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Application of Fuzzy Logic Model for Study the Wear Behavior of Chrome Coating by Physical Vapour Deposition (PVD)

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Abstract

This paper deals with innovative tactic for analysis wear behavior of coating by means of fuzzy logic. The Coatings with Thickness of 10µm Were Physical vapour Deposited from Mixture of Different Powder under the Controlled Environment of Process Gas (N2), Current, and Voltage, Temperature & Time (Heating, Bombardment, and Coating). Pin-on disc troibometer was used to conduct the experiment with varying load, sliding velocity for a particular time and distance experimental design is used for analyzing the performance measures such as wear loss, and frictional force by using fuzzy logic in order to obtain minimum wear and frictional force. The results indicate that increasing of sliding velocity the specific wear rate is decreasing.

***Keywords**: PVD Coating, Chromium Nitride, Wear, Fuzzy Logic*

1. Introduction

Surface engineering is a group of processes which deals with increase the life of base materials. Different methods are available to coat the base materials namely Chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD) and thermal spray coatings, are accessible to enhance the existence of automotive components like piston rings [1]. Fuzzy logic model, in a broad-spectrum sense, refers to the establishment of a system or a procedure, in statistical terms, which characterize different input behavior like different load, velocity and sliding distance for a controlled time the output behavior specific wear rate of the coating. Surface coating by physical vapour deposition have mainly preferred because of its less specific wear rate as compare to uncoated sample used for piston ring. Cast iron has good wear resistance among many materials so it is used as base material. Fuzzy logic modeling of experiments is an effective way which can be employed for analyzing the frictional force and dry sliding wear of coating. Some real life problems in the automotive industry or any other relevant field where research is concern about the life of materials needs accurate and precise analysis of data with the help of a complex mathematical model is formed which deals with number of variables as an input and output. Such a model formulation is known as mathematical model of real word system. Pin on Disc tribometer follow a process of control system that relates the input and output in a similar way of mathematical analysis by avoiding different functions of mathematics and tedious equation and such a process is known as static system while dynamic system is computation of result by experimental set-up. Current study deals with

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static fuzzy system model together with its stability investigation and the dynamic fuzzy systems model follows, along with its controllability analyses [2, 4].

The piston-rings of ICE (internal combustion engines) are subjected to variable temperature, load, velocity and lubrication conditions. Various types of coatings on piston rings material can be deposited by thermal spraying, PVD and CVD methods and studied by considering the above conditions to improve their tribological behaviours. The temperatures generated at the point of contact between the rubbing parts due to frictional force and elevated heat which causes to major wear damage. If the metal has a tendency to oxide formation increasing at a higher elevated temperature, the oxidation occurred in these conditions can alter the amount of wear [5]. Tribological behaviours of various thermally and plasma-sprayed coatings against cast iron were studied in literatures [6–8] under nearly similar test conditions to those of the present study except this coating materials composition and test configuration. Materials performance in automotive industry like piston ring coatings, uses some hard material including Mo, CrN and PVD and diamond-like-carbon (DLC), sliding against cast iron cylinder liner segments was studied under standard instrument conditions[9].

2. Experimental Set Up

2.1. Materials and Method

Fuzzy logics statically approach may be used as an efficient tool to determining the wear behavior of chromium nitride coating. Expert system of fuzzy logic will be considered as soft computing technique use as a pattern the exiting data of specific wear rate during wear test to analyze and interpretation of the results. Some hard computing tools and techniques can be avoided in this approach. The benefit by means of applying fuzzy logic interpretation is the purpose of linguistic information that is the important criteria for human statement. Such type of approach controller vary one or more than one input and obtained the one or more than one output to that system with the help of fuzzy control rules. Physical Vapour Deposition (PVD) is an efficient and most commonly used process suitable for automotive industrial applications due to its high ionization ratio and deposition rate, which allows the deposition of various functional coatings. Two sets of wear tests have been done at room temperature without lubrication in laboratory air, one with the variation of the normal load and the other with the change of sliding velocity. The wear depth profiles of CrN coatings can be examined using a surface profilometer. A set of equally spaced depth profiles covering the whole wear track area was used to evaluate the volumetric wear. Two cases (case-I & case-II) repeated wear measurements were carried out at the given test conditions to evaluate the specific wear rate and friction force [10, 11]. PVD process is an atomistic deposition method that involves the vaporization and subsequent deposition of coating material which has the advantage to deposit metals, alloys and ceramics on most materials and a wide range of shapes. To achieve the desired columnar ceramic coating structure, the parts must be preheated to a certain temperature. Development of the fabrication technique, process parameters it's limits, and monitoring/control techniques to give a good quality component. The surface of sample were structured by means of micro-milling machine.PVD device was used to deposit the coating system. Specimen was heated up to a temperature of 450^0 approximately during the coating process. Vacuum chamber mainly consist of nitrogen as a carrier gas and acetylene with the argon in rest condition at a pressure of 550Mpa. Chromium cathodes were powdered with 2600-2800 W and a pulse frequency was adjusted .and the temperature of the chamber increases and at a particular temperature around 1536^0c nitrogen gets converted to its nitride phase.

