Wear Model of Dry Sintered Bearing Material by Dimensional Analysis

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Abstract : The aim of this research was to investigate and analyze the wear of sintered dry bearing material. A mathematical model considering lump parameters was developed using dimensional analysis technique and expressed in terms of the operating parameters and constructional parameter of the material. Tribo-experiments were conducted on a dedicated test set-up which simulates the actual contact conditions as practiced in industry. This paper highlighted the wear characteristics of a sintered dry bearing material under sliding contact conditions to anticipate possible wear regime.

Keywords: Wear model, Dimensional analysis, sintered material, Dimensional analysis, wear

I. INTRODUCTION

The wear of material depend on different parameters in tribo-system and these parameters could be linked with a group of parameters such as process parameters, constructional parameters, interacting bodies and the working environment etc. [1].In a tribo-system wear is not an intrinsic material property; rather it depends on operating variables and/or physical quantities and the contact conditions. Bellow et al. [2], Kar et al [3] Rhee et al [4] and Viswanath et al [7] have developed various forms of equations/relationships for the wear of plastic materials. Few authors used different type of mathematical model to prove wear and friction equations or relationships [8, 9, 10, 11, and 12]. All these models have expressed wear volume as a function of either operating variables such as speed, pressure and duration or some properties of material. Various models representing wear volume as a function of either operating variables or material properties were developed but they are limited to plastic/polymer materials and lubrication condition/lubricants additives only[13, 14, 15, 16]. And the friction and wear characteristics of different material were evaluated with the help of Pin-on-disc and four ball testers under sliding conditions.

The aim of the present work is to investigate and analyze the wear of sintered bearing under dry condition with the help of simulated test condition. Various parameters like process parameters, constructional parameters and environmental parameters etc affect wear with increasing or decreasing effect. It becomes difficult to study all parameters at a time; therefore, authors felt that on forming lumped dimensionless parameters may be useful in estimating wear. Hence a mathematical model is developed with the help of a dimensional analysis. In order to study wear characteristics, a dedicated set-up is developed and dimensional wear values were measured on three dimensional co-ordinate measuring machine (CMM) having a least count of 0.1μm and thereby calculating volume of wear over contacting area of bearing.

II. DIMENSIONAL ANALYSIS MODEL

Dimensional analysis (DA) is a mathematical technique which makes use of the study of dimensions as an aid to the solution of problems. It is based on the hypothesis that the solution of the problem is expressible by means of a dimensionally homogeneous equation in terms of specified variables. The principal use of DA is to characterize a phenomenon in terms of the relationships among dimensionless variables which are fewer in number than the original physical variables and in turn reducing the complexity of experimental variables which affect a given phenomenon. There are many methods of DA, the authors tried to investigate the wear of bearing specimen made up of sintering material under dry condition. Using a dimensional analysis of Buckingham Π theorem method. As mentioned earlier, the operating parameters are Pressure (P), sliding speed (v), Time or test duration (T) and/or sliding distance. Constructional parameters are Hardness (H), Density (ρ), Specific heat capacity (Cp), Thermal conductivity of material (k) and Modulus of Elasticity (E). Wear rate (W) was measured as the main dependent variable.

The variables involved in this process are as W, P, v, T, Pc, Cp, k, H and E. The functional equation for wear (W) may be expressed as,

$$W = f\,(P, v, T, Pc, Cp, E, k, H) \qquad (2.1)$$

General form may be written as,

$$\psi\,(W, P, v, T, Pc, Cp, E, k, H) = C \qquad (2.2)$$

A set of variables with their dimensions taken for consideration are as follows (ref. Table-1).

