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Theoretical Computation of Wear By FEM

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Abstract* - Wear plays a very important role, whileinmotion with respect to each other. It is dependent on a various number of operating parameters. The major concern of industry is to know wear depth of the component (pin on disc),by minimizing the experiments, operational cost and to know which combination of parameters such as diameter of pin, applied load, rotational speed, pin material provides the minimum optimum value of wear amongstAluminum 2024-T4, Polyamide and Steel.Usually, wear coefficient is considered to be the significant parameter forcalculating wear. However, applied load also become an important parameter because they are helpful to find out the contact pressure at each contact node. This paper examines both wear coefficient and contact pressure induced by the model to obtain more consistent results.The major concern of the work is to know the theoretical computation of wear by using Archard's equation of wear with the aid of FEM and validates the results with the literature. The required geometry of pin on disc model is made by using the modelling software SOLID EDGE ST7. FEM software ANSYS 15.0 has been used for the contact pressure determination. The required programming for calculating the wear depth is prepared in C++. To obtain the minimum optimum value of wear,design of experiment is prepared by using Taguchi Method with the aid of MINITAB 17 Software.

Keywords: "Archard's Equation; Solid Edge ST7; Ansys15.0; C++;Minitab 17".

I. INTRODUCTION

Mechanical systems employ mechanisms that are used to transformone type of motion into another. These systems compriseof connections such as joints where two components of the system establish contact and are in relative motion while in operation. Depending on the kinematics of the mechanism, either of several contact conditions may exist at the connection. One particular contact conditions that is widely encountered is the sliding contacts.Wear phenomena are closelyrelatedto frictional processes. Friction forces are generally the result of two main physical processes: shearing and ploughing. If solid surfaces in relative motion and are not separated in some way, wear can be expected. Lubricants are used to separate contacting surfaces in relative motion and thus to reduce wear.Here the attentionis on wear resulting from direct solid to solid contact. Wear phenomena are deeplyinfluenced by the fact that most engineering surfaces are rough.

The material for pin on disc model available in literatureis EN 31 steel, Nylon polymer and steel for disc, and material for pin is Aluminum 2024-T4, Polyamide and steel. Each and every material is provided the material properties for the ease of work.The wear process can be modeled and simulated, with some restrictions. By knowing the workingwear process, or how to model the wear process, it is quite easy to predict wear. Usually, wear coefficient is considered to be the significant parameter to calculating the wear. However, applied load also become an important parameter because they are helpful to find out the contact pressure at each contact node.

Earlier, many wear simulation studies were undertaken to simulate pin on disc model by using Archard's equation [1] which are unable to simulate wear without getting the value of wear coefficient until performing experiment. Ohmae and Tsukizoe [2] have studied wear process of pure aluminium by using a finite element elastic-plastic analytical computer program. Yielding of the material introduced by sliding and a heavily deformed region originated below the surface. Void nucleation and crack propagation were simulated with a large- scale computer. A difference between adhesive wear and delamination wear was discussed in terms of the results of the finite element method calculations. Lim and Ashby [3] have proposed a diagram which shows the rate and the regime of dominance of each of a number of mechanisms of dry wear (delamination, mild and severe oxidation, melting, seizure, etc.) are constructed empirically and by Modelling. The method is applied to steels, and has wider application as a way of classifying and ordering wear data. Podra and Andersson[4]have developed surface topography and used to calculate wear in conical spinning contacts both numericallyand with FEM, using the commercial software Ansys15.0. The model used is based on the linear wear law and the Abbott curve linearisation. In wear simulations, Euler integration scheme was used.

Podra and Andersson [5] furtherstudied the wear simulation approach using Ansys software. A modeling and simulation procedure was proposed with the linear wear law and the Euler integration scheme. A spherical pin on disc un-lubricated steel contact was compared with both experimental and with simulated data, and the Lim and Ashby wear map was used to identify the wear mechanism.It was shown that the FEA wear simulation results of a given geometry and loading can be treated on the basis of wear coefficient-sliding distance change equivalence. The finite element software Ansys was well suited for the solving of contact problems as well as the wear simulation. Hegadekatte et.al [6]studied wear simulation based on Archard's wear law. In their study wear is calculated and then integrated over the sliding distance using the Euler integration scheme. The wear simulation approach works in a loop and performs a series of static FE-simulations with updated surface profiles to get a realistic contact pressure distribution on the mating surfaces. This approach can simulate wear for both two-dimensional and three dimensional surface topologies.