Table 1. Composition of Substrate Material (Cast Iron) Used for Coatings

Element	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Cu (%)
Target	3.75±0.05	2.70±0.05	0.53±0.01	0.36±0.02	.06±0.005	0.04±0.01	0.035±0.03

2.2. Pin on Disc Test

Pin on disc type wear monitor with data acquisition system was used to evaluate the wear behavior of coated material against a pin embedded in the setup. These systems allow for the accurate identification of wear and friction characteristics between two mating engine components. The wear test can be performed on any wear tester, but for thin coatings pin on disc tribometer is mostly used now a days.

Lower sample is disc which is mounted on rotating disc holder and the upper sample can be a pin. Unique feature of this machine is the ability to perform unidirectional as well as bi- directional sliding test without any cumbersome changeover attachment. Test load, rotational speed of disc and wear track diameter are PC controlled. They can be held constant or changed during a test. Frictional force, wear, co-efficient of friction and temperature are measured and recorded continuously. Temperature of disc is measured for recorded by using the Infra red Camera. The test was performed under dry condition without lubricating agents. Pin on disc type tribometer used to supervise wear with data attainment or processing unit system and to evaluate the wear behavior of coated material adjacent to a pin embedded in the setup. Load was varied as a input and applied on the pin by the pulley string arrangement as shown below. Maximum loading capacity of the system was 200 N. The wear test can be performed on any wear tester, but for thin coatings pin on disc tribometer is mostly used now days. The wear rate is evaluated by weighing the disc before and after the wearing in grams (g) and the least count of the electronic weight balance used is 0.00001g. We alter the two parameters only viz. load and speed to determine the rate of wear and coefficient of friction. It is generally carried out at room temperature of 20℃. During testing some amount of debris generally deposited on the pin, so we clean the pin after each iteration so that pin will always remain in direct contact with the disc.

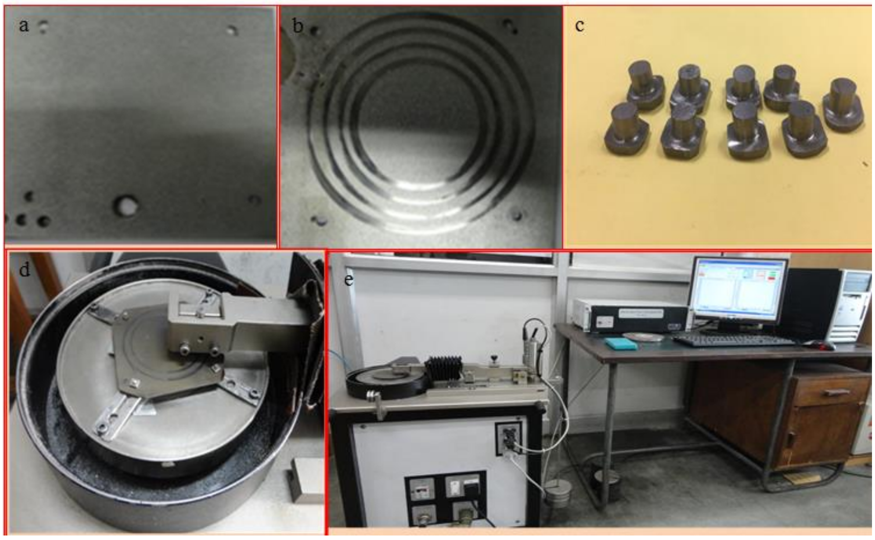

Figure 1. Experimental Set Up (a) Coated Sample by PVD,(b) Sample after Wear Test at Tribometer, (c) Counter Body Made by Cylinder Liner Material, (d) Top View of Tribometer During Test, (e) Complete Set of Wear Test

3. Results and Discussion

3.1. Fuzzy Logic Description of Input-Output Relations

The fuzzy expert system in wear behavior uses a fuzzy if-then rule base consisting of a set of intuitive fuzzy rules, interpreting an input and producing a crisp output. In this study output is significantly influenced by the input variables, which are: critical force, coating thickness, loading rate, sliding distance, substrate roughness, coefficient of friction, friction force, type of wear damage.

