ISSN XXXX XXXX © 2017 IJESC

Research Article Volume 7 Issue No.9

Contact Stresses Analysis & Material Optimization of Deep Groove Ball Bearing using Hertzian Contact Theory

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Abstract:
A subsurface originated stress has mainly responsible for failure of rolling contact bearings. Bearing is most important and considered as critical component in the rotating machines. In present work find the tribological differences between stresses induced in SKF 7204B number deep groove ball bearings manufactured with steel material and compare its performance with different ceramic materials. In present study of ball bearing design evaluated best material to be used for manufacturing of bearing balls with the discussion of Hertz contact theory and the performance variation in point contacts pressure. The numerical model was developed to find contact pressure, hertzian contact stresses and deformation of bearing balls. The numerical model was further validated using finite element model in ANSYS and experimental results on compressive test. The results obtained in this work it was investigate that ceramic materials has less density, high wear resistance, electrical insulator to reduce electric arc damage, noiseless operation, less discolouring, overheating & corrosion problem which can completely eliminate the problems in steel ball bearing.

Keywords: contact pressure, Deep groove ball bearing, Hertz Contact Stress Analysis material optimization.

I. INTRODUCTION

Rolling element bearings are consider as a most critical components such as in electric motors, material handling etc. in engineering fields. The reliable performance of rolling element bearings is required for proper functioning of machines to prevent failure of machinery. In field survey it is observed that most of steel ball bearings are fails due to electric arc damage & contact fatigue. The material selection is a most important in ball bearing design, since it affects bearing performance determined by the strength of bearing material in relation to the contact stresses the bearing experiences during operation. A proper designed geometry and smooth surface finish reduce the contact stress. A majority quality alloy steel, carbon steels & ceramics.[12] Fig.1 shows structure of single row deep groove ball bearing with having element like inner raceways, outer raceways, balls etc.

Figure.1.Structure of single row deep groove radial ball bearing [12]

In this present work Hertz contact theory used is useful to analyze the stresses induced in rolling element bearing. According to Hertz contact theory, when solids either spherical or cylindrical which are in contact together there will be deformation & surface stresses are induced in each of them the contact region. In this paper illustrated the major differences that occur in bearing materials are used for the rolling elements. Ball bearing rings are generally manufactured from steels. This work focused on steel as a baseline to compare with Ceramics materials. For high speed applications significant centrifugal loading may be generated on the raceway. Assuming that all loading conditions are equivalent, the loading due to centrifugal force will be lessened by using lighter ball materials. One material of interest is ceramic, which has a density of about 40% of that of steel. As with all material selections in this paper discussed the performance differences between a ball bearing with steel balls and Ceramic balls using analytical method of Hertz contact stress analysis which can be further validates using FEM model simulation & experimentation for material optimization of ball bearing.

