Wear Rate Analysis of Metal Matrix Composite Using Machine Learning Algorithms

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Abstract: There is a lot of interest in a compound with improved mechanical power, toughness, wear resilience, and increased electric and thermal conductance. This work examined the tribological conduct and fabrication of the titanium metal matrix composite (TiMMC) augmented with graphene (Gr) and tungsten carbide (WC) fragments. The TiMMC, which had 8 percent mass percentages of WC and Gr, was created using stir casting. Taguchi's L27 orthogonal grid method was used for designing the tribological investigations, which were then conducted as wear experiments with a pinon-disc gadget. ANOVA and Taguchi's study show that loading and range have the most effect on wear percentage, accompanied by speed.By examining the worn areas of the composite samples using scanning electron microscopy, the wear mechanism was determined. The wear rate statistics were correctly categorized by machine learning classifying techniques such as random forest, support vector machines, and XG-Boost methods, which provided accuracy values of 72%, 66%, and 56.3%, respectively. Notwithstanding the encouraging outcomes, the research acknowledges that the system's efficiency may differ depending on certain properties of the composite component and operating circumstances. Therefore, it motivates further research to validate and extend these novel discoveries over a larger range of components and circumstances.

Keywords: Wear analysis, Metal matrix composite, Titanium alloy, Wear rate, and Machine learning.

1. Introduction

Artificial or spontaneously occurring, composite elements are made up of multiple substances with significantly varying tangible properties. Within the finished construction, these parts maintain their uniqueness no matter the macro or microscopic sizes. Blocks made from straw and clay for building were the first examples of composite components created by humans [1].

Composite components are made from essential components, of which a minimum proportion of every kind is needed. The matrix component encloses and maintains the supporting components by preserving their respective positions. The unique mechanics and physical characteristics of the reinforced components contribute to the enhancement of the matrix's properties [2, 3].

Metal matrix composites (MMC) have garnered a lot of interest lately because of their outstanding qualities. These composites exhibit anisotropy conduct, and it may be difficult to produce them using conventional methods, even if the reinforcing frequently adds many desired mechanical qualities. Particulate-reinforced MMC is currently gaining popularity because of its advantageous isotropic qualities and affordability [4, 5].

Because of their exceptional blend of outstanding toughness, rigidity, durability, corrosion opposition, minimal density, and wear opposition, titanium alloys (Ti alloy) are utilized extensively in a broad spectrum of technical uses. Based on their remarkable strength-to-mass proportion, Ti alloys are frequently employed in the automobile, aircraft, sports, logistics, and health-related sectors to reduce power usage, boost profitability, and prolong product lifetime [6]. Depending on the dispersion and geometry of additives, Ti MMC (TMMCs) may be roughly divided into two categories: intermittently strengthened TMMCs and constantly supported TMMCs [7].

The procedure of choosing and optimizing components depends on evaluating the specific wear rate. This is particularly important in industries like manufacturing, aircraft, and automobiles, where element lifespan and dependability are greatly impacted by wear resilience [8]. In several sectors, like manufacturing and medical services, artificial intelligence (AI) has produced numerous advantages and achieved notable advancements. AI has proven to be very helpful in the healthcare field for activities like patient surveillance, medicine growth, treatment organizing, and identifying illnesses [9].

Similar to this, AI has significantly altered production processes by enabling predictive service, boosting output, and simplifying processes. Evolving computation and machine learning (ML) methods have great potential in several domains [10]. By fusing the learning and forecasting skills of ML techniques with the adaptable search skills of evolving computation, scientists can more successfully tackle challenging optimal forecasting activities. There are several materials research and manufacturing fields where this combination may be subsequently applied. This hybrid approach can enhance choosing features in ML systems, boost the accuracy and efficacy of optimization methods, and assist in identifying the optimal approaches in difficult issue areas [11].

Hence this study aims to investigate the wear rate analysis of Ti alloy-based MMC using ML algorithms.

2. Literature Review

According to the investigation [12], pure titanium augmented with a ten percent weight percentage WP had tangible characteristics that were similar to the ones of the Ti alloy. According to an investigation by [13], the mechanical properties of WP/Ti compounds are strongly influenced by the WP's dimension. [14] studies of the different size dispersion of TiC addition to Ti by DED resulted in a variety of microstructures with outstanding tensile performance and elasticity.