Zmitrowicz [7] studied wear in various patterns such as abrasion, fatigue, ploughing, erosion and cavitation. The results of abrasive wear are identified as irreversible changes. The profile of model after wear is a useful measure of the removed material. The wear depth can be predicted with the help of wear laws. In this study also investigated thatconstitutive equations of anisotropic wear are additions of the Archard law of wear. Hegadekatte et.al [8] presented a veryproficient,incremental implementation of Archard's wear model on global scale for pin and disc wear in a pin on disctribometer.The identified wear model is employed in a finite element based tool for 3D wear simulation and the results compare with that from the global wear Modelling scheme.The results from the model are in good agreement and compatible with experimental results. Hegadekatte et.al [9] studied computationally efficient incremental implementation of Archard's wear model on the global scale for modellingsliding and slipping wear. The fast simplistic numerical tool can be used to recognize the wear coefficient from pin-on-disc experimental data and also to predict the wear depths within a limited range of parameter variation. Further, this methodenables study the effect of friction coefficient into the wear model and also to modelled wear lubricated experiments. A similar tool is offeredto model wear due to a defined slip in a twin-disc tribometer.

Baby and Jayadevan [10]developed a finite element numerical model specifically for sliding contact wear in aluminium. The model re-creates the dry sliding wear similar to that observed on a pin on disc tribometer setup. The method implemented is referred to as incremental wear modelling. It combines FEM with fundamental wear equationsto forecast wear heights.Mesh validation studies were carried out to validate the contact model. The wear values obtained from the script are reasonably close to that predicted by the fundamental wear equation and that obtained from the experiments.Prabhu et.al [11]predicted wear on sliding surfaces in the advancestage which results in the increase of durability of the components. The wear for a polymer-polymer sliding surface contact in dry condition can be obtained by making simulation. There are two inputs required for determining the wear volume loss over its usage time. One is the nodal pressure value at the contact area for small sliding steps which can be calculated by subjecting the geometrical model to the finite element analysis. Another one is the friction coefficient which can be attained by custom designed experiments. For the calculation of friction coefficient, prototype to be subjected to unlubricated pin-on-disc experimental setup. The wear rate can be calculated and showed by plotting graph between pressure and cycles.

The current theoretical work computes wear of different materials by adopting the commonly used wear coefficient and validates the simulated results with the published work. The study further examines, various combination of parameters which includes diameter of pin, applied load, rotational speed and pin material for wear minimization using optimum parametric values for a large variety of materials which includes ferrous material, non-ferrous material and polymers. The procedure uses Taguchi method for the design of experiments. This simulation approach is quite useful for predicting wear because, it eliminates cost of experimentation. The contact pressure used in theoretical computation of wear has been calculated using Ansys.

1.1 Wear model

The wear is simulated using Archard equation. Furthermore the current study of wear model assumes linearity; i.e. wear is directly proportional to the contact pressure. The most oftenused model is based on the Archard's wear law [1]. Archard's equation for sliding wear is normally expressed as:

$$\frac{V}{S} = k\frac{Fn}{H} \tag{1}$$

Where V is the wear volume, S is the sliding distance, F_n is the normal load, H is the hardness of the worn surface and k is the dimensionless wear coefficient. In order to simulate the growth of the mating surface profiles with wear cycles, it is essential to determine the wear depth at each contact node of the finite element model. Therefore, small apparent contact area, ΔA, the increment of wear depth, dh^W, linked with anincrement of small sliding distance, ds, is determined. This can be obtained by applying (1) locally to the area ΔA and for the increment of sliding distance, ds;

$$\frac{dV}{dS} = k\frac{Fn}{H} \tag{2}$$

Then, dividing both sides by ΔA, the following equation becomes;

$$\frac{dV}{dS.\Delta A} = k\frac{Fn}{H.\Delta A} \qquad (3)$$

The $F_n/\Delta A$ term is the local contact pressure, P, while $dV/\Delta A$ is the required increment of local wear depth, dh^W. The following equation is thus obtained for the prediction of the increment of local wear depth;

