. Subsequently, the wear rate remains constant. As a result, Carbon/Carbon composite weight loss is at its greatest when the brake is operated at low temperatures with low rotational speed and applied brake load. This occurs during the taxi-out phase just prior to takeoff while the disc brakes are still cold, [6]. It is important to optimize Brake operation strategy to minimize the wear rate and governs service life.**

Table 4 S/N ratio weight loss and coefficient of friction

| #exp | weight loss (gm) | S/N |
|---|---|---|
| 1 | 0.0207 | 35.54876 |
| | 0.01712 | |
| | 0.0107 | |
| 2 | 0.0347 | 28.89344 |
| | 0.0375 | |
| | 0.0355 | |
| 3 | 0.0184 | 34.11831 |
| | 0.022 | |
| | 0.01843 | |
| 4 | 0.044 | 26.81602 |
| | 0.0476 | |
| | 0.0452 | |
| 5 | 0.0184 | 33.87725 |
| | 0.023 | |
| | 0.019 | |
| 6 | 0.0248 | 32.96651 |
| | 0.0204 | |
| | 0.022 | |
| 7 | 0.0193 | 34.18262 |
| | 0.0192 | |
| | 0.0201 | |
| 8 | 0.0217 | 33.8930 |
| | 0.0189 | |
| | 0.0199 | |
| 9 | 0.0502 | 25.80197 |
| | 0.0524 | |
| | 0.0512 | |

Table 5 S/N ratio for coefficient of friction

| #exp | Friction Coefficient | S/N |
|---|---|---|
| **1** | **0.1301** | **17.37528** |
| | **0.1429** | |
| | **0.1325** | |
| **2** | **0.2725** | **11.19525** |
| | **0.26** | |
| | **0.2932** | |
| **3** | **0.235** | **12.09221** |
| | **0.2668** | |
| | **0.2427** | |
| **4** | **0.3348** | **9.458825** |
| | **0.3448** | |
| | **0.3299** | |
| **5** | **0.4205** | **7.41762** |
| | **0.444** | |
| | **0.412** | |
| **6** | **0.4367** | **6.91488** |
| | **0.4561** | |
| | **0.4601** | |
| **7** | **0.451** | **7.15027** |
| | **0.4357** | |
| | **0.4301** | |
| **8** | **0.3652** | **8.48468** |
| | **0.3917** | |
| | **0.3721** | |
| **9** | **0.43323** | **7.25616** |
| | **0.4108** | |
| | **0.4292** | |

**Statistical analysis of experiments**

**The data presented in Table 4 and Table 5 were derived from a series of experimental tests designed using the Taguchi method applying L9 OA. The statistical analysis package Minitab® 18 was used to analyze the collected data. The ranking of process parameters is displayed for each level in the S/N response tables for weight loss and coefficient of friction. The S/N ratio was used to measure the quality characteristics and the effect of control parameters (braking pressure, speed, and braking time) on wear rate (weight loss) and coefficient of friction was analyzed in S/N response Table 7.**

$$\mathrm{S/N} = -10\log[\frac{1}{\mathrm{n}} \sum_{\mathrm{i=0}}^{\mathrm{n}} Y_i{}^2] \quad (2)$$

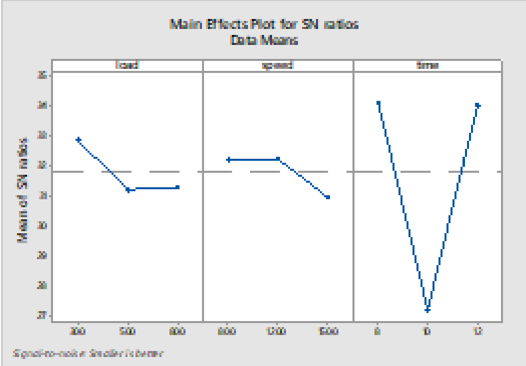


Fig. 4 Main effect plot for S/N ratio for weight loss.