Table 1. Variables under consideration

Variables	Symbol	SI Unit	Dimensions
Wear	W	Mm^3/Nm	$M^{-1} L^1 T^2 \theta^0$
Pressure	P	N/mm^2	$M^1 L^{-1} T^{-2} \theta^0$
Sliding speed	*v*	m/s	$M^0 L^1 T^{-1} \theta^0$
Time	T	Hrs	$M^0 L^0 T^1 \theta^0$
Compaction Pressure	Pc	N/mm^2	$M^1 L^{-1} T^{-2} \theta^0$
Specific heat capacity	Cp	KJ/KgK	$M^0 L^2 T^{-2} \theta^{-1}$
Modulus of Elasticity	E	N/m^2	$M^1 L^{-1} T^{-2} \theta^0$
Thermal conductivity	k	W/mK	$M^1 L^1 T^{-3} \theta^{-1}$
Hardness	H	N/mm^2	$M^1 L^{-1} T^{-2} \theta^0$

Thus the total number of variables are m = 9, and all the variables may be completely described by the four fundamental dimensions M-L-T- θ. Hence n = 4, there are (m-n) = 5 dimensionless π- terms, so that

$$\psi\ (\pi1, \pi2, \pi3, \pi4, \pi5) = C1 \qquad (2.3)$$

In order to form these π terms, there is need to choose repeating variables, and variables should be such that,

1. No two variables have the same dimensions.
2. They themselves do not form a dimensionless parameter.
3. None of them should be dimensionless.
4. All the fundamental dimensions are included collectively in them

And as far as possible the dependent variable should not be taken as a repeating variable as otherwise it will not be possible to obtain a explicit relationship. Since in this case n = 4, the repeating variables chosen are Pressure (P), sliding speed (v), thermal conductivity (k) and Time (T). By applying Buckingham's dimensional analysis,

$$\pi1 = W, P^{a1}, v^{b1}, T^{c1}, k^{d1} \qquad (2.4)$$

$$\pi\ 2 = Pc, P^{a2}, v^{b2}, T^{c2}, k^{d2} \qquad (2.5)$$

$$\pi\ 3 = H, P^{a3}, v^{b3}, T^{c3}, k^{d3} \qquad (2.6)$$

$$\pi\ 4 = E, P^{a4}, v^{b4}, T^{c4}, k^{d4} \qquad (2.7)$$

$$\pi\ 5 = Cp, P^{a5}, v^{b5}, T^{c5}, k^{d5} \qquad (2.8)$$

Substituting the proper dimensions for each variable in this exponential equation in M L T system.

$$\pi1 = M^0 L^0 T^0 \theta^0 = M^{-1} L^1 T^2 (M^1 L^{-1} T^{-2})^{a1} (L^1 T^{-1})^{b1} (T^1)^{c1} (M^1 L^1 T^{-3} \theta^{-1})^{d1} \qquad (2.9)$$

Equating the components of M, L, T and θ
For M: -1+ a1 + d1 = 0
For L: 1 - a1 + b1 + d1 = 0
For T: 2 - 2a1 – b1 + c1 – 3d1 = 0
For θ: d1 = 0
From this, a1 = 1, b1 = 0, c1 = 0 and d1 = 0
Hence,

$$\pi 1 = WP \quad (2.10)$$

Similarly, solving for $\pi 2$, $\pi 3$, $\pi 3$ and $\pi 5$,

$$\pi 2 = Pc/P \quad (2.11)$$

$$\pi 3 = H/P \quad (2.12)$$

$$\pi 4 = E/P \quad (2.13)$$

$$\pi 5 = (Cp\ P\ T)/k \quad (2.14)$$

Now, expressing

$\pi 1 = \psi\ (\pi 2, \pi 3, \pi 4, \pi 5) = C1$

$$WP = \psi\ (Pc/P, H/P, E/P, (Cp\ P\ T)/k) \quad (2.15)$$

In order to obtain the final expression in a desired manner,
$\pi 1$ and $\pi 3$ can be replaced by a new term as,

$$\pi a = \pi 1 \times \pi 3 = WH \quad (2.16)$$

$\pi 4$ and $\pi 5$ can be replaced by a new term as,

$$\pi b = \pi 4 \times \pi 5 = ((T\ E\ Cp)/k) \quad (2.17)$$

And $\pi 2$ can be written as $1/\pi 2$,

$$\pi c = P/Pc \quad (2.18)$$

The physical significance of each group is explained as follows

WH - This group contains the wear rate as a dependent variable. It represents the significance of strength characteristic of the material representing anticipated mechanism of wear i.e. predominance of abrasiveness or adhesiveness.