$$\frac{dh^w}{dS} = k_{D.}P \qquad (4)$$

Where the quantity k/H is replaced here by k_D, which is dimensional wear coefficient. Thus, the total wear depth h^W of every element between the contact surfaces could be formulated as;

$$h^W = k_D \times S \times P(5)$$

Where h^W is the wear depth in mm, k_D is the dimensional wear coefficient in Pa^{-1}, P is the contact pressure in Pa and S is the sliding distance in mm. This wear model is widely used to calculate wear. Current study of wear prediction adopted wear coefficient (k_D) from the literature. The nodal pressure in the contact region and sliding distance S can be determined from the rotational speed of the disk and time that the disk has rotated. Ultimately, calculations of wear depth/height at each of the contact surface nodes in the contact model by using Archard's wear equation.

II. METHODOLOGY

2.1 Solid Modelling

The three dimensional geometry of the required pin on disc model is made by using the modelling software Solid Edge ST7.First each partis prepared separately in the modelling software with the aid of main menu. From main menu the 'part design' option is selected. Then select the required plane for modelling, the first part is prepared by using extrude command called disc.The disc material used in the current study is EN 31 steel, Nylon polymer and steel. It has a diameter of 165mm and is 8mm thickness.The same approach is followed for making the otherpart of the model called pin.The pin material is made up of Aluminum 2024-T4, Polyamide and steel. The pin ismodelled for cylindrical shapeis 6mm, 12mm and 10mm diameter respectively.

Table 1 Mechanical properties of pin and disc materials

SET 1				SET 2					SET 3			
COMPONENT	MATERIAL	(Kg/m^3) DENSITY	TENSILE STRENGTH (MPa)	COMPONENT	MATERIAL	POISSON RATIO	(GPa) ELASTIC MODULI	VICKER HARDNESS(GPa)	COMPONENT	MATERIAL	(Kg/m^3) DENSITY	POISSON RATIO
Pin	Polyamide	1490	236	Pin	Steel	0.3	210	3	Pin	Aluminium 2024-T4	2785	0.3
Disc	Nylon	1400	172	Disc	Steel	0.3	210	4.6	Disc	EN 31 Steel	7850	0.3

For assembling these both parts, the main menu of the software assembly tab is used. Then select the 'existing component' option and click on the 'product' label. Then the required parts of the assembly are opened in order from disc and pin.The following mechanical properties of pin and disc materials are summarized in Table 1.

With the help of 'offset' option the pin is set into the center portion of the disc. Then use the 'contact constraint' option to make them in contact. Then the required assembly is obtained as shown in the Figure1.

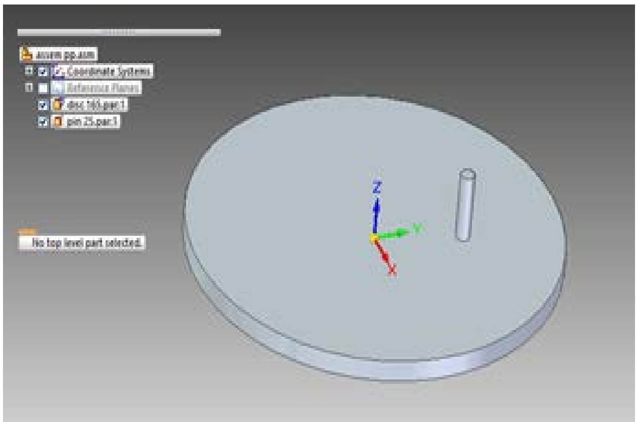


Figure1 3Dimensional view of Assembly

2.2 Finite Element Procedure

2.2.1 Discretisation

While making wear predictions the finite element method has to consider the exact variation of contact pressure with the effect of applied load on pin. The engineering simulation software Ansys Workbench15.0 is used for the current work to calculate pressure distribution at each contact node. The three-dimensional required model is prepared by using the Solid Edge ST7 software is alteredinto ‘igs’ then it is opened in the Ansys workbench 15.0. Open ‘Static structural’ and then click on the ‘Link to geometry file’ and then browse, select the required model in ‘igs’ format. Click on ‘new simulation’ option. The required materials are available in the software library.