II. LITERATURE REVIEW

Ching-Yao Tang, Chad E. Foerster, Michael J. O'Brien, Brian S. Hardy, Vinay K. Goyal, Benjamin A. Nelson, Ernest Y. Robinson, Peter C. Ward and Michael R. Hilton are Studied on the Effects of ball Defects on the Fatigue Life in Hybrid Bearings in this paper they presented for the an investigation on Hybrid ball bearings using silicon nitride Si3N4 ceramic balls with steel rings are being used in space mechanism applications due to their high wear resistance and long rolling contact fatigue life. In this reports he investigate the effects of ball defects that cause early fatigue failure. In this study includes types of defects encountered in use, similar defects in a laboratory setting, experiment execution on full bearing tests to obtain lifetimes using finite element modeling to understand the stress concentration of these defects. This method can be further used to evaluate other defects as they occur. [1] Cuneyt Oysu introduced a finite element and boundary element contact stress analysis with remeshing technique in this paper he presented for the an investigation on the Fundamental part of the contact stress problem solution using a finite element method is to locate possible contact areas reliably and efficiently. In this research, a remeshing technique is introduced to determine the contact region in a given accuracy. The remeshing technique is efficiently employed to adapt the mesh for more precise representation of the contact region. Two numerical. The remeshing method is shown to be an efficient numerical method for two-dimensional contact problems. The results obtained by the new method converge very close to those provided by analytical techniques. The remeshing technique can easily be implemented in future work for three-dimensional problems where accurate contact region estimation is necessary.[2] Eckart Uhlmann, Martin Bilz, Jeannette Baumgarten &Tiago Borsoi Klein done the review on the Innovative High-Performance Ceramics Challenge for the Life Cycle Engineering of Turbo machinery As part of the 2014 market and trend analysis on the subject of Life Cycle Engineering for turbo machinery, the market potential of the concept of Life Cycle Engineering for turbo machines as well as future trends and R&D issues have been identified. It has shown that the mechanical, chemical and thermodynamic characteristics of high-performance ceramics motivate new developments of Life Cycle Engineering in turbo machinery. However, particular material properties like high hardness and strength represent a challenge for the machining process of complex components made from high-performance ceramics this paper they focus on the importance of a hard ceramic matrix composites with regard to technical and economic criteria.[3] Michael K. Budinski done the research on Failure analysis of a bearing in a helicopter turbine engine due to electrical discharge damage, in this documents he found that the metallurgical evaluation of a rolling element bearing that failed due to electrical discharge damage. The rolling element bearing was used in a helicopter turbine engine that failed in-flight, resulting in a hard landing of the helicopter. Optical and electron microscopy as well as energy dispersive spectroscopy were used to evaluate the bearing. Pitting and material transfer on the external bearing races bearing and mating surfaces revealed that the electrical discharge damage occurred while the engine's components were not rotating. a complete loss of engine power due to the failure of the bearing, by electrical arcing that occurred at an unknown time prior to the accident flight. The bearings area common source of electrical [4] M. S. Starvin, S. Babu, Sriramachandra Aithal, K. Manisekar and P. Chellapandi Presented on the investigation of the Finite element simulation of non- linear deformation behavior in large diameter angular contact thrust bearing. In this, study the elastic 3D model is to be analyzing by finite element analysis using load deformation characteristic of large diameter bearing ball - raceway contact and the results are validated by conducting experiment on the actual bearing model. They compare these results of these experiments with the Hertz relation. This result shows good correlations between the other contact parameters such as contact area and contact pressure measured using FEA and with analytical results. The study of load–deformation characteristics of a single ball with the raceways can be used as a basis to analyze model of a full bearing by sub structuring technique. By using this type of simplification used for avoiding the multiple modeling of the contact problems in large diameter bearings.[5]

III. PROBLEM DEFINATION

As per the field survey it was observed that in maximum electric devices e.g. In Electric motor a steel ball bearing is mostly used but steel ball bearing has various drawbacks such as:

1) An Electric arc damage.
2) Non- linear deformation &Contact fatigue.
3) Surface depression & fracture.
4) Mechanical wear, contact stresses & noise.
5) Discolouring, overheating & corrosion problem.

In this project work select different ceramics material such as silicon nitride, aluminium oxide & zirconium oxide which has a less density, high wear resistance, Lower coefficient of expansion as compared to steel material. The proper material selections will discuss the performance differences between a ball bearing with steel balls and Ceramic balls analysis to replace steel ball bearing ball material to optimize & reduce the drawbacks in it.

Figure.2. Old electric induction motor.

Fig 2 shows old damage induction motor of 1 HP. The motor damaged due to damage of bearing. Bearing damages in various ways like electric arc damage, overheating, corrosion, mechanical wear etc.

Figure.3. Damage ball bearing.

IV. PARAMETERS AND MATERIAL SELECTION

In this study design, analysis and comparison of all parameters was done which give significant effect on bearing performance to fulfill the objective of this project.