((T E Cp) /k) - This group obtained by combining $\pi 4$ and $\pi 5$, which has duration of test as the operating variable. This group represents correlation between time and thermal properties.
P/Pc - This group represents homogeneity and porosity of material to withstand pressure due to loading.

Redefining Eq (2.15) by combining all the groups the following expression containing three dimensionless groups can be obtained:

$$WH = \psi\ ((T\ E\ Cp)/k, (P\ )/Pc) \quad (2.19)$$

For a more generalized relationship, Eq (19) is rewritten with exponents α and β, is expressed as

$$WH \propto\ ((T\ E\ Cp)/k)^{\wedge}\alpha\ \ ((P\ )/Pc)^{\wedge}\beta \quad (2.20)$$

The above equation is written with Kw as a proportionality constant.

$$WH = K^{w}\ ((T\ E\ Cp)/k)^{\alpha}\ ((P\ )/Pc)^{\beta}(21) \quad (2.21)$$

The response (WH) is expressed in terms of operating variables such as Time (T) and Pressure (P) which were controlled during the experiments. The material properties such as hardness (H), modulus of elasticity (E), thermal conductivity (k), compaction pressure (Pc) and specific heat (Cp) were kept constant. The number of experiments were planned to evaluate the function by varying only one operating variable at a time. The undetermined function ψ is evaluated from the experiments and then the relationship is established between the main parameter (WH) and the variables influencing the wear under dry condition.

III. EXPERIMENTAL DETAILS

3.1 Machine – Dry Bearing Test Rig

In tribo-system of food processing industries and paper industries bearings should be clean, free from contamination and allowed to run in for long duration. Therefore, for investigating the wear characteristics of bearing material under dry condition, explicitly designed set-up is needed, which would have well defined simulated contact condition; the operational parameters should depict the industrial adopted scenario and tests should be performed as functions of varied parameters as load, velocity, time or sliding distance.

In order to fulfill above requirements, authors developed a dedicated test set up called dry bearing test rig shown in Fig.1. In regard to operation of the test rig, firstly, the test bearing is mounted on the shaft after loosening the loading arm and removal of pedestal block. Once the bearing is mounted, radial load is applied through the loading arm at various speeds. As motor is freely supported in pedestal blocks, the friction which is being exerted at the bearing interface rotates the motor accordingly. This tilt of motor is measured by means of friction arm mounted on motor and the force exerted is obtained by force sensor attached to friction arm. The digital output of the frictional force on motor is noted at control panel from which the frictional force could be calculated at bearing interface. Temperature measurement is made by providing a hole in support bush and using a laser temperature gun device. This test rig provides friction and wear study by simulating the conditions in actual practice i.e. using test bearing mounted on a motor shaft enclosed in support bush. Hence, simulated study of friction and wear of bearings can be performed and the results give closeness towards the true values of tribological characteristics of bearing. All the operating parameters and yield value can be recorded digitally in a control panel. After running at required time a wear of bearing was measured using three dimensional co-ordinate measuring machine.

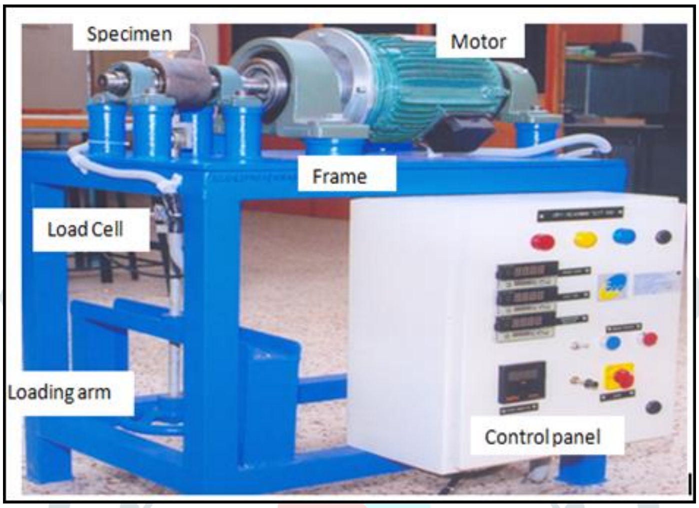

Fig.1. Dry Bearing Test rig

3.2 Materials

A material selected for experimentation was iron based sintered material with bearing specimen as internal diameter 50mm, length 70mm and outer diameter as 70mm. The description of chemical composition and properties of material is shown in table 2.