It is urgent to investigate novel and maybe more precise computing simulation techniques for estimating wear scores in these Al/SiC MMCs, as current prediction algorithms, like basic artificial neural networks (ANNs), have seen certain effectiveness in this field. The application of traditional ML algorithms for wear rate prediction has been the primary objective of earlier research [15].

Materials and Methods

Ti-6Al-4V, a titanium alloy, served as the main matrix component. The WC and Gr-reinforced granules were chosen. The graphite granules had a mean dimension of 25 μm, while the WC granules had a mean dimension of 45 μm. An electrical oven was used for melting the necessary quantity of Ti alloy in a graphene container. To eliminate the water content, the supporting granules were elevated to 500°C. The Ti alloy was combined with a predetermined amount of supporting granules. Regularly, the hybrid composite components were mixed. The blended compound was allowed to harden at room temperature after being placed into the designed mold at 800°C.

Optics and SEM were used to analyze the specimen's microstructures and worn areas. The MVH-1 autonomous trial load, which measures microhardness, weighs between 10 and 1,000 grams. It is a simulation of a micro-toughness analyzer by OMNI Technologies. The dry sliding wear assessment was carried out by ASTM G99-95 guidelines. A computerized equilibrium was used to determine the pin's first weight after it had been cleansed with acetone. The pin was then held firmly upon a rotating counter-area made of EN-32 steel that had a toughness of 65 HRC for the duration of the examination.

The mean weight, speed, and distance were all changed during the examination. Following acetone cleaning after each examination, the pin's final weight was determined. By subtracting the starting weight from the total weight, this research determined the weight depletion of the pin as a result of sliding wear. The density measurements associated with the pin were used to compute the volume drop due to wear. The compound pins' wear percentage was then determined.

The procedure for conducting a wear examination is as follows:

The experimental specimen is initially meticulously measured on a cutting-edge electronic equilibrium, and its initial weight is noted. The sample's exterior is then set up to make a connection with the disk once it has been firmly fastened employing the notch. After that, the path of the radii is adjusted to satisfy the particular needs of the experiment. The sliding speed is adjusted by the experiment's conditions after the sample is positioned correctly and the required typical weights are applied. The experiment is then conducted over a calculated duration to cover the designated distance.

The pin-height drop technique was used to calculate the pin volume decline for every experiment. To ensure reproducibility, every examination was carried out on multiple occasions. The wear percentage was calculated employing Eq. (1) by averaging the three experiments. It is feasible to contrast wear features beneath different conditions using this technique.

$$\text{Wear rate} = (\text{Volume loss} * \text{Hardness}) / (\text{Normal Weight} * \text{Sliding distance}) \quad (1)$$

The Taguchi approach uses a solid study structure to reduce operational variance. The primary goal of the process is to give the maker an inexpensive, outstanding product. The Taguchi approach was created by Professor. Genichi Taguchi of Japan has continued to use that variant. Poor operational standard therefore affects society as much as the industry. He created an experimental design method to examine the effects of various variables on the average and variation of a procedure efficiency metric that indicates the procedure's functionality.

Taguchi's research approach saves duration and money by collecting the data required to determine the factors that have a major impact on product standards with only minimal research.

This is achieved by organizing the parameters affecting the process and the values where they ought to be changed by employing orthogonal panels. Through the use of ANOVA, important operational variables were found. In the present study, an L27 orthogonal grid was selected.

In this research, ML methods like RF, SVM, and XG Boost are used to classify and forecast the wear percentage of hybridized MMC. To accurately determine the wear percentage through categorization and to develop a confusion matrix and AUC-ROC graphs for more thorough evaluation, samples were created employing MATLAB synthesized data production instruments depending on the trial statistics. The categorization approach uses training statistics to classify novel findings as part of supervised learning. In the classifying procedure, the application discovers ways to classify new data into different categories or groupings employing the database or provided findings. The present research's statistics are separated into two categories based on whether the reading is greater than or less than the mean of all wear percentage readings, which is 0.085. The Python measures component from the Skilearn library was used to display the confusion matrix. The database was divided into two parts: 20% of random trial statistics and 80% of training statistics to obtain accurate results for data forecasting. To get a variety of classification statistics, RF, SVM, and XGBoost categorization were used, and K-fold (k = 1).