The connection is requiredbetween the parts of the model. Between the pin and disc, frictional connections is provided, value of co-efficient of friction as per literature [5,10 and 11]and it is applied in between thebottom face of the pin topand face of the disc.Then generate mesh of the require geometry. Provide a default element size of nodes and elements to the entire model.Ansys Workbench supports both rigid to flexible, flexible to flexible and surface-to-surface contact elements. These contact elements use a “target surface” and a “contact surface” to form a contact pair. In general, when a soft material comes in contact with a hard material, the problem may be assumed to be flexible to flexible.

In current work the elements selected by the Ansys tool areconta174, target170 and solid 186.The target surface is identified with eithertarget170 or target169 (for 2-D and 3-D, respectively).The contact surface is identified with elements conta171, conta172, conta173, and conta174. The solid 186 is a higher order 3 dimensional 20- node solid element that shows quadratic displacement behavior. The meshed view of the model is given in the Figure2.

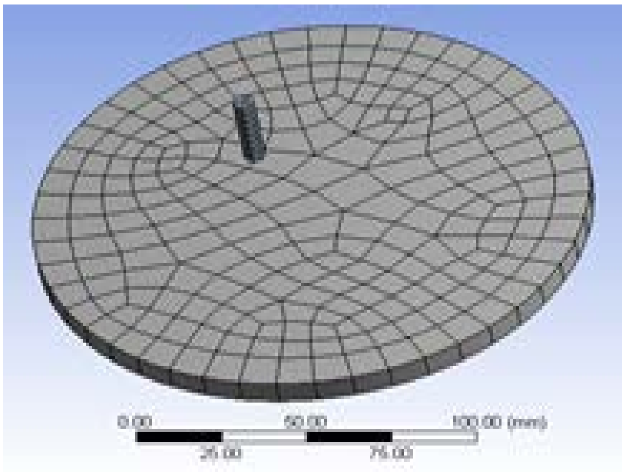


Figure 2Meshed view of pin on disc model

2.2.2Boundary Conditions

The model pin on disc in Figure 3 is clearly defined the boundary conditions. The load is provided at the upper face of the pini.e. in z direction, it means that pin is free to move in z direction,movementin the x and y direction of the pin is detained, so given the value as zero. At the same time displacement in the x and y direction of the disc is remain free for allowing the movement of disc only in the x and y direction.But z direction displacement is detained, so given the value as zero. The load which is applied at the top of the pin and rotational velocity of disc is provided as per Ref [5, 10 and11].

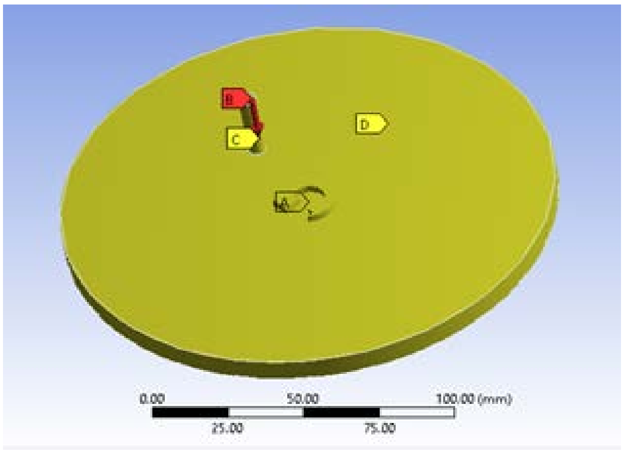


Figure 3 Boundary condition and load of the model

2.2.3Solution Procedure

The ANSYS solver computes the nodal contact pressure, which is used to obtain sliding contact wear in Aluminium2024-T4, Polyamide and steel. For this study,wear coefficient (k_D) for the contact pair, the nodal pressure in the mating region determine the contact pressure and sliding distance S. The calculation of wear depth/height at each of the contact surface nodes in the contact model by using Archard’s wear equation (based on contact pressure) is determined using a code developed in C++.The process is repeated in a loop for small sliding distances until the maximum total sliding distance (100m) is reached. This value in the work has been taken from Ref [8].

