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Residual stress variations during rolling contact fatigue of refrigerant lubricated silicon nitride bearing elements

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Abstract

The residual stress field of rolling contact silicon nitride bearing elements with refrigerant lubrication was studied. Residual stress measurements were performed using X-ray method. Rolling contact fatigue tests were performed at various Hertz contact stresses using a modified four ball machine coupled with a pressurised chamber. Residual stress value of −242 MPa measured at 0.1 millions stress cycles and −60 MPa at 5.6 millions stress cycles shows an inverse relationship between residual stresses and rolling contact fatigue cycles. These results are helpful in predicting rolling contact fatigue life. Residual stress measurements were also performed on the contact path at various distances from the induced ring crack. The residual stress field analysis shows that residual stresses are relieved due to sub-surface damage. Maximum contact stresses at the edges of the contact path due to Hertz contact stress causing a weaker residual stress field at the sub-surface crack front.

Keywords: Rolling contact; Silicon nitride; Bearing elements; Refrigerant lubrication; Residual stress

1. Introduction

Silicon nitride Si_3N_4 bearing elements have shown practical advantages over traditional steel elements due to their mechanical and physical properties [1,2]. Leading technology, demands for high efficiency and importance of sustainable development have caused loading bearing contacts in all kinds of machinery to be subjected to high speeds, high contact stresses and severe conditions of lubrication. In addition the introduction of new generation of hydrocarbon refrigerants in various systems, where these rolling contact silicon nitride bearing elements are employed raises further demands to evaluate the rolling contact fatigue performance of these elements with refrigerant lubrication.

Since these rolling contact bearing elements are subjected to high cyclic contact stresses the surface and sub-surface residual stresses are highly important in establishing a relationship to fatigue life performance. An understanding of residual stress within complex materials is needed to evaluate the effect of the manufacturing process, characterise failure modes and evaluate the in-service loading conditions of the concentrated rolling contacts [3]. The finishing process parameters have influences on the residual stresses [4]. It is important to carry out an assessment of residual stresses induced during the manufacturing process and in-service conditions to make suggestions on the design parameters related to residual stress. Analysing the relationship of residual stresses with rolling contact fatigue is an important study which will provide guidelines on the design, process and manufacturing of these elements. The residual stress value within the silicon nitride will vary due to primary processing (hot isostatically pressing) and surface finishing methods [3]. In respect to surface finishing methods there is significant pressure to

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accelerate material removal rates to reduce product financial costs. In addition to traditional grinding and lapping methods new processes such as magnetic force [5] and tribochemically [6] assisted have been considered for silicon nitride materials. It is therefore necessary to monitor manufacturing residual stresses with in the finished silicon nitride bearing elements.

In this paper experimental residual stress measurements of silicon nitride are presented. Residual stress measurements were performed on refrigerant lubricated rolling contact fatigue (RCF) failed bearing elements with ring crack defects. A feature of this study is the small irradiation volume of 0.0942 mm^3 which enabled residual stress measurements of specific points on the rolling contact path. Rolling contact fatigue tests with refrigerant lubrication is briefly described. X-ray methodology for residual stress measurement is briefly outlined followed by experimental results and discussion.

2. Testing methodology

2.1. Residual stress measuring procedure

Rigaku Rint X-ray diffractometer was employed during this research for RS measurements. The machine parameter can be controlled by an engineering workstation using Rint 2100 XG control in Unix system. A schematic of the measurement apparatus is shown in Fig. 1. The type of X-ray used was Cr K-Alpha1. The X-ray tube voltage was 40 kV, tube current was 200 mA and power of 8.0 kW was used, 2θ peak angle/peak was 125°. A scanning range of 120° start and 130° stop were selected with a step angle of 1° and sampling time of 100 s. An incident beam of X-ray is radiated through a collimator. The collimator diameter chosen was 2 mm in order to enable X-ray penetration on a comparatively larger surface area as compared to 1 mm diameter collimator. Larger surface area for sampling RS measurement data increases accuracy. The incident X-ray beam is penetrated sub-surface with in the material to a depth of 30 μm. Thus the residual stress is measured through 0.0942 mm^3 cylindrical volume of irradiation. Material young's modulus for silicon nitride was taken as 27.4×10^4 MPa, and Poisson ratio as 0.26. A detailed description of the fundamentals of X-ray analysis can be found in [7,8].

