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Residual stress measurements of silicon nitride and coated tungsten carbide rolling contact elements

M. Hadfield[a], R. Ahmed[a], S. Tobe[b]
[a]*Brunel University, Department of Mechanical Engineering, Uxbridge, Middlesex UB8 3PH, U.K. Mark.Hadfield@brunel.ac.uk*
[b]*Ashikaga Institute of Technology, Department of Mechanical Engineering, Ashikagashi, Tochigiken 326, Japan*

Abstract

High quality ceramic materials used in rolling element bearing applications show some practical advantages over traditional bearing steels. Silicon nitride has been found to have the optimum combination of properties suitable for certain high speed, low mass and high stiffness applications. Hybrid silicon nitride rolling element bearings are now supplied as standard components by manufacturers. Coatings may also be considered to enhance the capability of hybrid bearings for applications such as high speed and high temperature. A modified four-ball machine was employed to produce accelerated rolling contact fatigue failures of these materials. Silicon nitride verses steel, silicon nitride verses silicon nitride and tungsten carbide coating verses steel configurations were considered. The lubricated tests were performed at relatively high loads and speeds ie. maximum compressive stress from 4.5 to 8.1 GPa at 4000 to 10,000 r/min.

Measurement of residual stresses is an important aspect of surface engineering. An X-ray method was employed since it is the only practical non-destructible means of measuring residual stress of these materials at the pre-test and post-test stages. Experimental testing, surface examinations and residual stress measurements are described for case study failures. Results are presented for a selection of surface failures of hot isostatically pressed silicon nitride and thermally sprayed tungsten carbide rolling elements. The role of the residual stress within these materials before and after rolling contact fatigue testing is discussed.

1 Introduction

The use of specialist materials in surface engineering such as ceramics and hard coatings applied to rolling element bearings are needed to enable the design of components to higher performance specifications. Industries requiring high technological growth such as aerospace and energy supply require the use of rolling element bearings which operate in unconventional tribological and high temperature conditions respectively. Advancement of experimental surface analysis techniques is providing the understanding required to fully utilise these materials. One such technique is the non-destructive measurement of residual stresses within materials by means of X-ray diffraction. The understanding of residual stress within complex materials is needed to characterise failure modes, evaluate the in-service loading conditions and to help classify the material quality of the contacting rolling elements. In the present study a modified four-ball machine was used to produce accelerated contact fatigue failures and two test materials were considered. Residual stress analysis of the pre-test, contact path and failed rolling elements were performed.

Hot Isostatically Pressed (HIP) silicon nitride was used because of its practical availability overall suitability of qualities for use in rolling element applications. High quality engineering ceramics have been used in wear resistant applications for many years. This has enabled experience to be gained with regard to solutions where ceramics are suitable and economically advantageous. There has been a gradual improvement in the properties of advanced ceramics including the ultra-hard materials and reduction in cost, such that the promise of fully dense silicon nitride for bearing applications (noted for example by Scott [1] and Gielisse et al. [2]) has now been realised to the extent that ceramic ball bearings have been available commercially, for over five years. The second material used in this study was Detonation Gun (D-Gun - SDG2040) tungsten carbide coated to a steel substrate. Thermally sprayed coatings are deposited by a variety of processes such as flame, arc wire, plasma, Detonation Gun (D-Gun) and High Velocity OxyFuel (HVOF). The specific spraying process and material was selected because of high impacting particle speed and high wear resistance respectively. A typical example of the techniques and applications for thermally sprayed coatings is the gas turbine engine. Rhys-Jones [3] describes the aero-engine components which were coated to protect against wear, erosion, oxidation and corrosion.

