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TITLE: Rolling wear of silicon nitride bearing materials with refrigerant lubrication

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ABSTRACT BODY:

Body: This paper presents the experimental results of wear in rolling hybrid ceramic (Si_3N_4) bearing material with hydrocarbon HC (R600a, CH (CH3)3, 2-methyl propane/Isobutane) refrigerant lubricants. A novel pressurised chamber was designed to construct the special purpose rig to achieve saturated liquid state of the refrigerant as fluid for the rolling contact fatigue experiments. High Speed four ball Rotary Tribometer was used for rolling contact fatigue tests.

This paper presents an experimental study of the influence of the HC (R600a) refrigerant environment on rolling wear of the silicon nitride/steel elements and shows various modes of failures. Rolling fatigue test methods were used to measure the wear performance of silicon nitride/steel bearing materials. Light microscopy was used to examine the material surface before carrying the tests. Light microscopy was employed for surface examination during and after tests. Scanning Electron Microscopy (SEM) was used for imaging. Failure modes and rolling wear performance for these ceramic materials in HC refrigerant environment were analysed. Experimental results are presented in this paper.

Introduction

Due to environmental impact legislation, refrigerants have evolved to include Hydro fluorocarbons (HFC) such as R134a and Hydrocarbons (HC) such as R600a. Obtaining material wear properties of these refrigerants used in mechanical applications is difficult due to the high saturation pressure of the refrigerants. It is important to assess the in-use durability performance of these products from a sustainable development viewpoint. This research responds to the need for bench testing of rolling contacts using the new generation refrigerants as lubricants. Typical properties of the refrigerants used during rolling contact fatigue testing are provided in Table 1.

Table 1 Typical Properties of Refrigerants used1

Property on a weight basis	R600a	R134a
Boiling point, °C, at 1 atmosphere	-11.8	-26.1
GWP2	<4	420
ODP3	0	0
Viscosity of liquid at 30°C, centipoises	0.14	0.20

It is necessary to build a Pressurised Chamber (PC) to provide a controlled atmosphere with respect to temperature and pressure while conducting tests on a four-ball rotary tribometer. The advantage with the new PC is that it can be fitted

1 Source of data (Acrib 2000)
2 GWP (global warming potential) is relative to carbon dioxide = 1
3 ODP (ozone depletion potential) is relative to R12 = 1

with shaft rotation as high as 5,000 rpm. The new chamber has a cylindrical structure that reduces its dimensions, increases safety and a new smaller shaft seal replaces the mechanical seal [1, 2]. Some of the Pressurised Chamber PC test characteristics are tabulated as follows in Table 2.

Table 2 Test and Fluids Characteristics

Characteristics	Rolling test
Inside Pressure	3-4 bar
Refrigerant temperature	30 °C (Max)
Shaft Speed	Up to 5,000 rpm
Refrigerant state	Liquid/gaseous

The environment pressure of the lubricant was 3-4 bars to achieve the liquid state of the refrigerant according to the pressure enthalpy chart. The lubricant temperature was ~25 °C.

Surface wear

Test results are shown in table 3

Table 3 Test results at 2000 rpm spindle speed

Test Ball	Test Ball condition	Environment	Max. contact pressure (GPa)	Time to Failure	Stress cycles
1	30 deg (h)	R600a -liquid	3	6hrs	1.62×106
2	30 deg (h)	R600a -liquid	5	18hrs 23min	4.96×106
3	30 deg (h)	R600a -liquid	4	1hr 33min	4.19×105
4	30 deg (v)	R600a - vapour	6	0hr 03min	1.35×104
5	30 deg (v)	R600a - liquid	4	0hr 33min	1.49×105
6	18 deg (v)	R600a - liquid	3	20hr 48min	5.62×106

Surface wear is one of the most common mechanisms of failure in rolling contact ceramic bearings. In ceramic/ceramic contact, wear particles are generated mechanically without the mechanism of fatigue wear even under elastic contact [3]. This is the representative wear mechanism of ceramics when specific wear rate is larger than 10-6 mm3 / Nm [4]. At a critical number of fatigue cycles the break-up of the material surface results in the formation of pitting. The fatigue crack develops and a region of metal is separated from the base metal and eventually detaches and spalls out. Eventually these cracks grow large enough to emerge at the surface and produce wear particles; these particles then become large spalls or flakes. Preliminary work used a modified four-ball machine to assess hot-pressed silicon nitride as a rolling bearing material [5].

