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RESEARCH

Effect of Lubricant Viscosity and Surface Roughness on Coefficient of Friction in Rolling Contact

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A B S T R A C T

The main objective of this paper is to investigate the effect of surface roughness and lubricant viscosity on coefficient of friction in silicon nitride- steel rolling contact. Two samples of silicon nitride with two different values of surface roughness were tested against steel counter face. The test was performed on four ball tester in presence of lubricant with two different values of viscosity. Taguchi technique a methodology in design of experiment implemented to plan the experimentation and same is utilized to evaluate the interacting effect of surface roughness and lubricant viscosity. Analysis of experimental results presents a strong interaction between surface roughness and lubricant viscosity on coefficient of friction in rolling contact.

1. INTRODUCTION

In the field of tribology study of friction and wear in rolling/sliding contact is always important for improving the performance of the components. Contact fatigue can be defined as kind of damage resulting from cyclic relative motion between surfaces. As a result component service life may be reduced and maintenance could increase in terms of inspection and repairs. The various engineering system affected by contact fatigue is long and stretches across aerospace systems, micromechanical systems, in roller bearings, cams, valves, rails and gear couplings etc. Contact fatigue produces a surface damage that is unique and well recognized. Numbers of parameters which are influencing the contact fatigue are contact pressure, material properties, lubricant properties, material roughness, amount of sliding or slip in the contact, microstructure, residual stress and inclusion size and nature.

Continuous development for modern engineering applications with development of devices for operating at extreme conditions needs some potential substitute for traditional material in rolling contact conditions, silicon nitride (Si_3N_4) based ceramics are good substitute for such conditions. The performance of ceramic material like silicon nitride (Si_3N_4) in rolling contact condition is advantages over steel material. Silicon nitride has unique tribological and physical properties like low mass density, low thermal expansion, high hardness, low thermal expansion and excellent chemical stability over broad range of temperature makes it suitable for high speed application in aerospace and high speed precision machine tools. Hybrids bearings containing silicon nitride balls with steel rings are finding application in high speed precision machine tool spindles and aerospace application and found to be advantages than conventional bearings. Due to low density of Si_3N_4 rolling elements, provides less centrifugal force on the raceway than steel rolling elements in hybrid bearings. Silicon nitride material retain is strength and corrosion resistance over very high temperature makes it suitable for application up to 500 ^{0}C in hybrid bearing and up to 1000 ^{0}C in all ceramic bearings.

J.F. Dill [1], in his work attempted to provide a tribological performance database of ceramic bearing materials in relation with standard bearing steels. The majority tests conducted were aimed for evaluating performance of ceramic/steel hybrid combinations in rolling contact fatigue. Hybrid precision ball bearings (with advanced ceramic balls as rolling elements, and steel inner and outer rings) are now extensively used in aerospace engineering and precision machine tools, because of the thermal resistance, corrosion resistance, low density, high elastic modulus and low friction properties of ceramic rolling elements [1]. But during practice, the rolling contact fatigue failure of steel raceway very often is the limiting factor in hybrid precision ball bearings compared to the failure of silicon nitride balls. The advanced ceramic rolling elements normally exhibit much better rolling contact fatigue performance. So the rolling contact fatigue life between ceramic/steel contacts is of great interest.

Surface asperities present on the rolling body affects all aspect of component during rolling conditions. Number of experimental and theoretical work has beed performed to investigate the effect on surface roughness adhesion and abrasion which occurs during friction and wear.