Residual stresses were measured on steel rolling element bearings by Munro et al [4]. In this study the compressive residual stresses were shown to peak at the position of maximum shearing stress due to normal contact pressure. Also, early fatigue failure was observed when residual compressive stress appeared near the surface. The residual stress measured by X-ray diffraction of silicon nitride rolling contact fatigue failures was performed by Hadfield et al [5]. Variation of measured residual stress with depth of delamination fatigue and brittle fracture was discussed. During that study the compressive residual stress values increased with silicon nitride delamination failure depth.

In this present study residual stress measurements of silicon nitride and tungsten carbide coating on a steel substrate examples are presented. The accelerated rolling contact fatigue tests are briefly outlined. X-ray diffraction residual stress methodology is presented. The results of the residual stress measurements are discussed with respect to contact conditions.

2 Accelerated rolling contact fatigue tests

2.1 Test machine

Accelerated rolling contact fatigue tests were performed using a modified four-ball machine.. This machine was employed as it correctly models ball bearing motions and precisely defines the contact load. This machine consists of an assembly which simulates an angular contact ball-bearing. The stationary steel cup represents a bearing outer-race, three lower balls represent the rolling elements within a bearing-race and the upper ball represents the inner-race. The assembly was loaded via a piston below the steel cup, from a lever-arm load. The upper-ball was assembled to a drive shaft via a collet and contacts with three lower-balls when the machine was stationary. The contacting positions between the upper ball and lower balls were immersed with lubricating oil.

2.2 Test materials

The silicon nitride balls were manufactured by a Hot Isostatically Pressed (HIP) method.

Ball blanks were ground and polished to 12.7 mm diameter, standardised procedures were adopted to ensure consistent quality of material and geometry. Average roughness (Ra) of the silicon nitride ball surfaces were 0.008 μm and ball roundness was within ball bearing tolerances. The tungsten carbide cobalt (WC 15%Co) coating was deposited on a steel substrate using a D-Gun method . The coating thickness was 100 μm before grinding and polishing to 60μm and final ball diameter of 12.7 mm with a roughness of 0.025 μm Ra. The steel balls were grade 10 (ISO 3290-1975) carbon chromium steel with a surface roughness of 0.02 μm Ra.

2.3 Test conditions and results

The contacting elements were loaded under extreme stresses between 4.5 and 8.1 GPa. Lubrication film thickness was calculated using elastohydrodynamic theory for thin films. Shaft/upper-ball speed is set at speeds of 10,000, 5,000 and 4000 r/min. At these conditions, thin film separation exists and stresses may be considered Hertzian. Table 1, describes the basic test conditions for test 'A' to 'E'. Oil Lubrication is designated (LV) for low viscosity oil and (HV) for high viscosity oil. The low viscosity lubricant is a synthetic oil which has a kinematic viscosity of 12.5 c.s.°C at 40°C and 3.2 c.s.°C at 100°C. The high viscosity lubricant is a mineral oil of 200 c.s.°C at 40°C and 40 c.s.°C at 100°C.

Silicon nitride Vs silicon nitride tests 'A', 'B' and 'C' were suspended without failure after 150 million stress cycles to the upper ball. The maximum contact pressures for tests A, B and C were 7.1, 7.6 and 8.1 GPa respectively. The tests were conducted at 10,000 r/min with the contact area immersed with the HV lubricant. Test 'D' configuration was a steel upper contacting silicon nitride lower ball, this configuration simulates a hybrid bearing. In this case the silicon nitride was surface pre-crack using Vickers (5 kg) hardness indentors. The lower balls failed after 0.54 million test cycles (figure 1a), full test results and surface analysis of the complete pre-cracked test series are reported by Hadfield et al [6]. The tungsten carbide coating in contact with steel (test 'E') was conducted at 4000 r/min. This test failed by coating delamination (figure 1b), full surface analysis is reported by Ahmed et al [7].

3. Residual stress measurement

3.1 Background

The X-ray stress measurement was used to find residual stress within the ceramic and tungsten carbide areas. A $\sin^2\psi$ method was used, this technique is appropriate for materials composed of a crystal structure. A detailed description of this method may be found from Farrahi [8]. A schematic of the measurement apparatus is shown as figure 2.