Wear particles are continuously detached from the surface during propagation of surface cracks. When a tangential traction is acting along the contact surfaces, the maximum tensile stresses always occur at the trailing edge of the contact [6]. The stress field around the contact area is provided by the classical solution from [7]. The maximum tensile stress at the edge of the contact area is given by

$$s_{t,\max} = \frac{1}{8} p \left(4+v\right) f p_0 + \frac{1}{3}\left(1-2v\right) p_0 \qquad (1)$$

Where f is the friction co-efficient, p_0 the maximum Hertzian contact pressure and v is Poisson ratio.

The positioning and orientation of the induced ring crack for this specimen 3 is shown in figure 24 A [1]. This result was recorded at 4.19×105 stress cycles. Initiation and propagation of secondary cracks results in the loss of material particles due to rolling contact wear. Specimen 5 result was recorded at 1.49×105 stress cycles.

Figure 1 is an atomic force micrograph (AFM) for specimen 1 showing a 3-dimensional surface profile. Specimen 1 was tested at 3 GPa maximum Hertz contact stress. The positioning of the ring crack for specimen 1 is shown in figure 24 A [1]. The surface profile at the contact path was recorded at 6 hours of test time and 1.62×106 stress cycles, with liquid refrigerant lubrication. The surface roughness Ra on the contact path was 0.02 µm. after 6 hours of test time compared to 0.01 µm average surface roughness of the ceramic ball.

A wear profile of the contact path is shown in figure 2 for specimen 6. A contact type Profilometer was used to obtain this result. The probe radius of the Profilometer was 5 µm. This result was obtained after 20 hours 48 minutes of test time. Wear profile on the contact path with projected edges and centre is generated by differences between steel and ceramic balls according to Young's modulus. The lower steel ball has a Young's modulus of 210 GPa while that of the upper ceramic ball is 320 GPa. Other reasons may be due to stick and slip during rolling contact.

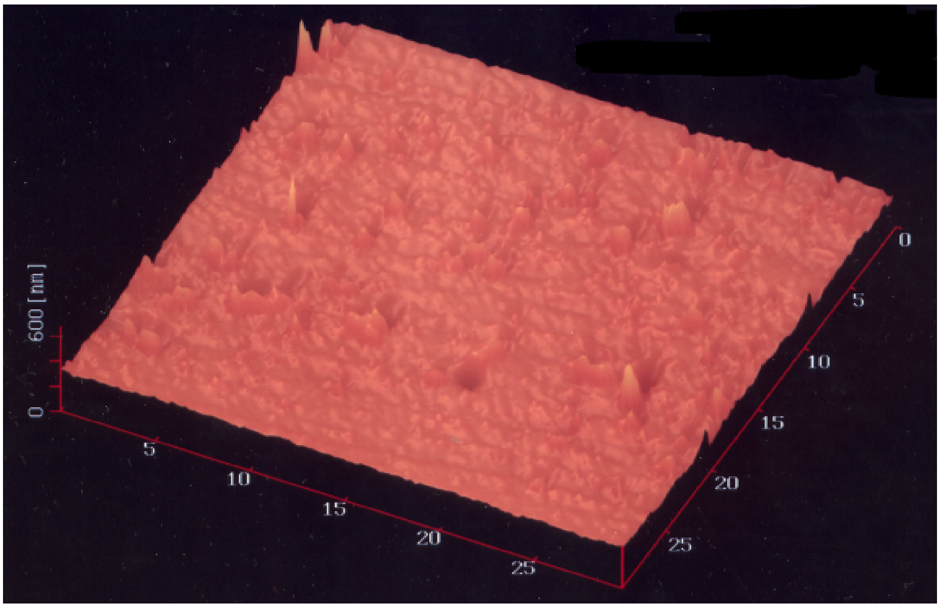

Figure 1 Atomic Force Micrograph surface profile; specimen 1

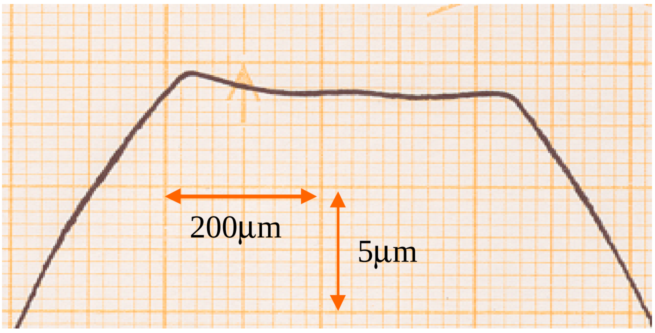

Figure 2 Contact path wear profile for specimen 6

Figure 3 and 4 shows surface profiles of the spall for specimen 2. Specimen 2 was subjected to a maximum contact stress of 5 GPa, spindle speed of 2000 rpm with liquid refrigerant lubrication. The induced ring crack was positioned horizontally to the contact path as in figure 24 B [1]. Specimen 4 was subjected to maximum contact stress of 6 GPa, spindle speed of 2000 rpm with vapour state of the refrigerant as lubrication. The induced ring crack for specimen 4 was positioned vertically as in figure 24 B [1].