A mathematical system modeling is important with its own right and fuzzy systems control. During analysis we consider a black box or an unknown process/system for that system as a input load, sliding velocity and sliding distance *etc.* are taken as x1, ….xn where as output is frictional force and coefficient of friction and wear are taken as y1…..yn. we analyze the experimental result that was in discrete time series and by the unknown model description and characterization, and the mathematical explanation by applying input x1 the corresponding output y1 can be established known as unknown system mathematical modeling represent in Figure 2 [12,13].

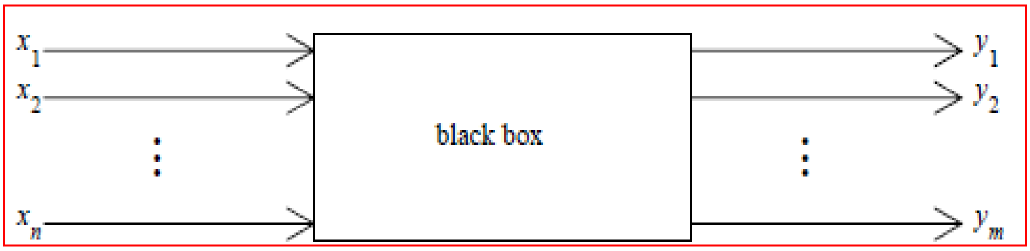

Figure 2. A System of Black Box

Current study deals with IF-THEN rule for more than one fuzzy (N>1)

R^i: if (x_1 is X_{i1}) and ... and (x_n is X_{in}) then $y_i = a_{i0} + a_{i1} x_1 + ... + a_{in}x_n$, i=1,...,N,

Then, with the given set of inputs

$x_1 = x_1^0 \in X1$, ..., $x_n = x_n^0\ x \in X_n$,

Namely, the same inputs applied to all the different rules, we will have

$$Y_1=a_{10}+a_{11}x_1^0+\dots\dots\dots\dots+a_{1n}x_n^0$$
$$Y_2=a_{20}+a_{21}x_1^0+\dots\dots\dots\dots+a_{2n}x_n^0$$
$$\dots$$
$$\dots..$$
$$Y_N=a_{N0}+a_{N1}x_1^0+\dots\dots\dots\dots+a_{Nn}x_n^0.$$

A membership function is taken for corresponding output by a general rule where i=1….to N. Final output for y_1….y_2…yn can be obtained by the weighted average formula for typical mathematical modeling approach using all y_{i0} with the weights µY(y_{i0}), usually called the center-of-gravity formula:

$$Y = \frac{\sum_{i=0}^{N} \mu_y(y_i)\,.y_i}{\sum_{i=0}^{N} \mu_y\,(y_i).y_i}$$

Above equation is simple algebraic multiplication of real numbers and a convex combination of all output. weighted average equation is a purpose of generating a sensible output which, already has proven to be successful in many application, is by no way the only feasible formula to use (and may not be optimal in general)[14,16].

So with the given input

$$x_1€\ X_1,\ x_2€\ X_2 \dots\dots\dots\dots\ x_n€\ X_n$$

The output becomes

$$Y=A_0+A_1.X_1+A_2.X_2+\dots\dots+A_n.X_n$$

This yields the fuzzy subset (interval) for y, with the membership functions given by the general rule as

$$\mu_{Y,\,i}(y_i)=\{\mu_{X1}(x_i)^0\wedge\ldots\ldots\ldots\wedge\mu_{Xn}(x_i)^0\}$$

Where *i* = 1... *N*. In the α-cut notation, this algorithm can be represented by

$$(S_y)\ \alpha=\{y_i€\ Y_i|\ y_i=a_{i0}+a_{i1}.x_1+\ldots\ldots\ldots\ldots\ldots+a_{in}.x_n,$$

$$x_1€\ (S_{x1})\ \alpha\ \ldots\ldots\ldots\ x_n€\ (S_{xn})\ \alpha\}$$

In which since all the a_{ij}'s are real numbers, their members identically to be1. Finally the output Y is computed by:

$$Y=\frac{\sum_{i=1}^{N}\mu_{Y,i}(y_i)\cdot y_i}{\sum_{i=1}^{N}\mu_{Y,i}(y_i)}=\sum_{i=1}^{N}\beta i.Yi$$