J.Kang *et al.* [2] investigated the silicon nitride bearing balls with different surface roughness values rolling against two types of steel balls with different surface roughness and hardness in fully lubricated condition. The results show that the composite surface roughness of silicon nitride/steel contact is most influential in rolling contact fatigue (RCF) life. The improved wear resistance and lifetime of hybrid bearings using Si_3N_4 rolling elements offer advantages in fuel economy and repair costs. Ceramic rolling elements are also non-magnetic and, unlike all-steel bearings, will not weld when exposed to extreme rotational speed, friction heat, or loss of lubricant during operation. David J. Mitchell *et al,* [3] performed rolling contact fatigue experiments on all-steel and hybrid Si_3N_4-M50 steel rolling bearing systems using particulate contaminated lubricants. The effects of contaminant composition and morphology on rolling contact fatigue and wear behavior were explored. The effects of bearing element material properties on fatigue and wear behavior were also examined. They found that rolling wear behavior is related to bearing component material configuration and the type of particulate contaminant present in the lubricant. Component and particulate material properties such as hardness and elastic modulus are found to affect rolling wear behavior. Jingling Zhou *et al.* [4] developed pure rolling fatigue test rig with three contact points for bearing balls and used to conduct rolling contact fatigue test on GCr_{15} steel balls and Si_3N_4 balls. They found that the fatigue life performance of Si_3N_4 was good in comparison to GCr_{15} steel and showing less temperature rise during operating. Wei Wang *et al.* [5] used sintered and reaction bonded silicon nitride (SRBSN) to study the surface machining effects on its rolling contact performance. Three types of surface with coarse, fine and conventional finishing conditions were examined. Flexure strength test and C-sphere shows increasing surface strength from coarse, fine to conventionally machined surface. Rolling contact fatigue lifetime increases from pre-cracked coarse, fine to conventional machining surface.

Many efforts are made to improve the performance of bearings like increasing the conformity of ball/raceway in order to reduce the Hertzian contact stresses [6]. Other parameters include the surface quality control and surface treatment of steel raceway. Hamilton *et al.* [7] are pioneer to consire the effect of surface roughness in the field of tribology. They developed theory of hydrodynamic lubrication between two surfaces considering effect of surface roughness. N.K. Myshskin *et al* [8] presented various methods for surface roughness analysis along with different surface roughness. They also presented theoretical and experimental problems occurring in tribology due to surface roughness. M. Gulzar *et al.* [9] investigated two grade oil different parameters on wear phenomenon of rough piston skirt. They incorporate flow factor method in tow dimensional 'Reaynolds' equation to model the effect of surface roughness characteristic on piston skirt elstohydronamics lubrication. Effect of surface roughness in steel-ceramic rolling contact is only evaluated by J. Kang *et.al.* [2]. The surface roughness parameters which are the most influential in rolling contact fatigue are therefore of great interest and concerns of both industry and academia. Here in this paper attempt has been made to evaluate the effect of surface roughness and lubricant viscosity on frictional torque and co-efficient of friction in rolling contact between Si_3N_4 - steel ball using four ball tester.

2. EXPERIMENTAL INVESTIGATION

2.1 Silicon Nitride test samples

Two kinds of HIPed samples of Silicon nitride of two different grades were purchased from Jayshree Speheres Ltd., Pune. Samples designated as A and B with surface roughness value (*R*a) of 0.025 μm and 0.05 μm respectively. Geometric and property description of samples is given in Table 1.

Table 1. Geometric and material properties of HIPed samples of Si_3N_4.

Sample	Dia. (mm)	Surface roughness Ra (μm)	Density (Kg/mm³)
A	12.7	0.025	3220
B	12.7	0.05	3220

2.2 Steel Test samples

In this study steel test samples were supplied by Ducom Instruments Pvt. Ltd, Banglore. Material 52100 AISI bearing steel was used for RCF test along with Silicon Nitride. The geometric and material property description of steel sample is given in Table 2.

Table 2. Geometric and material properties of Steel samples.

Property	Steel sample (52100 AISI bearing steel)
Diameter (mm)	12.7
Density (Kg/mm3)	7789
Surface roughness *R*a (μm)	0.024

2.3 Lubricating oil

In order to evaluate the combined effect of surface roughness and viscosity of oil two types of lubricating oil used. The property description of lubricating oil is as in table 3.

Table 3. Properties of lubricating oil.

Lubricating oil	Viscosity
MAK Hydrol 32	32 CST at 29.5⁰C
Castrol GTX SAE-20W50.	68 CST at 29.5⁰C

2.4 Testing machine:

Rolling contact Fatigue (RCF) test was performed on DUCOM made TR 30L four ball test machine. Four ball test machine was configured according to Institute of Petroleum (UK) IP 300 rolling test procedure. TR 30L machine comes with WinDucom software for data acquisition and display of results. Loading configuration is shown in Fig. 1. Silicon nitride ball held in upper collet and rotate at spindle speed. Rest of three steel ball held in retainer cap filled with lubricating oil.