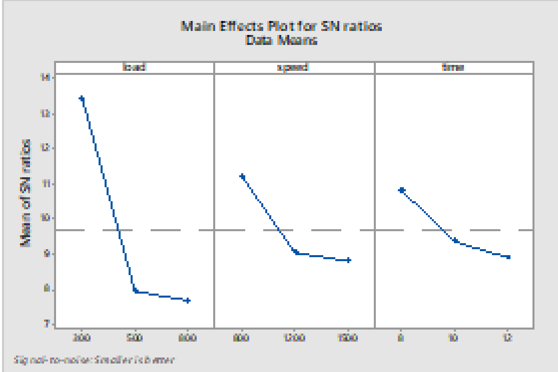


Fig. 5 Main effect plot for S/N ratio for friction coefficient.

**according to Table 6 of the s/n response for weight loss, the most influential factor in weight loss is the time of contact, followed by the applied load and speed. similarly, Table 7 of the s/n response for the coefficient of friction shows that the applied load has the greatest impact on the disc material coefficient of friction, then by speed and time. each experiment was conducted three times, and the average of the result was considered. the s/n ratio was then determined using the average of two responses. the best process parameters for measuring weight loss are a load of 300 n, a rotational speed of 1200 rpm, and duration of 8 minutes. on the other hand, the optimal parameters for measuring the friction coefficient are a load of 300 n, a rotational speed of 800 rpm, and duration of 8 minutes.**

**Table 6 Response for the weight loss**

| Level | Load (N) | Speed (rpm) | Time (s) |
|---|---|---|---|
| 1 | 32.85 | 32.18 | 34.14 |
| 2 | 31.22 | 32.22 | 27.17 |
| 3 | 31.29 | 30.96 | 34.06 |
| Delta | 1.63 | 1.26 | 6.97 |
| Rank | 2 | 3 | 1 |

**Table 7 Response Table Coefficient of Friction**

| Level | Load (N) | Speed (rpm) | Time (s) |
|---|---|---|---|
| 1 | 13.429 | 11.203 | 10.800 |
| 2 | 7.930 | 9.033 | 9.343 |
| 3 | 7.670 | 8.794 | 8.887 |
| Delta | 5.760 | 2.410 | 1.913 |
| Rank | 1 | 2 | 3 |

**Analysis of variance**

**The results of the experiment were evaluated using the ANOVA technique, which helps to identify the most influential factors and their contribution percentage of the independent factors. The analysis was set at a confidence level of 95%. Table 8 shows that time has the greatest impact on wear rate, with a contribution of 87.4 %, making it a crucial factor in controlling weight loss in Carbon/Carbon composites. Load and speed affect weight loss by 5.22 % and 3.7 %, respectively. Table 9, reveals that load has the greatest impact on the coefficient of friction, and had a contribution of 76.99 %, making it a key factor in controlling the friction coefficient in Carbon/Carbon composites. Speed and time affect the coefficient of friction by 8.97 % and 4.03 %, respectively.**

**Regression model analysis**

**A regression model was constructed using Minitab®18 statistical. The model generates an equation that establishes a relationship between the test variables: Time (t) in seconds, Applied load (F) in Newtons, and test speed (n) in rpm, and the output responses for both the weight loss ($\Delta m$), in grams and the coefficient of friction (f). The significance of the regression equation is the ability to predict the most prominent factors and the interactions between them.**

$$\Delta m = -0.5142 + 0.11828t - 5.783 \times 10^{-3}t^2 + 10^{-5}(6.5F - 10.8n - 0.4Ft) + 10^{-7}(n^2 + nF - F^2)$$

$$f = -1.363 + 10^{-3}(1.922F + 1.298n + 68.9t) - 10^{-6}(6270t + 2F^2 + Fn - 107Ft)$$

**The equations shows that the braking cycle time has the greatest effect on the weight loss (wear rate), followed by the braking pressure (applied load) and then the aircraft speed. Value of $R^2$ was higher than 97%. As shown in Table 10 and Table 11**