This was achieved by analytical investigation of Hertz contact stress, variation in point contact fatigue and validation with analytical result by using FEM simulation & Experimentation in order to quantify the effectiveness of the different bearing ball materials. Nomenclature is given as follows:

Young's modulus	E
Poisson's ratio	ν
Density	ρ
Contact by force	F
Maximum contact pressure	$Pmax$
Contact zone diameter	$2a$
Maximum stresses occur on the x-axis	σ_X
Maximum stresses occur on the y-axis	σ y
Maximum stresses occur on the z-axis	σ_z
Maximum shear stresses	τ_{max}
Depth of max shear stress	z
Bore diameter	di
Outer race diameter	do
Mean diameter	dm
Ball diameter	d
Width	B
Number of rolling elements	N_b
Contact angle	α

Table.1. Ball bearing specifications

BALL BEARING	SPECIFICATIONS
Model No.	SKF 7204B
Bore diameter (di)	20mm
Outer race diameter (do)	47mm
Mean diameter (dm)	33.5mm
Ball diameter (d)	8mm
Width (B)	14mm

Table.2. Mechanical properties use for bearing

Mechanical properties	Stainless steel	Ceramic sSi_3N_4	Ceramics ZrO_2	Ceramics Al_2O_3
Young's modulus (Gpa)	200	320	210	380
Poisson's ratio	0.3	0.26	0.3	0.22
Density (kg/m^3)	7800	3300	6100	3900

V. MATHEMATICAL MODEL

By applying different load on the ball of different materials it was find that the analytical results as given below using theory of hertzian contact fig 4 shows two solid spheres having diameters d1 and d2 pressed on each other with a application of force F. having E1 ,E2 Young's modulus and v1 , v2 poissons ratio of the two spheres , the radius a of the circular contact area is given by the equations ,

$$a = \sqrt[3]{\frac{3F}{8}\,\frac{\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_2^2}{E_2}}{\frac{1}{d_1}+\frac{1}{d_2}}} \quad (1)$$

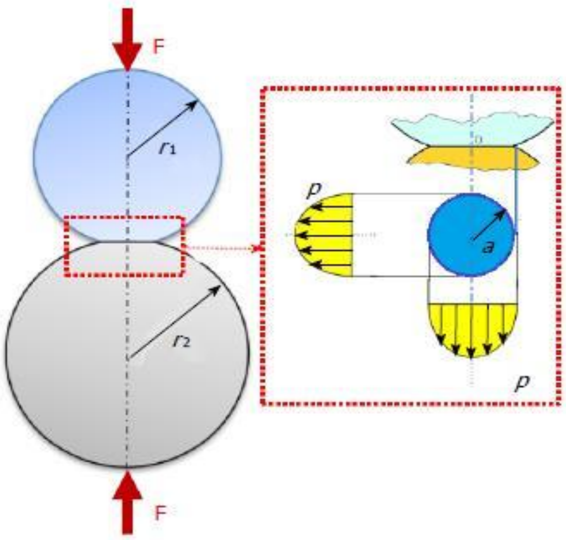

Figure.4. Two solid spheres in contact by force *F*. (b) contact stress distribution across hemispherical contact zone of diameter 2a.

The pressure distribution within the contact area of each sphere is hemispherical. As shown in Fig.2.2. (b)The maximum pressure occurs at the center of the contact area is

$$P_{MAX} = \frac{3F}{2\pi a^2} \quad (2)$$

The maximum stresses occur on the z-axis, and these are principal stresses. Their values are,

$$\sigma_X = -p_{max}\left[\left(1-\frac{|z|}{|a|}\tan^{-1}\frac{1}{|z/a|}\right)(1+\nu)-\frac{1}{2\left(1+\frac{z^2}{a^2}\right)}\right]$$

$$\sigma_y = -p_{max}\left[\left(1-\frac{|z|}{|a|}\tan^{-1}\frac{1}{|z/a|}\right)(1+\nu)-\frac{1}{2\left(1+\frac{z^2}{a^2}\right)}\right] \quad (4)$$

$$\sigma_z = \frac{-pmax}{1+\frac{z^2}{a^2}} \quad (5)$$

The maximum stresses occur on the z-axis. Since $\sigma_1 = \sigma 2$ and $\tau_{1/2} = 0$

$$\tau_{max} = \frac{\sigma x - \sigma z}{2} = \frac{\sigma y - \sigma z}{2} \quad (6)$$