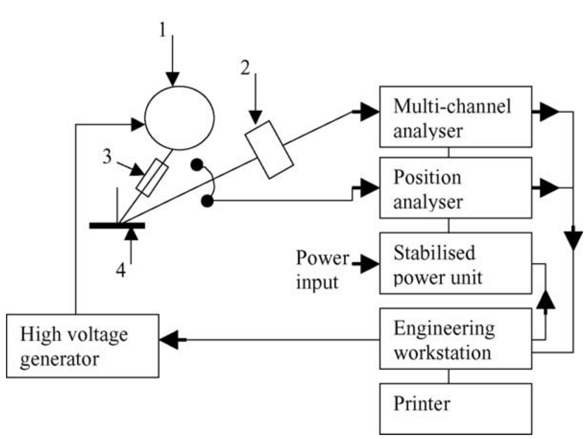

Fig. 1. Schematic diagram of X-ray apparatus. (1) X-ray tube (rotary type); (2) position sensitive proportional counter (PSPC); (3) collimator and (4) specimen.

Table 1
Residual stress measured values for RCF tested specimens ($x = 0.1$ mm)

Specimen	Number of stress cycles × 10^6	Time to failure (min)	Residual stresses (MPa)	Reliability (MPa)
A	0.08	17	−242	±57
B	1.07	237	−217	±73
C	1.08	240	−209	±67
D	1.62	360	−164	±44
E	3.11	692	−84	±54
F	5.62	1248	−60	±26

2.2. Rolling contact fatigue experiments

During this research the rolling contact bearing elements were pre-cracked with ring cracks that have known geometry. The influence of the geometry, orientation and positioning of these ring cracks on the rolling contact fatigue life have been studied in recent researches [2,9].

In this paper a residual stress measurement survey is presented for the rolling contact silicon nitride/ceramic bearing elements. The RCF tests were conducted with pressurised hydrocarbon (HC) refrigerant lubrication. RCF experiments were performed at 3, 4 and 5 GPa maximum contact stress.

3. Results and discussions

Twenty RS measurement results for six specimens are presented in Tables 1–5. CRS values for six specimens measured at various stress cycles are provided in Table 1. These values are measured at a distance of 0.1 mm away from the ring crack on the contact path. A high value of compressive residual stress (CRS) 242 MPa is measured for specimen A with least number of stress cycles. While a lowest CRS value of 60 MPa was registered for specimen F with highest RCF stress cycles. These results demonstrate a consistent relationship of CRS with the RCF stress cycles. The CRS–RCF relationship is shown in Fig. 2. This

Table 2
Residual stress measured values for RCF tested specimen A

x (mm)	Residual stresses (MPa)	Reliability (MPa)
0.1	−242	±57
0.2	−162	±55
0.3	−161	±45
0.4	−144	±35
0.5	−97	±31

Table 3
Residual stress measured values for RCF tested specimen B

x (mm)	Residual stresses (MPa)	Reliability (MPa)
0.1	−217	±73
0.2	−150	±23
0.3	−146	±29
0.4	−127	±24
0.5	−121	±27
0.6	−38	±9

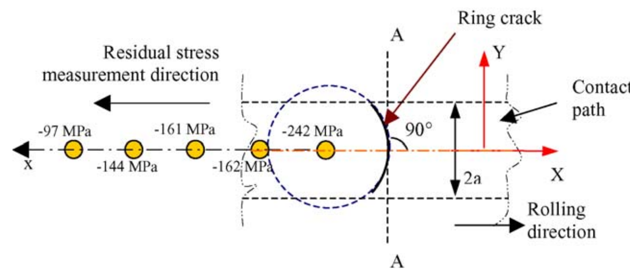

Fig. 3. Showing residual stress measurements points for specimen A.

Table 4
CRS values along rolling direction for specimen F

x (mm)	Residual stresses (MPa)	Reliability (MPa)
0.0	−73	±26
0.1	−60	±26
0.2	−42	±21

Table 5
CRS values opposite to rolling direction for specimen F

x (mm)	Residual stresses (MPa)	Reliability (MPa)
0.0	−73	±26
0.1	−52	±18
0.2	−48	±27

relationship is useful in predicting RCF performance of bearing elements.

Fig. 3 shows RS measurements points and direction of measurement for specimen A. The measured CRS values at five different points on the line X are presented in Table 2.