RF is an ensemble learning method that comprises a huge set of DT classifications. It creates numerous offspring databases of the parent database via sampling and substitution and subsequently uses these offspring databases to form DT. Lastly, it gets at the ultimate predicted outcome depending on the bulk of the estimations generated by each of the DTs. It is important to note that RF has two main points: randomization and forest. Unpredictability indicates that the procedure of creating offspring databases is completely random, i.e., any characteristic and specimen can influence the creation of a DT; forest indicates that RF estimates from a large number of DTs that can create a forest. RF excels at processing large amounts of data quickly and accurately, outperforming DT. Thus, it is frequently utilized in technological and scientific fields.

SVMs were developed to address problems with binary classification. Nevertheless, several binary models are constructed and connected to produce SVMs that can perform these multiple-class categorizations employing binary approaches as analytically difficult multiple-class situations become more prevalent. Input variables such as the border, the hyperplane, and the kind of kernel are utilized to establish the SVM classifier functionality (SVC). The test statistics are forecasted employing the trained and verified statistics after the statistics have been trained employing the SVM algorithm.

By pushing the statistical limits of boosted tree methods, XGBoost is an adjustable and precise gradient-boosting approach that mainly improves ML system efficiency and analytical efficiency. XG-Boost has gained popularity as a forecasting method in the past decade as a component of an ensemble strategy designed to generate better forecasts with imbalanced-class statistics. After training and validating the training database, XGBoost categorization chooses the most promising characteristics to forecast the statistics, much like the F-test. It keeps going until no characteristics are left in the database for evaluation and the most effective characteristics that have the most impact on the data are chosen. Depending on the most effective characteristics, the findings are next examined to determine the optimal wear loss percentage.

A performance evaluation has been done to evaluate the accuracy, precision, recall, and F-score of the result for each AI approach. Equations (2-5) given below were used for calculating all of the parameters.

$$\text{Accuracy} = \frac{\text{TN} + \text{TP}}{\text{FN} + \text{FP} + \text{TN} + \text{TP}} \qquad (2)$$

$$\text{Recall} = \frac{\text{TP}}{\text{FN} + \text{TP}} \qquad (3)$$

$$\text{F} - \text{value} = \frac{2 \times \text{Precision} \times \text{recall}}{\text{Recall} + \text{Precision}} \qquad (4)$$

$$\text{Precision} = \frac{\text{TP}}{\text{FP} + \text{TP}} \qquad (5)$$

3. Result and Discussion

Pin-on-disc apparatus was used to conduct the dry sliding wear study. The important variables were identified using signal-to-noise (S/N) proportion and ANOVA approaches. The impact of noise effects on efficiency measures is assessed using S/N proportions. Three S/N proportions are common and widely used; they assess how much the response's statistics vary and how well the mean response matches the aim. In theory, the best among them are those that are greater, lesser, and more effective. It's preferable to be little. To lower the wear percentage, a protocol was used in this investigation.

The S/N proportion measures how vulnerable the performance characteristic being studied is to unpredictable occurrences brought on by experimentation.

The influence of weight, speed, and distance on the wear rate was examined using an ANOVA; the findings are displayed in Table I. The F-test and p-value findings showed that the weight and distance significantly affected the wear incidence. The response tables for averages and S/N proportions are shown in Fig.1, 2, Tables II and III, respectively. According to the findings, the wear percentage is influenced by the load, accompanied by speed and distance.

Table I ANOVA Outcomes of Wear Rate

Origin	DF	Sequential SS	Adj SS	Adj MS	P-Value	F-test
Weight	3	0.0000002	0.0000002	0.0000002	0.058	3.32
Speed	3	0.0000002	0.0000002	0.0000002	0.623	0.50
Distance	3	0.0000002	0.0000002	0.0000002	0.057	3.36
Error	21	0.0000003	0.0000003	0.0000003		
Overall	27	0.0000005				

Table II Response Outcomes of S/N Proportions

Stage	Weight	Speed	Distance
1	71.95	75.32	72.71
2	76.41	78.34	78.89
3	79.97	74.67	78.79
Delta	8.03	3.68	6.19
Rank	1	3	2

Table III Average Response Outcomes

Stage	Weight	Speed	Distance
1	0.000229	0.000202	0.000230
2	0.000171	0.000128	0.000115
3	0.000106	0.000177	0.000117
Delta	0.000124	0.000074	0.000117
Rank	1	3	2