**Table 8 ANOVA for Weight Loss**

| Source | Load. | Speed. | Time. | Error. | Lack-of-Fi.t | Pure Error. | Total. |
|---|---|---|---|---|---|---|---|
| D.F | 2 | 2 | 2 | 20 | 2 | 18 | 26 |
| Seq. SS. | 2.153E-1 | 2.507E-2 | 1.127E-2 | 2.797E-2 | 2.489E-2 | 3.082E-3 | 2.796E-1 |
| Contr. | 76.99% | 8.97% | 4.03% | 10.01% | 8.90% | 1.10% | 100% |
| Adj. SS. | 2.153E-1 | 2.507E-2 | 1.127E-2 | 2.797E-2 | 2.489E-2 | 3.082E-3 | |
| Adj MS | 1.076E-1 | 1.254E-2 | 5.636E-3 | 1.399E-3 | 1.245E-2 | 1.710E-4 | |
| F-Value. | 76.95 | 8.96 | 4.03 | | 72.69 | | |
| P-Value. | 0 | 2E-3 | 3.4E-2 | | 0 | | |

**Table 9 ANOVA for friction coefficient**

| Source | Load. | Speed. | Time | Error. | Lack-of-Fit. | Pure Error. | Total |
|---|---|---|---|---|---|---|---|
| DF. | 2 | 2 | 2 | 20 | 2 | 18 | 26 |
| Seq SS. | 2.170E-4 | 1.540E-4 | 3.627E-3 | 1.520E-4 | 5.200E-5 | 1.000E-4 | 4.150E-3 |
| Contr. | 5.22% | 3.70% | 87.40% | 3.67% | 1.26% | 2.41% | 100.00% |
| Adj. SS. | 2.170E-4 | 1.540E-4 | 3.627E-3 | 1.520E-4 | 5.200E-5 | 1.000E-4 | |
| Adj. MS. | 1.080E-4 | 7.700E-5 | 1.814E-3 | 8.000E-6 | 2.600E-5 | 6.000E-6 | |
| F-Value. | 14.23 | 10.09 | 238.06 | | 4.69 | | |
| P-Value | 0 | 1.000E-3 | 0 | | 2.300E-2 | | |

**Table 10 (model summary for weight loss)**

| S | $R^2$ | $R^2$ (adj) | pressure | $R^2$ (pred) |
|---|---|---|---|---|
| 2.3589 E-3 | 97.59 % | 96.51 % | 0.2254 E-3 | 94.57 % |

**Table 11 (model summary for friction coefficient)**

| S | $R^2$ % | $R^2$ (adj) | pressure | $R^2$ (pred) |
|---|---|---|---|---|
| 13.0843 E-3 | 98.9 | 98.41 % | 6.933 E-3 | 97.52 % |

**Table 12 Verification experiment parameters**

| Exper. | Load. | Speed. | Time. |
|---|---|---|---|
| 1 | 500 | 1200 | 8 |
| 2 | 800 | 1500 | 8 |

**Table 13 Verification experiments results**

| **Experiments** | $\Delta m$ **(expected)** | $\Delta m$ **(regression)** | **Error %** | $f$ **(expected)** | $f$ **(regression)** | **Error %** |
|---|---|---|---|---|---|---|
| **1** | **0.0152** | **0.01678** | **9.4** | **0.412** | **0.43712** | **5.4** |
| **2** | **0.0328** | **0.028586** | **12.2** | **0.401** | **0.352** | **12.21** |

**The last stage in designing the process is conducting a confirmation experiment. The variables chosen in Table (11) and ASTM D3702 test using dry abrasive sliding were used to compare the results with the calculated figures forcasted by the regression equations. As shown in Table (12), the expected values closely match the values predicted by the regression equation. For a statistical analysis to be considered reliable, the error percentage must be below 20% [12].Since the values of the errors were below the threshold, then the obtained regression equations may be used for the prediction of the weight loss and coeffiect of friction.**

## CONCLUSIONS

**This study employed the taguchi method to reach the most suitable operating parameters to enhance the behavior of carbon/carbon composites. the experiment was designed using an l9 orthogonal array with four factors (sliding speed, sliding distance, applied load, and temperature) at three levels. the response variables measured were the coefficient of friction and weight loss.**

**The ANOVA technique was employed at a 95% level of confidence to assess the significance of each factor and their interactions on tribological performance. The findings revealed that braking cycle duration had the greatest effect on wear rate(weight loss), while applied braking pressure (applied load) had the greatest impact on the coefficient of friction.**

**A regression equation was formulated for each response to predict wear rate and friction coefficient under different operating conditions. The verification experiment confirmed the effectiveness of the regression equations in predicting the behovir of the C/C carbon disc brakes material.**

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