When a stress is applied to a material, the interatomic distance within the crystal will be extended or compressed in proportion to its force within the elastic limit. The X-ray diffraction technique measured the variations of the interplaner spacing within the crystal and stress was calculated. Using the Bragg's condition for diffraction (1), strain is then calculated from the quantity of variations of the X-ray diffraction angle.

$$n\lambda = 2d \sin \theta \qquad (1)$$

$$\epsilon = \frac{\Delta d}{d} = \cot \theta_0 \, \Delta\theta \tag{2}$$

Stress is then calculated from the expression (2).

$$\sigma = \frac{E}{1+\nu} \frac{\partial(\epsilon)}{\partial(\sin^2\psi)} = -\frac{E \cot \theta_0}{2(1+\nu)} \frac{\partial(\theta)}{\partial(\sin^2\psi)} \tag{3}$$

Equation (3) is described by the constant 'K' and gradient 'M', shown as equation (4).

$$\sigma = K\,M \tag{4}$$

where

$$K = -\frac{E \cot \theta_0}{2(1+\nu)} \tag{5}$$

and

$$M = \frac{\partial(\theta)}{\partial(\sin^2\psi)} \tag{6}$$

At these settings, the diffraction angle is measured and hence gradient 'M' is evaluated from a regression line. The constant elasticity parameter 'K' is evaluated from material properties and the stress-free diffraction angle.

3.2 Measuring procedure

3.2.1 Silicon nitride

The incident X-ray was varied at 0, 15, 25, 35 and 45°. The measurements were performed on a Rigaku Strainflex MSF-2M machine. The X-ray tube has a maximum load of 40 kV and 40 mA, incident and receiving parallel slits direct the beam. A wide angle goniometer enabled a detector scanning range of 120 to 170° with standard stepper motor control, accuracy is within standard tolerances. The detector is a scintillation counter probe type, the rate meter transforms the count rate to direct current voltage which is fed into the recorder. The X-ray tube and filter is selected and for silicon nitride material Cr-Kα is used typically. The choice of characteristic X-ray influences the depth of measurement, measurement time and diffraction plane.

3.2.2 Tungsten carbide coating

These measurements were performed using a Rigaku RINT 2000 machine.This machine has a maximum capacity of 18 KW at 300 mA and 60 kv. The measurements on Test 'E' was conducted at 60 kv and 200 mA.

4. Results and discussion of residual stress measurements

4.1 Silicon Nitride Vs Silicon Nitride

The residual stress measurement of untested silicon nitride was 227 MPa compressive. This stress level compares well with the HIP manufacturing pressure of around 200 MPa. The measurement depth is 175 µm means that surface stresses caused by finishing (grinding and polishing) do not contribute to this stress. The measurement depth is such that material 'shakedown' or plasticity during testing is not measured at the maxima as this occurs near the surface or at the position of maximum orthogonal shear stress.

The upper and lower silicon nitride rolling elements for tests 'A' and 'C' were measured. In the case of test 'A' the upper ball measurement was 80 MPa compressive within the wear track. This compared with 197 MPa compressive within a lower silicon nitride ball. This result indicates that the lower ball residual stress has not changed within the measurement tolerance. The explanation for this could be the fact that the lower ball surface receive much less stress cycles than the upper test ball. The reduced residual stress on the upper test ball wear track indicates a tensile sense from 227 MPa to 80 MPa. The Hertz contact shear stress is maximum at 118 μm below the surface and therefore it is plausible that this stress influences the residual stress at the measurement depth. In the case of test 'C' the upper ball measurement was 140 MPa compressive. This value again is changing in a tensile direction and the maximum shear stress is maximum at 118 μm below the surface.