The results predicted by using the incremental wear Modelling technique are in reasonable agreement with the one that were predicted from Archard’s wear equation. The results point out that proposed model for sliding contact wear inAluminium2024-T4, Polyamide and Steel material is reasonably satisfactorily.

The current incremental method of predicting wear is a macro-scale approach based on wear equation. Briefly, it consists of a number of iterations, where the first step is the use of finite element analysis software to find pressures. The second step is to find out the sliding distance by using the iteration Si+1=Si+ΔS, whereas ΔS is the interval of the sliding distance, i is the current wear increment number. The next step is use of Archard's wear equation to calculate contact nodal wear. The flow chart of how the incremental wear model works is shown below in the Figure 4.

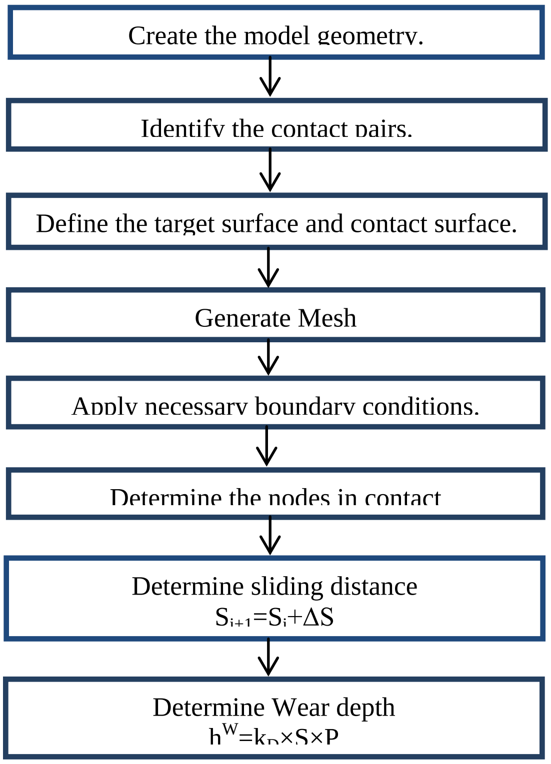


Figure 4 Modelling process

Table 2 Design of Experiments

PIN DIAMETER(mm)	ROTATIONAL SPEED (RPM)	LOAD (N)	MATERIAL
4	200	10	Polyamide
4	300	20	Aluminium
4	400	30	Steel
8	200	20	Steel
8	300	30	Polyamide
8	400	10	Aluminium
12	200	30	Aluminium
12	300	10	Steel
12	400	20	Polyamide

The simulation task based on the above flow diagram is used to know which combination of parameters (diameter of pin, applied load, rotational speed, and pin material) provide the minimum value of wear amongst Aluminum 2024-T4, Polyamide and Steel. The optimum combination of parameter isselected on the basis of the most commonly used geometrical and operating data parameter.Design of experiment to obtain minimum wear is prepared by using Taguchi Method with the aid of MINITAB 17 Software. From Table 2 it is quite clear that the minimum wear can be obtained on the basis of given set of experiments and combination of parameters.

III. RESULTS AND DISCUSSION

The results presented are obtained after the theoretical computation of wear by taking the value of wear coefficient [11] and validates the results with the experimental results[5,10 and11].

It is observed that the current predicted results are to be more consistent and closer as compare to experimental results. The main inputs to the programming code are:

(a) Maximum total sliding distance (b) Sliding distance(c)The wear coefficient was treated as a constantk_D=0.0001 (d) Contact pressure whereas the output is Wear depth/height(h^W) at each of the contact surface nodes.

Table 3 Results from the simulation in comparison with the experimental results [10]at three different loads.

LOAD (N)	SLIDING DISTANCE (mm)	EXPERIMENTAL WEAR DEPTH (µm)	SIMULATED WEAR DEPTH (µm)
21	1000	15	15.6
21	2000	19	29.4

Table 4 Results from the simulation in comparison with the experimental results [11] at six different loads.