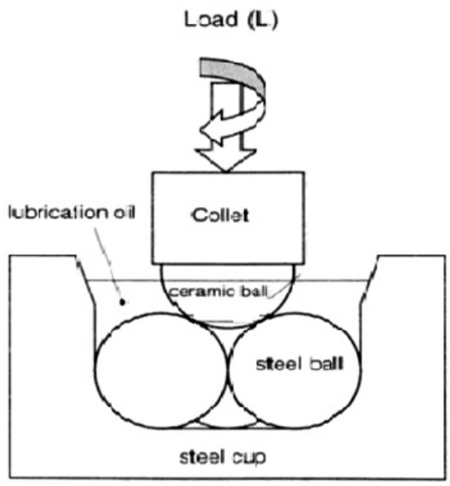

Fig. 1. Loading configuration.

2.5 Test program

Wear test were conducted with four ball tester, loading description is given in section 2.4.

Rolling contact fatigue (RCF) of two kinds of commercially finished HIPed silicon nitride rolling elements/ balls with surface roughness values (*R*a) of 0.025 µm and 0.05 µm rolling against one kind of chrome alloy steel (AISI 52100) balls. Four sets of RCF test were conducted, each test is conducted of 1 hr. (3600 sec.) duration with maximum speed of rotation is 1200 rpm and maximum load is 200 N. the frictional torque and corresponding coefficient of friction is recorded during test.

3. IMPLEMENTATION OF TAGUCHI METHOD

The technique of defining and investigating all possible conditions in an experiment involving multiple factors is known as the design of experiments (DOE). DOE refers to the process of planning, designing and analyzing the experiment so that valid and objective conclusions can be drawn effectively and efficiently [10]. Taguchi method is a powerful tool for the design of high quality systems, products and processes. It provides simple, efficient and systematic approach to optimize design of experiments for process or product improvement. Taguchi method is efficient method for designing process that operates consistently and optimally over a variety of conditions. To determine the best design of experiment it uses orthogonal array technique [11]. During machining process it is important to determine the optimal setting of machining parameters so as to reduce the machining coat and achieve the required quality. D. Lazaravic *et.al.* [12] implemented Taguchi technique for minimizing the surface roughness of polyethylene during turning. The effect of four cutting parameters-cutting speed, feed rate, depth of cut and toll nose radius on surface roughness during turning was analyzed on the basis of L_{27} orthogonal array.

The material selected for test program as shown in Table 1 to 3.

3.1 Factors and Levels

The input parameters selected with corresponding factor and levels are shown in Table 4. While the frictional torque or coefficient of friction during rolling condition is output.

Table 4. Factor and levels of each for experimentation.

Factor	Level 1	Level 2
A-Surface roughness	0.025 µm	0.05 µm
B- Lubricant viscosity	32 cst at 29.5 ^{0}C (Mak Hydrol 32)	68 cst at 29.5 ^{0}C (Castrol GTX SAE 20W50)

3.2 Selection of orthogonal array and experimentation

For two factor and two levels orthogonal array of L4 is selected and experiments were conducted. Table 5 gives description of experimental conditions.

Table 5. Experimental conditions.

Trial No.	Factor	
	A	B
01	1	1
02	1	2
03	2	1
04	2	2

3.3 Analysis of S/N ratio

According to Taguchi method, S/N ratio is the ratios of 'Signal' representing desired value i.e mean of output characteristic and the 'noise' representing the undesirable value i.e squared deviation of the output characteristic. It is denoted by η and the unit is dB. The S/N ratio is used to measure significant parameter affecting desired value. The S/N ratio, which condenses the multiple data points within a trial, depends upon the type of characteristic being evaluated. It may be lower is better (LB), nominal is better (NB), higher is better (HB). In this case coefficient of friction is expected to be minimum, so S/N ratio is calculated for lower is better. Table 6 below gives result of experiment and corresponding S/N ratio.

Table 6. Results of Experiment.

Trial No.	Factor		Coefficient of friction (µ)	S/N ratio
	A	B		
1	1	1	0.10079	19.93165
2	1	2	0.07164	22.89689
3	2	1	0.08695	21.21461
4	2	2	0.08854	21.05721

3.4 Analysis of experimental result

The experimental results based on plan of experiment are analyzed with the software MINITAB 15. Figure 2 to 6 shows various plots obtained after analysis.