Table 2: Composition and Properties of material

Material	Plain iron based sintered bearing
% Fe	99
% Cu	1
Specific heat capacity (Cp) KJ/Kg k	0.52
Thermal conductivity (k) W/mk	38
Density (ρ) g/cm³	6.30-6.32
Hardness (VHN)	118

IV. EXPERIMENTAL RESULTS

The slope of the plot (WH) against the operating variables determines the exponents for an equation (2.21) obtained by dimensional analysis. The varying parameters values taken into consideration are time (T) of (8 hrs to 16 hrs) and pressure (P) of (2 N/mm2 to 6 N/mm2) and the constant parameters are specific heat capacity (Cp) as 0.52 KJ/Kg °K, thermal conductivity (k) as 38 W/m °K, hardness (H) as 118 N/mm^2 and Modulus of elasticity (E) as 210 x 103 N/mm^2. The tribological experiments were performed on the test rig

Table 3. Experimental results

Sr No	$\frac{T\,E\,Cp}{k}$	$\frac{P}{Pc}$	Wear (mm^3/Nm)	WH	K_w
1	82.76E9	2.5E-3	2.88E-6	3.40E-7	0.643E-7
2	124.12E9		3.02E-6	2.37E-7	0.450E-7
3	165.52E9		3.19E-6	1.88E-7	0.358E-7
4	82.76E9	5E-3	1.49E-6	1.76E-7	0.417E-7
5	124.12E9		1.57E-6	1.24E-7	0.295E-7
6	165.52E9		1.66E-6	0.98E-7	0.234E-7
7	82.76E9	7.5E-3	1.05E-6	1.24E-7	0.335E-7
8	124.12E9		1.09E-6	0.86E-7	0.233E-7
9	165.52E9		1.16E-6	0.68E-7	0.180E-7

V. DERIVATION OF EXPONENTS FOR WEAR EQUATION

The graphs for (WH) verses (TECp/k) and (P/Pc) were plotted as shown in Fig 2. and Fig. 3. respectively. The mean slopes of the straight lines were the exponents used in the model.
The mean slopes of the straight lines were the exponents used in the model. The wear equation is written in the following for

$$WH = K_w \left((T\,E\,Cp)/k\right)^{(-0.011)} \left((P\ )/Pc\right)^{(-0.324)} \qquad (5.22)$$

Where, K_w is 3.492 x 10⁻8

Hence, the above equation can be written as

$$WH = 〖3.492 \times 10〗^{(-8)} \left((T\,E\,Cp)/k\right)^{(-0.011)} \left((P)/Pc\right)^{(-0.324)} \qquad (5.23)$$

Using hardness of material 118 VHN, the final equation can be written as under:

$$W = 〖3.492 \times 10〗^{(-8)} /H \left((T\,E\,Cp)/k\right)^{(-0.011)} (P/Pc)^{(-0.324)} \qquad (5.24)$$

$$W = 〖3.492 \times 10〗^{(-8)} /118 \left((T\,E\,Cp)/k\right)^{(-0.011)} (P/Pc)^{(-0.324)} \qquad (5.25)$$

$$W = 2.9593 \times 〖10〗^{(-10)} \left((T\,E\,Cp)/k\right)^{(-0.011)} (P/Pc)^{(-0.324)} \qquad (5.26)$$