The position and direction of residual stress measurements in test 'B' upper ball were conducted in more detail. Figure 3a illustrates the positions, magnitude and measurement direction of the measurements in relation to the wear path. The irradiation diameter and wear path width are 0.3 mm and 0.44 mm respectively. The measurements were positioned at the contact edges and contact centre to investigate the influence of the contact stress field. The maximum Hertz stresses for this contact are 7.6 GPa maximum compressive located at the wear track centre, 1.0 GPa maximum tensile located at the contact edges with a alternating maximum shear stress of 2.4 GPa located 111.0 μm below the surface. The results indicate that compressive residual stress has increased at position 'B' in the x-direction and position 'A' in the y-direction. The residual stress has decreased at position 'A' in the x-direction confirming the results from tests 'A' and 'C'. The differences of residual stress measurements can be explained in terms of the stress field and rolling direction although further experimental investigations are required to confirm the directionality of residual stress. Plasticity or shakedown effects may also have a considerable influence on the measured residual stress field within the material although it is not measured at the maxima. This result does show the importance of measurement direction when interpreting X-ray residual stress measurements in tribological applications.

4.2 Steel Vs Silicon Nitride

A failed lower silicon nitride ball which contained surface pre-cracks was measured, and figure 3b shows the measurements in relation to the failed area. The failed area is complex and has been examined using acoustic microscopy [6]. The failure area contains a delamination failure, subsurface crack propagation (measured using an acoustic microscope) and an unfailed incipient failure region. Measurement 'A' within the delamination area is 150 MPa compressive. The delamination depth measured using laser microscope. The failure depth varies and is maximum at 20 μm. The effective measurement depth is 195 μm within the material. The variation of residual stress with depth of delamination failure was discussed by Hadfield [5]. This study described much higher compressive stress within delamination fatigue failures at corresponding failure depths. The difference of the present delamination measurement could be a result of lower contact stresses and steel Vs silicon nitride contact.

The residual stress value at point 'C' is 108 MPa compressive. If the maximum residual stress occurred at the point of maximum orthogonal shear stress then the difference between point 'A' is understandable. At position 'B' and 'D' (figure 3b) the measurements are substantially lower to those presented for silicon nitride Vs silicon nitride contact. This could be a results of the subsurface crack propagation releasing HIP treatment compressive residual stress. It is clear that more detailed programs are required to investigate the nature of residual stress and its affect on silicon nitride rolling contact fatigue.

4.3 Tungsten Carbide Coating Vs Steel

Figure 4 shows the residual stress measurements within the tungsten carbide upper ball before and after testing. In this case principal stress behaviour was investigated by measuring in 0, 45 and 90° at each point. Residual stress behaviour within thermally sprayed rolling elements with corresponding X-ray diffraction measurements was presented by Ahmed et al [9]. Measurement point 'A' (figure 4a) is positioned at the potential contact path, point 'B' is halfway between the wear track and ball zenith. Figure 4b shows measurement point 'C' located in the middle of test 'E' contact path.

The pre-test measurements (figure 4a) show some variation between points 'A' and 'B'. The values at point 'A' are gereneally higher compressive than point 'B'. This was mainly a result of substrate geometry and complex cooling behaviour during the thermal spraying process. This result infers that the residual stresses measured are strongly related to the thermal residual stress. The calculated principal stress values at points 'A', 'B' and 'C' all indicate compressive direct stress. The maximum shear component is however some 200 MPa tensile. This point is interesting at thermal spray coated rolling elements have been shown to fail at the position of maximum orthogonal shear stress [9]. Clark et al [10] have shown that compressive stresses prolong the fatigue life of rolling element bearings and therefore mode II (shear) fatigue failure is expected from test 'E'.

5. Conclusions

X-ray measurement directionality is important to consider when interpreting residual stress values. The compressive residual stress decreases during rolling contact fatigue tests on HIP silicon nitride. The pre-test residual stress within fully dense silicon nitride corresponds to the HIP pressure. High pre-test residual stress was measured on D-Gun tungsten carbide coatings compared with silicon nitride. The compressive residual stress decreases on the surface of rolling elements during contact fatigue tests on D-Gun tungsten carbide coatings.