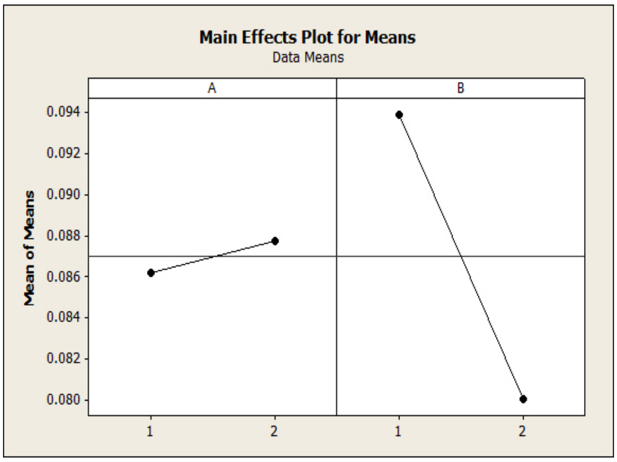

Fig. 2. Main effect plot for means (μ).

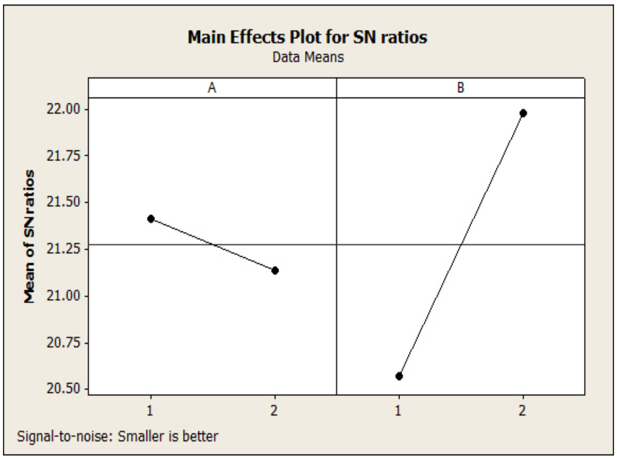

Fig. 3. Main effect plot for S/N ratio.

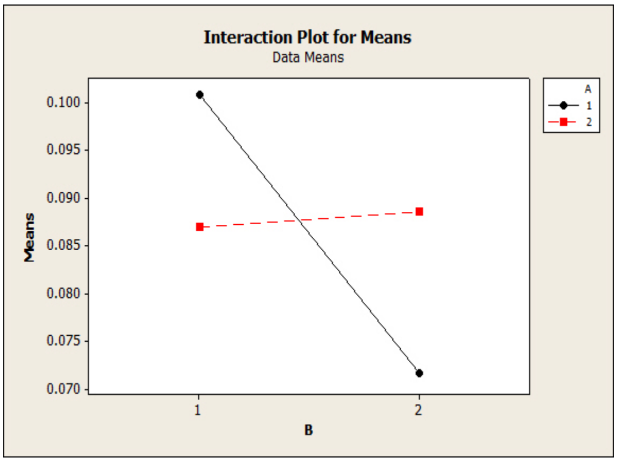

Fig. 4. Interaction plot for means.

From main plot in Figs. 2 and 3, of main plot of mean and main plot of S/N ratio it can be observed that optimum value of coefficient of friction can be achieved at the A1 and B2 levels of factor. From the interaction plot in Figs. 4 and 5, it can be observed that factor surface roughness (A) and factor lubricant viscosity (B) has strong interaction on frictional torque or coefficient of friction in rolling contact of silicon nitride and steel contact. Combined effect of surface roughness and viscosity can also be observed from below contour plot and surface plot (Fig. 7).