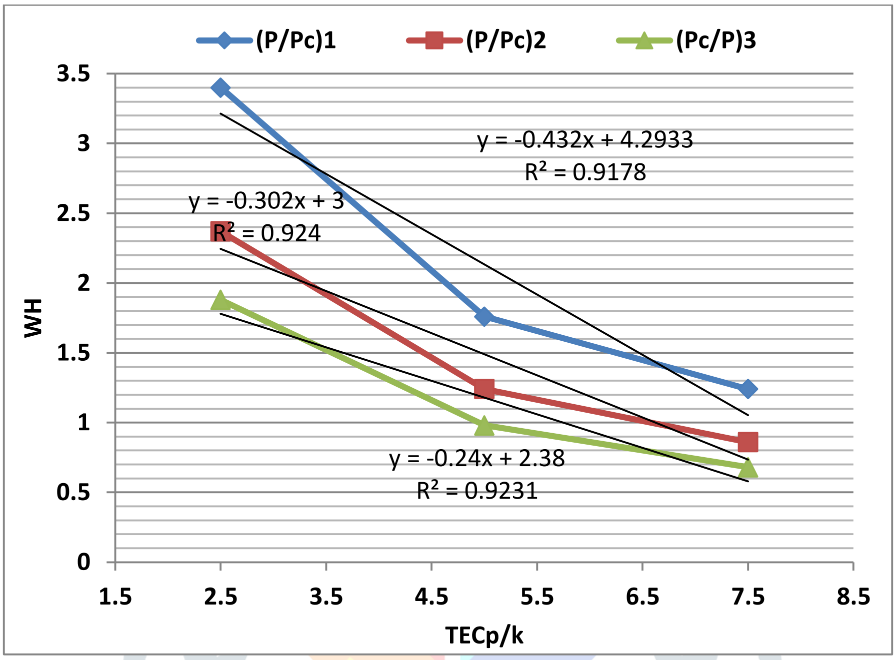

Fig. 2 (WH) v/s (TECp/k)

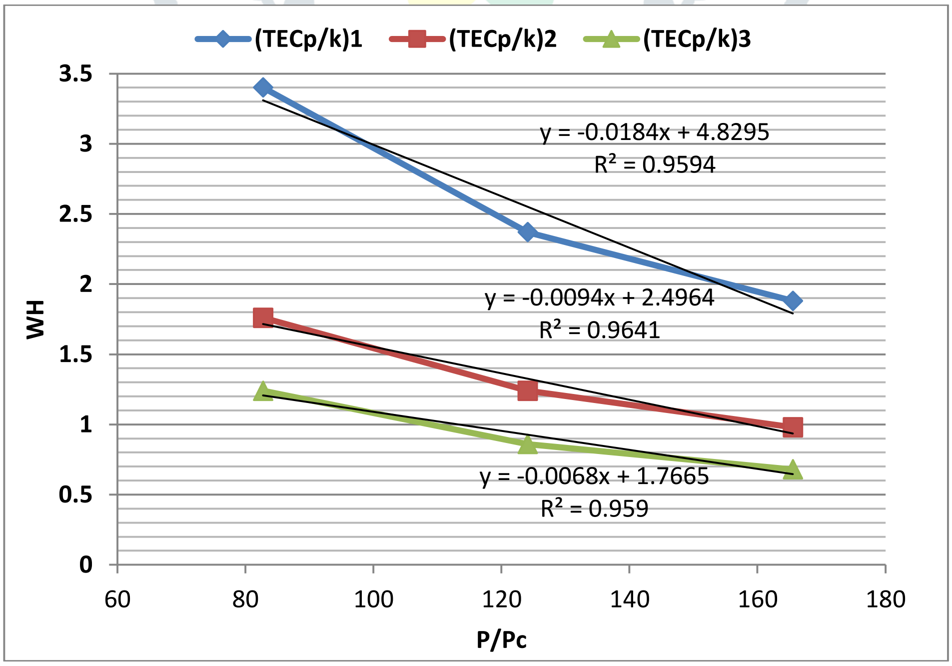

Fig. 3 (WH) v/s (P/Pc)

VI. CONCLUSIONS

This study suggested an approach to estimate the wear of sintered bearing material under sliding contact. Experiments were conducted on a dedicated test set up, developed by authors, which depict simulated industrial conditions. A mathematical model considering lump parameters was developed using dimensional analysis technique. From the study, it could be concluded that ratio of pressure emanating from load and compaction pressure plays a dominant role in dictating wear. However, strength and thermal properties of material did not show high significance on wear under experimental condition. Finally equation (5.26) gives a good and quick estimate of wear under experimental condition as outlined.

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