Nomenclature

n	Positive integral number indicating the order of diffraction
λ	X-ray wavelength
d	Interplaner spacing in the crystal
θ	Diffraction angle
ϵ	Quantity of strains
θ_0	Diffraction angle in a stress free condition
E	Elasticity modulus
ν	Poisson's ratio
ψ	Angle between sample normal and diffraction plane normal
FWHM	Full Width of Half Maximum

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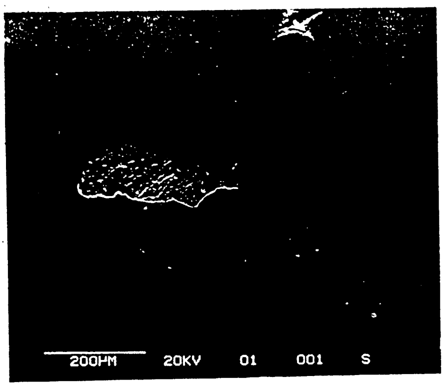
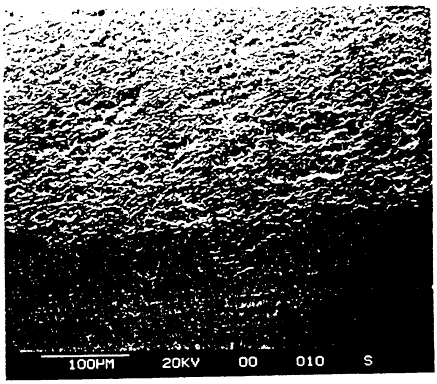
Table 1: Fatigue tests 'A' to 'E'

Test	A	B	C	D	E
Contact	silicon nitride on silicon nitride	silicon nitride on silicon nitride	silicon nitride on silicon nitride	steel on silicon nitride	WC-Co coating on steel
Po (GPa)	7.1	7.6	8.1	6.4	4.5*
Upper ball stress cycles	Suspend after 150 million	Suspend after 150 million	Suspend after 150 million	0.54 million	0.72 million
Oil	HV	HV	HV	LV	HV

*Based on steel/steel contact



(a) Lower ball - test ‘D’



(b) Upper ball - test ‘E’

Figure 1: SEM examples of test surfaces

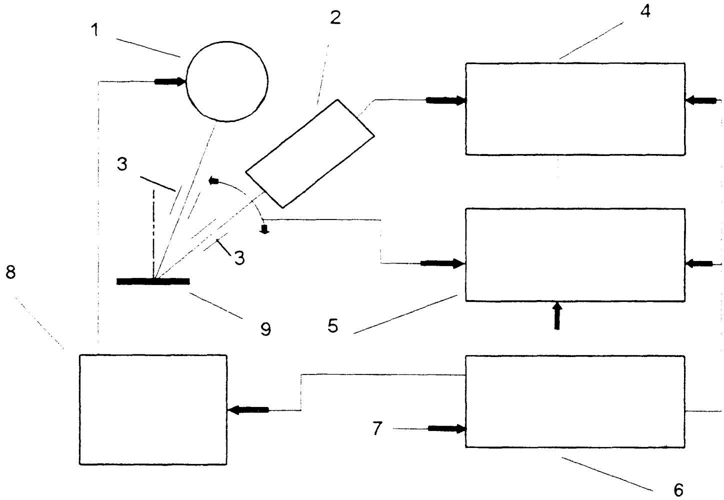
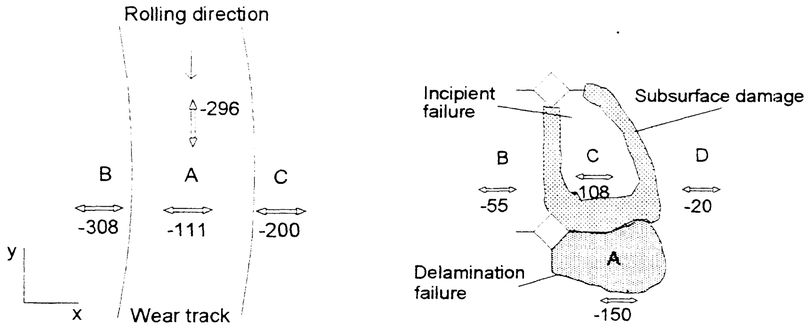