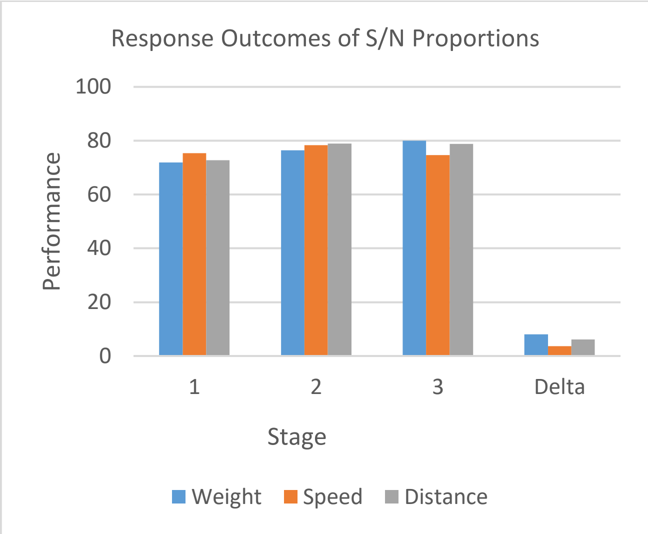

Fig.1. Response Outcomes of S/N Proportions

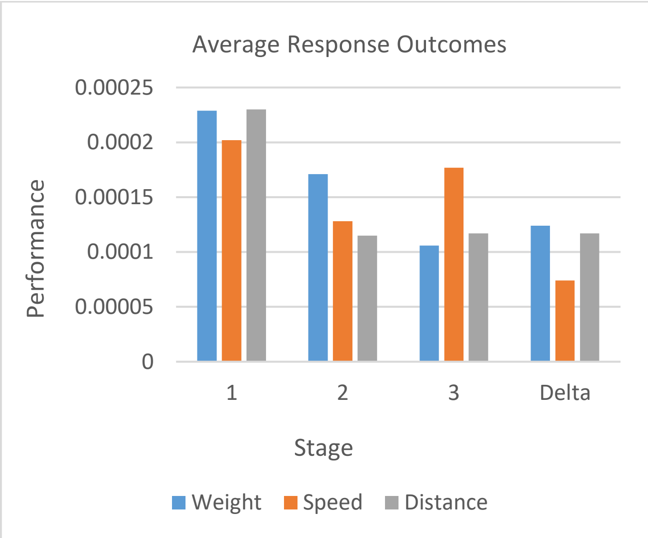

Fig.2. Average Response Outcomes

The quantity of component waste or wear capacity per unit weight and sliding distance is indicated by the wear percentage. By examining the wear incidence outcomes, several wear regiments were discovered in the wear pattern. These wear regimes include information about the main wear processes, such as adhesion, abrasion wear, breakdown, plastic distortion, oxidation, and evaporating, under a range of sliding speeds and standard weights. Wear modifications are variations in wear percentage across relatively small variations in variables such as mean weight, sliding speed, temperature, and duration. Typically, wear transformation graphs detect and describe different wear processes or regimes. The moderate wear regimen is characterized by lower wear values and gentle interface circumstances, with oxidation and adhesion wear predominating. Conversely, the extreme wear regime typically results from additional demanding operational conditions and is marked by higher wear levels. Extreme wear can result from a variety of processes, such as plowing, breakdown, and abrasion wear.

Since abrasion wear is caused by microscopic gaps on one surface interacting with the next, ploughing loses components. This process is associated with hard areas or the existence of solid granules. Oxide layers are created on the alloy layer as a result of the alloy's contact with atmospheric oxygen, which causes oxidation wear. This process may lead to an accelerated pace of wear and area degradation. The process by which layers separate off the material's surface is referred to as "breakdown." It usually occurs in regions where regional stress is concentrated, leading to the accumulation of wear debris and exterior hardness. When a substance streams and changes as a result of an imposed mean weight, this condition is called plastic distortion.