It is seen that maximum shear stress is responsible for the surface fatigue of contacting bearing elements because of crack originates at the point and progresses the surfaces .[9] The analytical calculations were done on all materials under the optimization study with the incremental load as 100N, 200N , 300N, 400N , 500N & results of analytical are given in table below,

Table.3. Analytical results of Maximum Hertzian contact pressure P max (Mpa)

Sr. No.	Load	Stainless steel	ceramic	ceramic	ceramic
	(N)	SS	Si_3N_4	ZrO_2	Al_2O_3
1	100	3880.2	5222.7	4018.7	5765.7
2	200	4888.7	6580.1	5050.4	7279.3
3	300	5596.2	7532.4	5781.2	8332.7
4	400	6159.4	8290.5	6363.1	9171.4
5	500	6635	8930.6	6854.4	9879.5

The table show result of Maximum Hertzian contact pressure by analytical method for these ceramic from load 100N to 500N result for stainless steel and zirconium oxide are nearly occurs same.

Table.4. Analytical results of Depth of max shear Stress z (mm)

Sr. No.	Load	Stainless steel	ceramic	ceramic	ceramic
	(N)	SS	Si_3N_4	ZrO_2	Al_2O_3
1	100	0.053	0.045	0.051	0.042
2	200	0.067	0.056	0.066	0.052
3	300	0.077	0.064	0.076	0.06
4	400	0.085	0.071	0.083	0.066
5	500	0.091	0.076	0.09	0.071

The table show result of Depth of max shear by analytical method for these ceramic from load 100N to 500N result for stainless steel and zirconium oxide are nearly occurs same.

Table.5. Analytical results of circular contact area diameter 2a.

Sr. No.	Load	Stainless steel	ceramic	ceramic	ceramic
	(N)	SS	Si_3N_4	ZrO_2	Al_2O_3
1	100	0.222	0.191	0.218	0.182
2	200	0.28	0.241	0.275	0.229
3	300	0.32	0.276	0.315	0.262
4	400	0.352	0.304	0.346	0.289
5	500	0.379	0.327	0.373	0.311

The table show result of circular contact area diameter by analytical method for these ceramic from load 100N to 500N result for stainless steel and zirconium oxide are nearly occurs same.

VI. FINITE ELEMENT ANALYSIS

FEA is a powerful tool to investigate the contact behavior of the bearing ball. In present work for material optimization and contact stresses analysis use software ANSYS 14.5 in workbench solver for different material and loading condition under static structural analysis.

The following procedure is done for simulation in ANSYS.

1. Make 3D model for sphere-1 in modeling module of ANSYS software having radius 4mm.
2. Make 3D model for sphere-2 in modeling module of ANSYS software having radius 4mm in contact with first one sphere at center distance of 8mm.
3. Select Solid 187 type of element (Brick & Node 187).
4. Apply the different material properties for sphere optimization purpose as a bearing ball.
5. For meshing purpose select tetra mesh size 4 for required accuracy in results.
6. Defining real constraint for geometry and contact sphere boundary conditions
7. The spherical balls and apply point force in Y-directions.
8. Plot the results showing contact stresses & deformation.