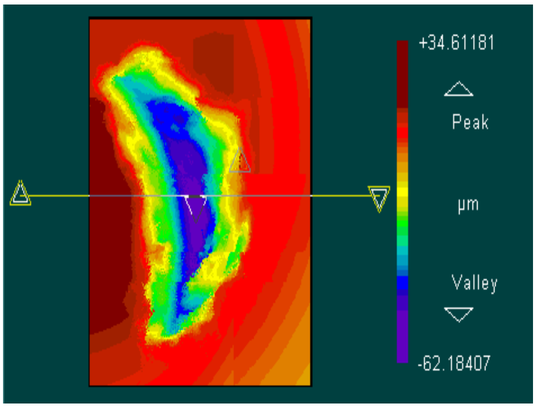

Figure 3 Surface profile; spall specimen 2

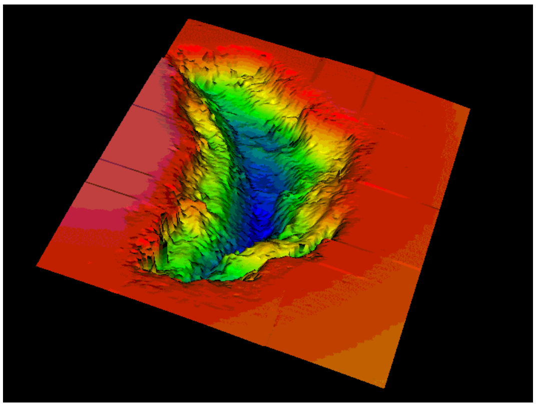

Figure 4 3-dimensional surface profile; spall specimen 2

A 3-dimensional surface profile of the spall for specimen 4 is provided in figure 5. A comparison of the spall characteristics for specimens 2 and 4 was performed. The comparison of the spall depth (peak valley), rms (root mean square) and roughness (Ra) is compared for specimens 2 and 4 in figure 6.

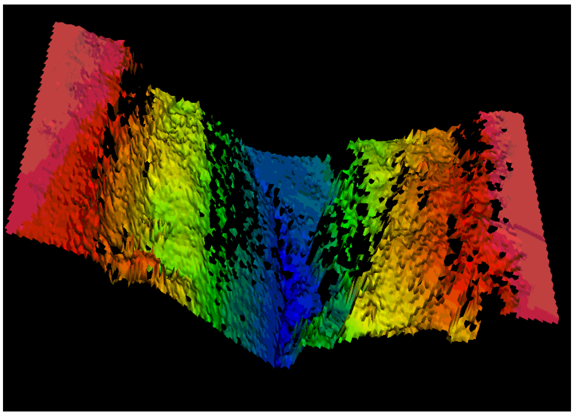

Figure 5 3-dimensional surface profile; spall specimen 4

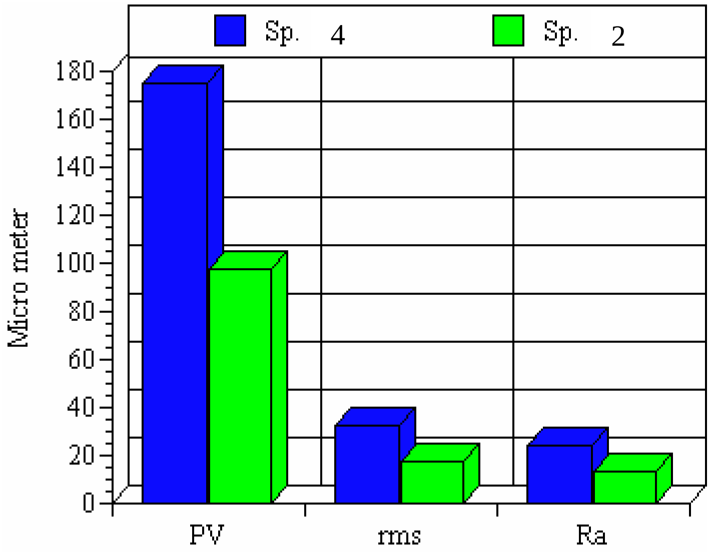

Figure 6 Comparison of the fatigue spall characteristics of specimens 4 and 2

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