Wear pattern assessment can be used to determine the optimal speed and weight mixture that minimizes wear percentage, allowing for the identification of functioning conditions in which the component performs exceptionally well under wear. This information serves as a guide for technological uses of the blended MMC alloy. This is particularly crucial in the scientific, automobile, and aviation sectors where wear resilience is essential. The wear percentage is reduced for the current research between 3.4 and 4.4 m/s speed and 24 N to 34 N weight; it is decreased between 27.4 N and 40 N load and 2,000 m to 1,600 m distance.

Optical and SEM Evaluation

For the WC-Gr support to be present in the Ti-6Al-4V matrices, it was uniformly dispersed among the material. Although Titanium Alloys Contact does not detect responses, the Ti-6Al-4V matrices contain evenly spaced small WC-Gr additions. It is crucial to remember that WC and Gr create a unique API architecture rather than a simple binary mixture. Employing microhardness testing, the blended composite's mean Vickers Microhardness score was 893 VHN (Fig 3 (A)).

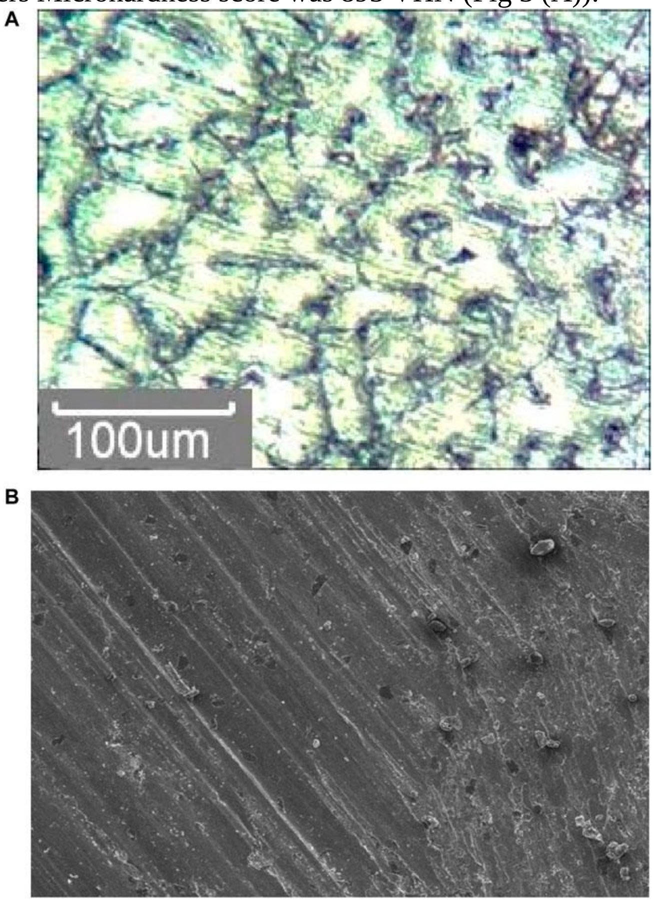

Fig 3 (A) Optical Micrograph of hybrid material and (B) SEM Analysis

An essential technique for precisely describing the wear conduct of the materials is SEM examination of the wear areas that formed into dry sliding wear in the constant stress domain (Fig 3(B)).The composite's exceptional toughness makes the worn-out areas hardly noticeable. At this point, the WC and Gr support granules are firmly attached to the matrices stage, giving this specimen an extremely smoother finish. Additionally, supports are still intact down just a bit. This results from the self-lubricating properties of the tribo exterior additions. Welded layers are visible due to the material's worn exterior. The visible sliding area in this image has been altered by the phase. This supporting element also makes the exteriors look smoother.

Wear Rate Estimation Using ML Algorithms

ML was used to classify the data according to the tapered inclination of the square gaps in the stainless steel sheet. For evaluating the feature value of input variables, such as weight, speed, and distance, F-test graphs were made employing Python modules.

A feature is considered inconsequential if its F-test result is less than the F-dispersion score, as seen in Table IV and Fig.4. Nonetheless, an input variable or feature will be considered important if its F-test score exceeds the crucial F-dispersion.By taking into account the tags or levels of its RF in the training database, the RF technique forecasts the tag or measurements of a novel data set. Referring to Table V, the results beneath the mean wear loss rate were regarded as 1 in the present evaluation, and the measurements beyond the mean level were regarded as 0. Wear decline ought to be kept to a minimum because it will improve outcomes. Table VI shows that the RF categorization of wear depletion has an estimation accuracy of 72%.