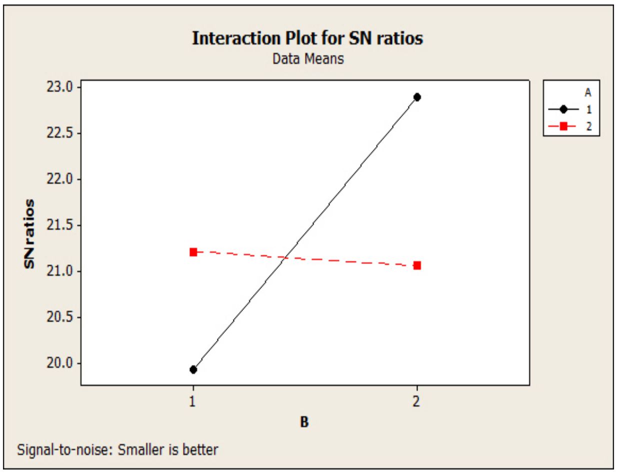

Fig. 5. Interaction plot for S/N ratio.

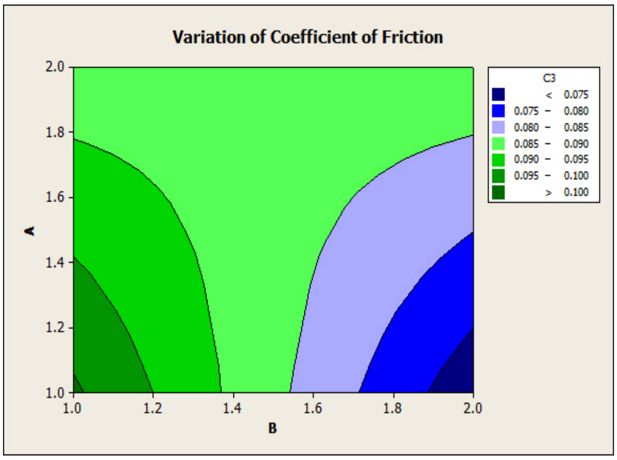

Fig. 6. Contour plot variation of coefficient of friction.

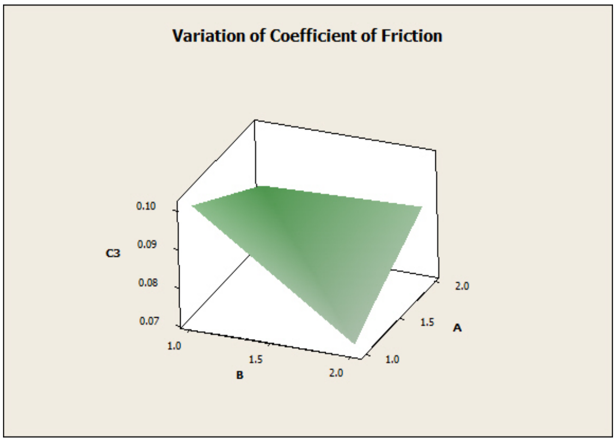

Fig. 7. Surface plot variation of Coefficient of friction.

From above surface and contour plots it is clear that there is strong interaction between surface roughness and viscosity on coefficient of friction.

3.4 Analysis of Variance (ANNOVA)

The ANNOVA is performed to investigate the design parameters and to indicate which parameters are significantly affecting the output parameters? This technique does not directly analyze the data, but rather determines the variability (variance) of the data. Analysis provides the variance of controllable and noise factors. The sum of squares, variance and percentage contribution of each factor on coefficient of friction and combined effect of both factors on coefficient of friction is given in below Table 7.

Table 7. ANNOVA table for experimental results.

Factor	Sum of squares	DOF	Variance	% Contribution
Surface roughness (A)	$2.36*10^{-6}$	1	$2.36*10^{-6}$	0.54
Lubricant viscosity (B)	$1.9*10^{-4}$	1	$1.9*10^{-4}$	44.18
Combined (A*B)	$2.36*10^{-4}$	1	$2.36*10^{-4}$	54.93

4. CONCLUSION

From analysis of results and various plots in Fig. 1 to 6, showing effect of controlled process parameter on coefficient of friction. It is clear that surface roughness and lubricant viscosity has strong interacting effect on coefficient of friction in rolling contact. While results of ANNOVA table presents, percentage contribution of lubricant viscosity is about 44.18 %, while the combined contribution of surface roughness and lubricant viscosity is about 54.93 % on coefficient on friction in rolling contact.

Implementation of Taguchi technique made it easy to obtain valid conclusion with only 4 number of experiment, it also proves importance of design of experiment in the field of research and development to obtain valid conclusion.

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