LOAD (N)	SLIDING DISTANCE (mm)	EXPERIMENTAL WEAR DEPTH(µm)	SIMULATED WEAR DEPTH (µm)
4.9	1507	59.79	45.01
9.8	1507	100.6	85.51
14.7	1507	127.94	128.17
4.9	1758	30.98	30.5
9.8	1758	47.77	61.01
14.7	1758	81.51	91.66

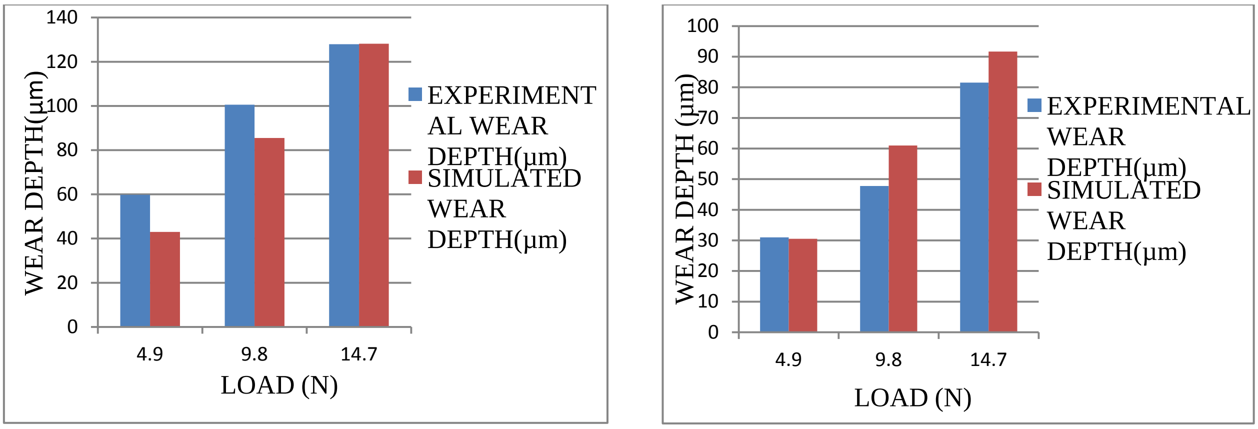
The current work did a good job of prediction wear depth. If an accurate value of kD is not used, then it would be difficult to predict wear.For the current work,assuming the linear wear law, the FEA wear simulation results can be treated on the basis of wear coefficient and sliding distance change equivalence.Table 3, 4 and 5 shows the results of wear depth as obtained from the simulation.It is clearfrom the result table that the wear depth is proportional to the applied load, it means that as the load increases the wear increases.

In this study, it is found that using adhesive wear model the value of wear coefficient kD can be adopted 0.0001.Further, it is also studied that the load, sliding speed and pin diameter affects the amount of wear depth.Incurrent study a comparatively softer cylindrical tipped pin sliding over a harder flat disc. For such a case it is assumed that most of the wear occurs on the pin and negligible wear on the disc.

Figures 5, 6shows the graph of wear depth versus the three different loads and Figure 7 shows the graph of wear depth versus sliding distance. It is clearly seen from these graphs that wear significantly increases when the load increases. It is also found from all the result figures that somewhere, the wear as compare to experiment results are very close or equal but somewhere not. It may be due to the possibilities of variation in pressure distribution in pin on disk model as compared to experimental performance. And other factor is the wear coefficient because the value of wear coefficient is constant in current work but in actual the surface conditions change continuously during the rubbing, influencing the actual wear procedure and the value of the wear coefficient also.

Table 5 Results from the simulation in comparison with the experimental results [5] at different sliding distance.

LOAD (N)	ROTATIONAL SPEED (RPM)	EXPERIMENTAL WEAR DEPTH(μm)	SIMULATED WEAR DEPTH(μm)
5	400	7	16
10	400	31	35.2
15	400	46	52.5
20	400	50	70.2
25	400	96	87.5
30	400	98	104.5



a) Wear at 1507mm sliding distance b) Wear at 1758mm sliding distance

Figure 5 Progress of wear over load for pin on disc in comparison with experimental results