Where $\beta_i=\frac{\mu_{Y,i}(y_i)}{\sum_{i=1}^{N}\mu_{Y,i}(y_i)}$

With the help of above fuzzy membership function, we can calculate the fuzzy mean (Y) for specific wear rate of chromium coating with applied load and sliding velocity. Optimization of input parameters of the wear test at Pin on Disc Tribometer grey relational analysis can be used to achieve better quality of minimized wear loss and fictional force. It is used for solving the complicated interrelationship among the multiple responses. This analysis helps to remove poor, incomplete, and uncertain data which are designated as "Grey" data. Fuzzy logic Concept is then incorporated into this multivariate system so as to get an improved grey-fuzzy grade. The grey fuzzy grades were calculated using MATLAB. The fuzzy inference system so developed incorporated triangular membership function and IF…THEN rules were formulated to fuzzify the grey relational coefficient of each grade is calculated.

Simplest way of measuring wear is based on measuring the weight loss in each track or after a test. It is direct method but one should be careful in taking the measurement. Wear volume can be calculated from equation based on the wear scar shape. The wear depth is considered a reliable way to assessing weight loss. A wear coefficient is often used to categories resistance to contact wear. It is used to calculate the specific wear rate or wear coefficient (K).

$$\text{Specific Wear Rate}=\frac{\text{Wear Volume}}{\text{Load}\times\text{Sliding Diastance}}$$

$$\text{Wear Volume}=\text{Wear Depth (Average value of Wear)}\times\text{Area Of Pin}$$

Diameter of Pin in all the experiment=6mm

Area of the Pin=28.2857 mm^2

Where wear volume in mm^3 and load in Newton and sliding distance in meter and wear volume can be calculated by above expression. Above wear coefficient was suggested by Holmberg and Matthews as a standard for wear test.

When two surfaces comes in relative motion to one another the wear is produced by generating third body that is also known as debris and Specific wear rate is calculated by Holmberg and Matthews's equation known as wear coefficient denoted sometimes by K. A common used equation to compute the wear rate is:

$$V_i=k_i\ F\ s$$

Where F is the normal load, s the sliding distance, V_i the wear volume and k_i the specific wear rate coefficient. Index i identifies the surface considered. The k-value is given in m^3/Nm or m^2/N, sometimes in mm^3/Nm. From design view the wear displacement h is more convenient than V. With $h_i = V_i / A$, the contact pressure p=F/A where A is the area subjected to wear then:

$$h_i = k_i \, p \, s$$

The sliding distance s can be replaced by s=v.t where v is the mean value for the slide rate and t the running time. Because the k-value depends just like the friction coefficient on a lot of parameters this factor is to be find experimentally. Specific wear rate variation (mm^3/Nm) with respect to load is plotted in Figue.3 (a) and 3(b).

For more than one fuzzy values, apply IF-THEN rule as below:
If applied load' is 'Low' then specific wear is Low (0.00004)
If applied load' is moderate' then specific wear is moderate (0.00003)
If applied load' is maximum then specific wear is excellent (0.00002)

CASE I:

In this case 1, specific wear rate is taken as output and applied load and sliding velocity is taken as input with constant sliding distance of 2500m.

Input: S = {50, 60, 70}
Output: I = {0.00004, 0.00003, 0.00002}

CASE II:

In this case II, specific wear rate is taken as output and applied load and sliding velocity is taken as input with constant sliding distance of 2500m.

Input: S = {80, 90, 100}
Output: I = {0.00006, 0.00004, 0.00003}

Figure 3(a) shows the effects of load and sliding velocity on wear volume of the coating Disc (CrN) and the pin (cylinder liner). It is clearly seen that the specific wear rate of coating is higher in the first run of the case-I wear conditions. The wear volumes coatings were in the range of 0.00004 to 0.000002 mm^3, depending on load and velocity. While the load is increases from 50 to 70 N, and sliding velocity from 1m/s to 3m/s wear volume is showing a considerable decrement. But it can be clearly observed that in Figure-3(b) that while load is increasing from 50N to 80N at a constant sliding velocity of 1m/s the specific wear rate is increasing. That is also mentioned in the above case-I and case-II.