The results during FEA modeling are given below,

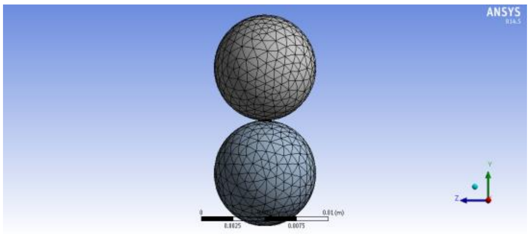

Figure.5. Meshed model

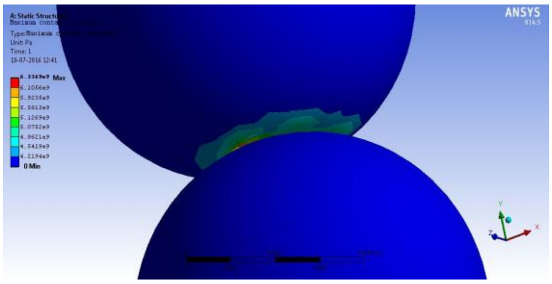

Figure.6. Maximum Hertzian contact pressure model

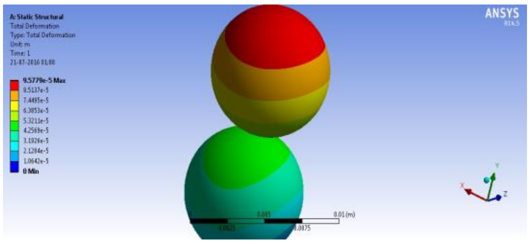

Figure.7. Maximum deflection model

VII. EXPERIMENTAL INVESTIGATION

In experimental validation the testing of different bearing balls materials is done under compression for different loading condition to find the results experimentally and it is compare with analytical & FEA simulation results. Fig.8 shows experimental setup, Test set up was made to determine the compressive strength, contact stresses and deflection due to contact pressure on balls under different gradually increasing load and plot the results under pure compression. During this test a fixture was to be made from tool steel material having 12mm thick plate with 8mm central hole with backing base plate. This was held on compression test rig specially constructed for this test. The test is performing for different ball materials. By testing different bearing balls materials for different loading condition under compression we can find the results experimentally and it will compare with analytical & simulation results.

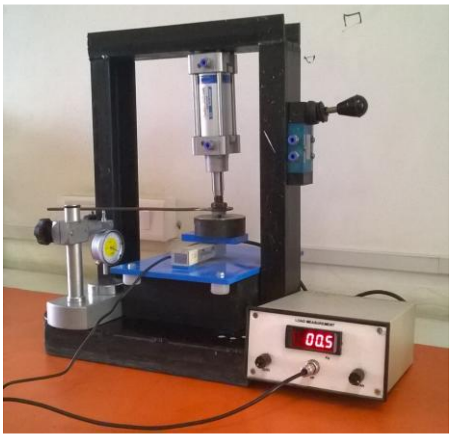

Figure.8. Test set up

Figure.9. Deflection of bearing ball

Table.6. Experimental results of Maximum Hertzian contact pressure P max (Mpa)

Sr. No.	Load (N)	Stainless steel SS	ceramic Si_3N_4	ceramic ZrO_2	ceramic Al_2O_3
1	100	4353.26	4944.62	3899.42	6484.26
2	200	4572.76	6922.57	5692.84	7765.70
3	300	6201.37	7267.94	6695.33	8713.30
4	400	6306.12	8384.49	6837.32	10700.45
5	500	6696.60	9565.33	7173.48	10858.18

The table show result of Maximum Hertzian contact pressure by experimental method for these materials from load 100N to 500N result for stainless steel and zirconium oxide are nearly occurs same.

Table.7. Experimental results of Depth of max shear stress z

Sr. No.	Load (N)	Stainless steel SS	ceramic Si_3N_4	ceramic ZrO_2	ceramic Al_2O_3
1	100	0.06	0.04	0.04	0.03
2	200	0.07	0.05	0.06	0.05
3	300	0.08	0.06	0.07	0.06
4	400	0.09	0.07	0.08	0.07
5	500	0.11	0.08	0.1	0.08

The table show result of Depth of max shear by experimental method for these ceramic from load 100N to 500N result for stainless steel and zirconium oxide are nearly occurs same.

Table.8. Experimental results of Circular contact area diameter 2a.