Table IV Feature Significance Outcome of Wear Rate

Feature	Significance Score
Weight	0.319
Speed	0.537
Distance	0.752

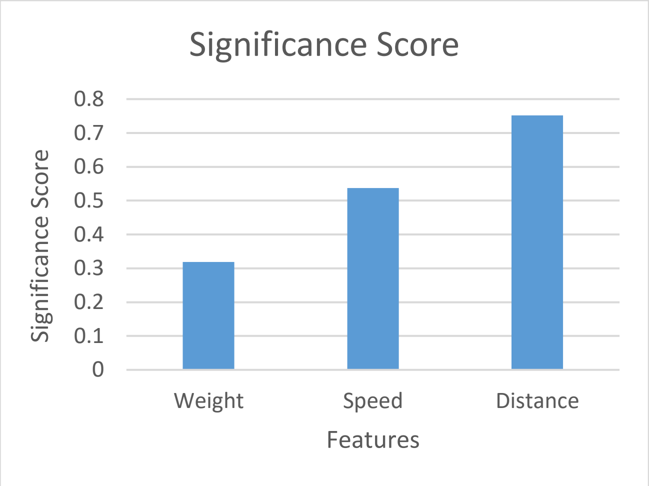

Fig.4. Feature Significance Outcome of Wear Rate

Table V Outcomes of Confusion Matrix of RFAlgorithm

Predicted Label			
P	N		
23	9	P	True Label
8	40	N	

Table VI RF Method Performance Outcomes

Class	Precision	recall	F1-Value	Support
0	0.64	0.62	0.63	32
1	0.77	0.79	0.78	50
Accuracy	-	-	0.72	81
Macro Mean	0.71	0.70	0.71	81
Weighed Mean	0.72	0.72	0.72	81

A 2-D hyperplane across the data is used to distinguish or divide the statistics in SVM categorization, also known as support vector categorization. The SVM technique can use either linear or non-linear statistics. There are several kernels available for configuration in an SVM algorithm. For a linear database, we can call the kernel "linear." Table VII shows how it categorizes readings that are beyond the typical wear decline (0) and those that are beneath the mean wear decline (1). Table VIII shows that the SVM's forecasting accuracy was 66%.

Table VII Outcomes of Confusion Matrix of SVM Algorithm

Predicted Label			
P	N		
28	4	P	True Label
1	47	N	

Table VIIISVM Method Performance Outcomes

Class	Precision	recall	F1-Value	Support
0	0.60	0.33	0.43	32
1	0.68	0.87	0.76	50
Accuracy	-	-	0.66	81

Macro Mean	0.64	0.60	0.59	81
Weighed Mean	0.65	0.66	0.63	81

XGBoost is a dispersed gradient-boosting repository designed for optimal likelihood, adaptability, and performance. It applies ML methods using the XG-Boost system. The confusion matrix for XGBoost is shown in Table IX. Results show that the XGBoost algorithms' forecast accuracy was 56.3%.

Table IX Outcomes of Confusion Matrix of XGBoost Algorithm

Predicted Label			
P	N		
24	8	P	True Label
12	36	N	

4. Conclusion and Future Scope

A unique hybrid material Ti-6Al-4V/WC/Gr was made by the stir-molding technique, and its tribological characteristics were investigated. The investigation's main conclusions are as follows:

i. The F-test, p-value resultsand ANOVA showed that the weight and range had an important effect on the wear percentage, with speed subsequent match.

ii. The wear percentage for the present study is reduced between 3.4 and 4.4 m/s speed and 24 N to 34 N weight, according to the wear charts.

iii. The visual micrograph of the composition shows how small and free of holes and micro-fissures this specimen is. The WC-Gr support had to be evenly distributed across the blends to be present in the Ti-6Al-4V matrices.

iv. SEM analysis of the wear areas established into dry sliding wear reveals that the WC and Gr augmentation grains are securely connected to the matrices stage at the equilibrium system, creating a smooth exterior. In addition, reinforcements have stayed comparatively large. The self-lubrication qualities of the tribo exterior assistance are what cause this.

V. The findings demonstrated that the SVM had a forecast accuracy of 66% and the XG-Boost algorithm had an estimation accuracy of 56.3%. The RF classifier was found to have a 72% estimation accuracy.

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