The wear process of CrN coating appears to be tribo-oxidation wear, in agreement with previous results reported from different hard nitride coating [15–18]. According to the analysis of coating, with release of N2, if nitrides oxidize to completion in contact with chromium at room temperature. However, from EDS analysis of the wear track shown in Table-2, confirms the oxidation during wear tests and oxide debris in oxidizing environments. Presence of oxygen is confirmed by EDS analysis of wear track. It is done by Energy dispersive spectroscopy (EDS) which is showing that oxygen content is in considerable amount of 14.29 % by weight that is enough to form an oxide layer at surface and causes to occur oxidation wear. Some impurity EDS but that is negligible. While the main constituent's chromium (54.88% by weight) and iron (30.05%) is being confirmed by Table-2. If silicon is present in considerable amount it worked as lubrication as reported by some authors discussed below. This may be attributed to the strong chromium–oxygen interaction which inhibits the phase formation of different structure. A fluctuation of the friction force can be also found during the test run at 50N and 80N, which may be related to the ejection behavior of wear debris from the tribo-contact area. The thermo-mechanical interactions at the point of contact or tribo-contact area results in the partial chemical reaction of these wear debris with oxygen in the atmosphere. Discontinuous transferred layers consisting of the constituents from both coating material and oxides are generated on wear track. The presence of these wear oxides will change the chemical composition, morphology and phase structure of the transferred layers on the coupled ball, and further influence the friction force and the material wear removal.

Table-2. EDS Analysis of Wear Track of Coating

Element	Net Count	Weight%	Weight%(Error)	Atom%	Atom%(Error)
Oxygen	2384	14.29	± 0.55	35.55	± 1.36
Silicon	141	0.69	± 0.13	0.98	± 0.19
Chromium	3467	54.88	± 1.58	42.02	± 1.21
Iron	1194	30.05	± 1.36	21.42	± 0.97
Molybdenum	12	0.09	± 0.32	0.04	± 0.13
Total		100.0			

Specific wear rate of chrome coating is increasing by increase the load at the same sliding velocity and while increasing both load and sliding velocity successively the specific wear rate is decreasing, there is a large reduction in the specific wear rate of coated sample when compared to uncoated sample at dry conditions. This was also reported by A. L. Bandeira *et al.* that wear and friction of Chromium coated sample in engine oil lubrication had a much lower value comparable to wear and friction of coated sample in dry condition and uncoated sample also. It is due to the tribo-chemical reaction, in which chromium reacts and forms a layer of oxides [19, 20].

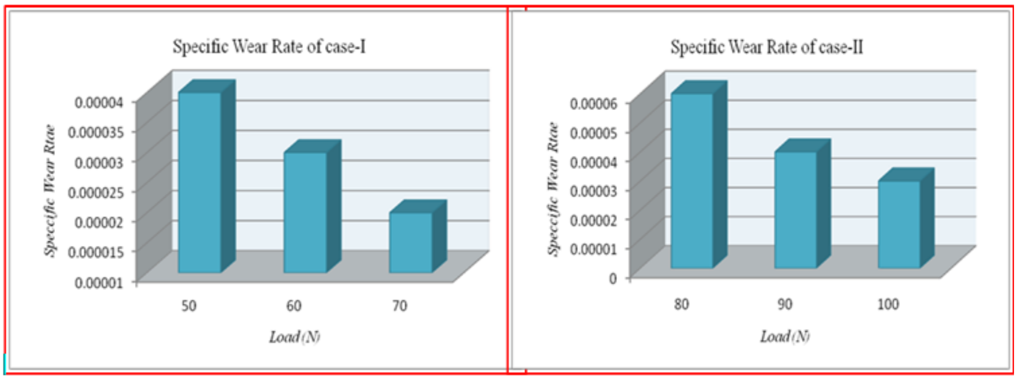

Figure 3. (a) Specific Wear Rate with Increasing Load and Sliding Velocity For Case-I, (b) Specific Wear Rate with Increasing Load and Sliding Velocity for Case-II

4. Conclusions

In this study new approach fuzzy logic reasoning is used for evaluation of wear behaviour of chromium nitride coating has been proposed. Selected parameters influence the wear behaviour, sliding distance is influencing factor followed by sliding velocity and load. This methodology provides a logical approach as compared to other conventional techniques it is a non-destructive testing technique used to evaluate the coating strength. Specific wear rate of chromium nitride coating is decreasing by increasing the load from 50to 70N at sliding velocity from 1m/s to 3m/s, while at a constant sliding velocity when load is increasing specific wear rate is increasing.

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