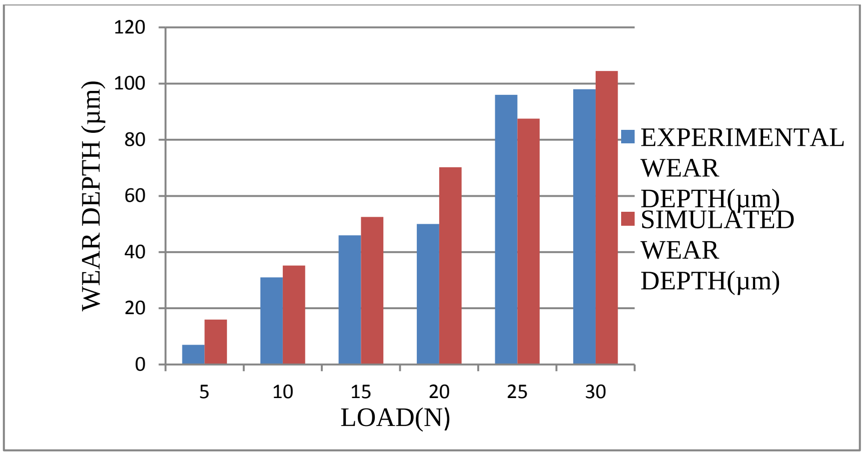


Figure 6 Progress of wear over load for pin on disc in comparison with experimental results

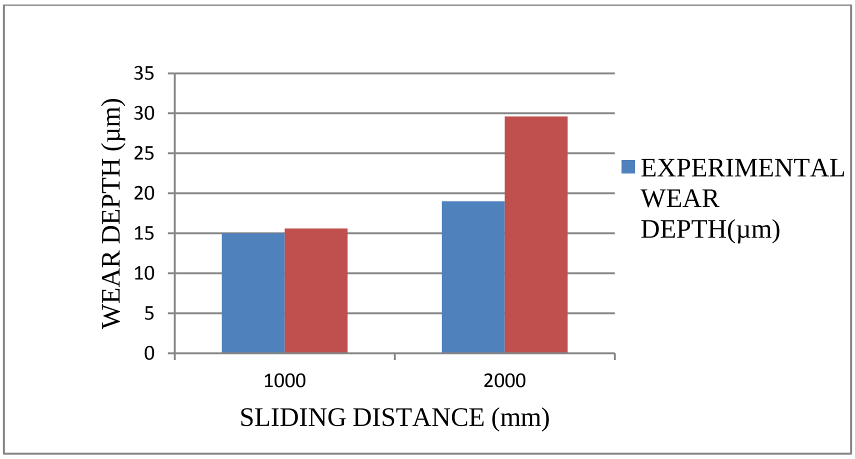


Figure 7 Progress of wear over sliding distance for pin on disc in comparison with experimental results

In order to determine the minimum value of wear,design of experiment(DOE) is prepared by using Taguchi Method with the aid of MINITAB 17 Software.The experiments are performed as per DOE and results are presented in Table 6.

Table 6 Simulated results on the basis of design of experiment

PIN DIAMETER(mm)	ROTATIONAL SPEED(RPM)	LOAD(N)	MATERIAL	WEAR DEPTH(µm)
4	200	10	Polyamide	79.6
4	300	20	Aluminium	159.2
4	400	30	Steel	238.6
8	200	20	Steel	39.8
8	300	30	Polyamide	59.6
8	400	10	Aluminium	19.9
12	200	30	Aluminium	26.5
12	300	10	Steel	8.8
12	400	20	Polyamide	15.1

It has been clearly seen from the Table 6 that theparameters with 12 mm diameter, 300 rpm rotational speed, 10 N load and pin material is steelgets the minimum optimum value of wear i.e. 8.8µm.

IV. CONCLUSIONS

The main issue faced in this theoretical computation of wear by using archard's equationis to identify the value of wear coefficient. In earlier studies, prediction of wear is dependent on the experiment, because wear coefficient k_D has to be calculated through experiment. The wear coefficient k_D is not an intrinsic material property but is also dependent on the operating condition. In this study, it is foundthat using adhesive wear model the value of wear coefficient k_D can be adopted 0.0001.Further, it is also studied that the load, sliding speed and pin diameter affects the amount of wear depth. The wear rate significantly increases when the load increases. On the other hand, as the diameter of pin increases, the wear depth decreases.

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