Figure 2: Schematic diagram of X-ray apparatus

1, X-ray tube; 2, counter; 3, slit; 4, rate meter; 5, recorder; 6, stabilised power unit; 7, power input; 8, x-ray generator; 9, specimen



(a) Test 'B' (b) Test 'D'

Figure 3: Residual stress of silicon nitride rolling elements

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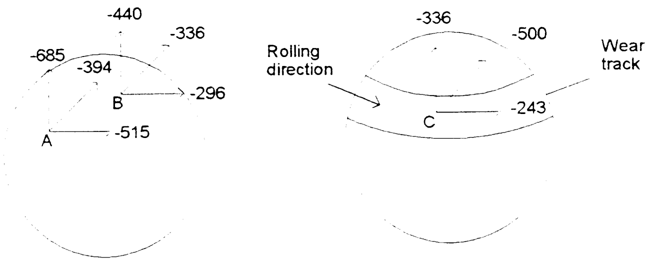

(a) Before RCF test

(b) After RCF test 'E'

Figure 4: Residual stress of tungsten carbide coating elements

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References

[1] Scott,D. and Blackwell,L.,"Hot Pressed Silicon Nitride as a Rolling Bearing Material - A Preliminary Assessment", Wear, Vol. 24, pp.61-67, 1973.

[2] Gielisse,P.J., Wilson,M.P., Borase,V.N., Heung,L.K. and Kiehle, A.J. "Ceramic Materials for High Temperature Gas Bearings" , Report on ONR Contract No. N00014-68-0215-008, September 1972.

[3] Rhys-Jones,T.N., "The use of thermally sprayed coatings for compressor and turbine applications in aero-engines" Surface and Coatings Technology, 42, 1-11, 1990

[4] Munro,H., Tsushima,N. and Nunome,K., "Failure Analysis of Rolling Bearings by X-ray Measurement of Residual Stress", Wear, Vol. 25, pp.345-356, 1973.

[5] Hadfield,M., Stolarski,T.A, Fujinawa,G. and Tobe,T., "Residual Stresses In Failed Ceramic Rolling Contact Balls" Ceramics International, Vol. 19, No.5, pp. 307-313, 1993.

[6] Hadfield,M and Stolarski,T.A., "Observations of Delaminated Fatigue on Pre-Cracked Ceramic Elements in Rolling Contact" Ceramics International, Vol. 21, No. 2, pp. 125-130, 1995.

[7] Ahmed,R. and Hadfield, M., "Rolling Contact Fatigue Performance of detonation Gun Coated Elements", Tribology International Journal, Vol 30, No. 2, pp.129-137, 1997.

[8] Farrahi,G.H., Markho,P.H. and Maeder,G., "A Study of Fretting Wear with Particular Reference to Measurement of Residual Stresses by X-ray Diffraction" Wear, 148, 249-260, 1991.

[9] Ahmed,R., Hadfield,M. and Tobe,S,"Residual Stress Measurement of HVOF Coated Elements" Proceedings of the 9th National Thermal Spray Conference, 7th-11th October, Cincinati, Ohio, USA, ISBN 0-87170-583-4, pp. 875-883, 1996.

[10] Clark,J.C., "Fracture Tough Bearings for High Stress Applications" Proc. 21st Joint Propulsion Conf., Paper AIAA-85-1138, 1985.