The maximum value of CRS measured is 242 MPa at a nearest distance 0.1 mm from the induced ring crack. The lowest value recorded on this line was at a distance of 0.5 mm which was 97 MPa compressive. These tests suggest a decrease in the CRS with increased distance from the initial crack. RS measurements for specimen B are presented in the Table 3. These results show similar phenomenon as specimen A. A maximum CRS value of 217 MPa was registered at 0.1 mm from the crack on the contact path. A minimum CRS value of 38 MPa at a distance of 0.6 mm was measured. The relationship of CRS and the distance from the induced defect is shown in Fig. 4.

Higher CRS at or near failure could be a result of the subsurface crack propagation releasing hot isostatically pressed (HIP) treatment CRS [3]. The sub-surface crack initiation and propagation causes a weaker residual stress field at the sub-surface crack front.

The measured RS values for specimen F are shown in the Tables 4 and 5. These RS values were measured along the rolling direction and opposite to rolling direction.

The value measured at zero distance from the crack on both directions remained unchanged. This could be explained in terms of the measuring point being right above the crack opening and measurement was performed at a depth of more than 30 μm. Therefore changing the direction has no significant influence on the CRS value at that particular point. However, when the direction for the 2nd measuring point was changed the CRS value changed from 60 to 52 MPa, keeping the difference in values and reliability factor in consideration, this change is not very big, however does suggest a relationship between the rolling direction and RS measuring direction. RS measurement the on 3rd point for specimen F repeats the same change. The CRS value changed from 42 to 48 MPa. The difference of residual stress measurements

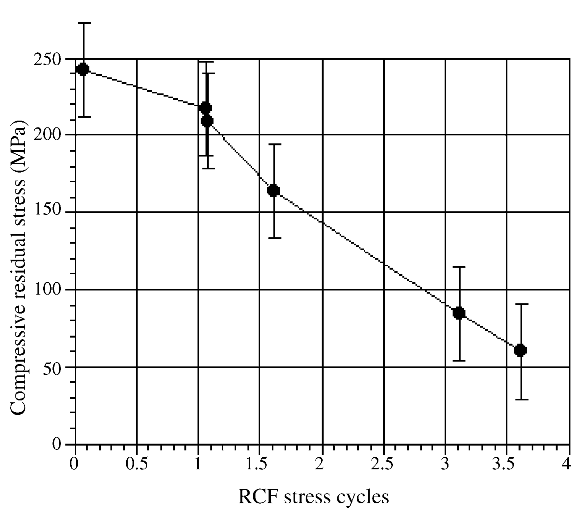

Fig. 2. Compressive residual stress relation to RCF stress cycles.

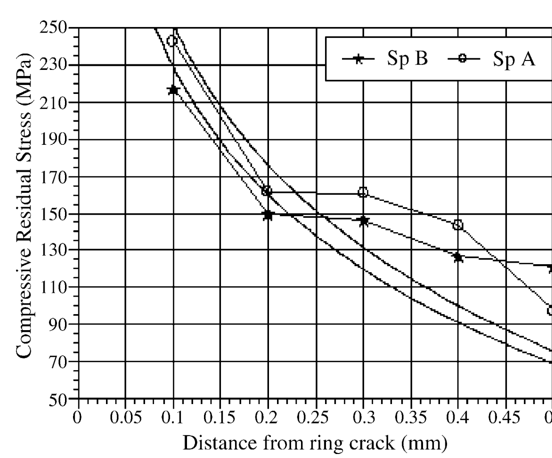

Fig. 4. Compressive residual stress analysis at various distances from ring crack (specimens A and B).

can be explained in terms of the stress field and rolling direction although further experimental investigations are required to confirm the directionality of the residual stress [3]. Current investigation suggests that the RS measuring direction will cause the RS value to change. Although the change in the RS values is not very big, the rolling direction in relation to RS measurement direction is significant.

4. Conclusions

Compressive residual stresses are indicative of the rolling contact fatigue life performance. The compressive residual stresses are acting in a plane opposite to the applied Hertzian contact stresses, therefore, enhances the fatigue life. An inverse relationship of compressive residual stresses to the number of stress cycles during rolling contact fatigue can be used as a measure of the remaining life.

Residual stresses are relieved much faster in the fatigue damaged region. The sub-surface crack initiation and propagation develops a weaker residual stress field at the sub-surface crack front. Secondary surface cracks reduce the magnitude of the residual stresses. High residual stress value at the crack could be the result of lower Hertzian contact stresses and phenomenon of the maximum orthogonal shear stresses at the pre-cracked area.

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