Sr. No.	Load (N)	Stainless steel SS	ceramic Si_3N_4	ceramic ZrO_2	ceramic Al_2O_3
1	100	0.21	0.2	0.22	0.17
2	200	0.29	0.24	0.26	0.22
3	300	0.31	0.28	0.3	0.26
4	400	0.35	0.3	0.34	0.27
5	500	0.38	0.32	0.37	0.3

The table show result of circular contact area diameter by experimental method for these ceramic from load 100N to 500N result for stainless steel and zirconium oxide are nearly occurs same.

VIII. RESULTS & DISCUSSIONS

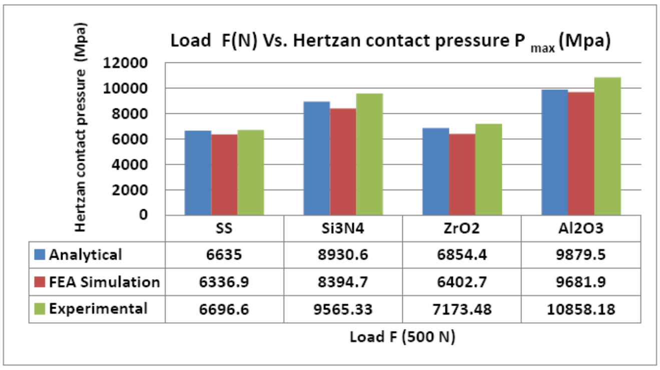

Figure.10. Load-Maximum Hertzian contact pressure at 500N

This graph shows comparison of Load-Maximum Hertzian contact pressure at 500N for analytical, FEA simulation and by experimental methods shows same result for these methods.

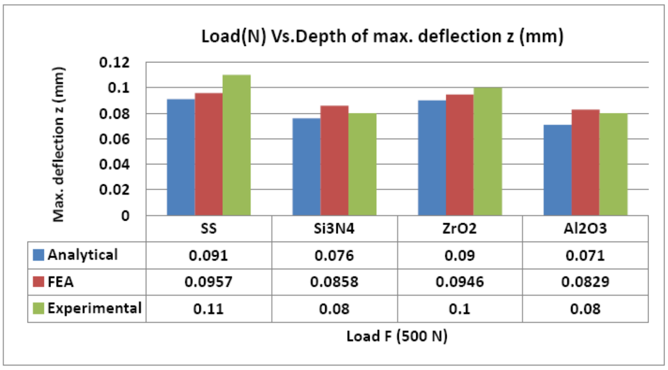

Figure.11.Load-max deflection at 500N

This graph shows comparison of Load-max deflection at 500N at 500N for analytical, FEA simulation and by experimental methods shows same result for these methods.

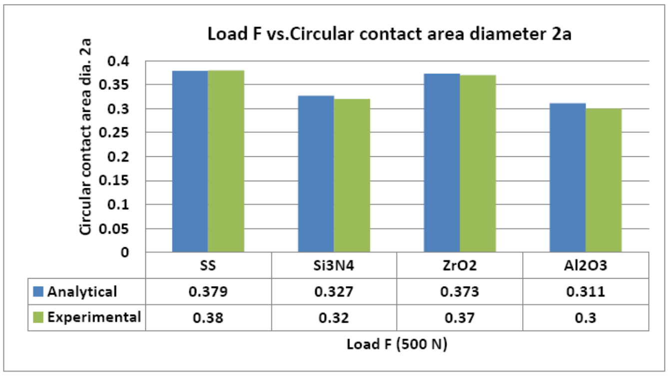

Figure.12.Circular contact area diameter at 500N

This graph shows comparison of Circular contact area diameter at 500N for analytical, FEA simulation and by experimental methods shows same result for these methods.

IX. CONCLUSION

The analytical results were based on the assumptions created by hertzian contact theory. This analytical result nearly validated by simulation and experimental results well. The results shows that there is increase in hertzian contact pressure pmax with contact load which gives significant deflection and contact stress on bearing ball as per assumption of hertzian contact theory which was very useful for material optimization of bearing .Future work of this paper is that stress history will used to calculate fatigue life of bearing and failure initiation of ball and race contact problem and experimental validation of maximum shear stress.

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