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MECHANO-EROSION: A NOVEL TEST METHODOLOGY TO ACCELERATE EROSION IN ROLLING CONTACT FATIGUE EXPERIMENTS

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ABSTRACT

Rolling contact fatigue testing of rolling elements with low saturation temperature lubricants result, in several difficulties. Mainly, uncontrolled phase changes due to flow dynamics often cause difficulties in assessing the lubricant effect on fatigue life. This work simulates these conditions for testing in a controlled environment to understand the mechanism of material wear. A rotary tribometer was modified to allow an ultrasonic transducer. This modification made it possible to bring the two different phenomena Rolling contact fatigue and Erosion together. With this novel testing method, erosion was created on the contact track within a short period of time. Moreover, Erosion characteristics and its effects on rolling contact fatigue testing were monitored and these preliminary results are presented in this paper.

KEYWORDS: Rolling contact fatigue, Rotary tribometer, Ultrasonic transducer, Erosion, Lubrication.

1. Introduction

Hybrid bearings made of silicon nitride rolling elements with steel races have shown several advantages over all steel bearings [1, 2, 3]. Particularly in refrigeration and air-conditioning units, the ability to run in working fluid eliminates the necessity for a separate oil lubrication system and offer many advantages [9, 11]. This concept of oil-free lubrication opened up huge potential applications in compressors and pumps used in refrigeration and air-conditioning units, high speed and light weight turbo pumps used in space applications. In employing refrigerant as pure lubricant, careful measures are made to ensure that the refrigerant stays in the liquid state for lubrication purposes. However, phase changes due to pressure variations at high speeds cannot be avoided which result in cavitation, a primary concern for material wear in this area of oil-free lubrication. Also, due to high speeds and loads rolling contact fatigue plays a part in material damage along with cavitation. Wear characteristics in this application is not clearly understood. Any further advancement in this field largely depends on understanding this wear mechanism which limits the bearing speed and life. Wear of mechanical systems with refrigerants and Rolling contact fatigue testing of these materials in refrigerant lubrication was reported [4, 10]. The gas/liquid phase transition has a significant influence on the wear mechanisms of traditional lubricants and need to be investigated [4]. Hence a controlled level of gas/liquid phase in lubricant whilst testing is necessary to perform this study. Rolling contact test machines alone are not suitable to perform this testing. A new test machine or an available test machine should be modified for this task. This work presents a novel test methodology to address this issue by modifying a rotary tribometer.

2. Testing methodology

A rotary tribometer and an ultrasonic vibratory system are utilized for this testing. Different types of rolling contact fatigue test machines are used to study material wear and lubrication characteristics in rolling contact. These are (1) Four-ball machine, (2) Five-ball machine, (3) Ball-on-rod machine, (4) Ball-on-plate machine, (5) Disc-on-rod machine and (6) Contacting ring machine. The major difference between these test machines are the contact geometry and loading configuration of test materials. Laboratory cavitation erosion experiments can be broadly divided into hydrodynamic and acoustic cavitation. Acoustic cavitation is a process of creating cavitation by applying high intensity ultrasound to liquids. This is advantageous over hydrodynamic method, with a small test rig size, consumes less power and creates erosion in a short duration of test time. Acoustic cavitation uses either a piezoelectric or magnetostrictive transducer.

2.1. Ultrasonic vibratory system

This work utilizes a commercially available ultrasonic vibratory system, which has an ultrasonic generator and a piezoelectric transducer as main components. This high power intensity system can generate acoustic power in the order of 400 -600 watts. This piezoelectric transducer end is coupled with a horn by a screw. The purpose of the horn is to amplify the vibration generated by the transducer. The transducer-horn assembly design is a stepped structure and is made of titanium alloy to provide superior resistance to cavitation.

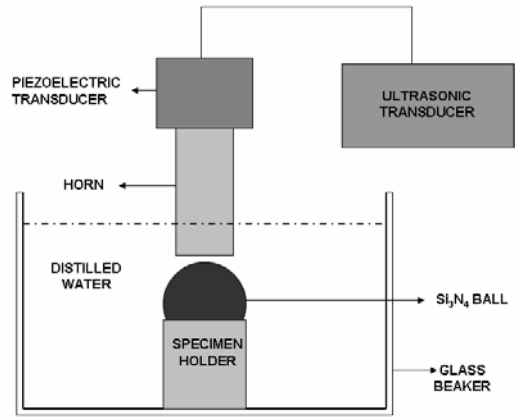

Fig.1. *Cavitation erosion test setup*

This system operates at a fixed frequency of 20 KHz. Amplitude of vibration of the horn can be adjusted from 0 – 60 μm peak-to-peak and continuously monitored during the tests. The horn design was carefully selected to couple with the test chamber of the rotary tribometer.

A horn diameter of 5 mm and the total length of the transducer horn assembly of 95 mm are selected for this purpose. Initially, cavitation erosion experiments on silicon nitride are conducted to test this system and also for later comparison to the results obtained from the new testing methodology. Fig.1 shows the schematic of cavitation erosion test setup. These experiments were conducted in distilled water.

Commercially available silicon nitride rolling elements were used as test materials. A low form beaker was used as testing system with distilled water in it. This test method was carried out in accordance with the ASTM standard [14]. Test specimens are generally machined to a threaded form which is then attached to the horn tip. For materials with machining difficulties, stationary specimen approach is used.

This approach allows holding the test specimen stationary in a holder close to the transducer horn. Because it is difficult to machine a silicon nitride ball, the stationary specimen approach was selected for this testing. Before testing, test specimens were visually examined using a light microscope to make sure they were free from any surface defects. The distance between the horn tip and the test specimen was determined by a feeler gauge. The piezoelectric transducer was excited at full power and a magnitude of vibration of 60 microns. Erosion initiation was noted in a very short duration of time of three minutes. These initial stages showed surface roughening, which accelerated the rate of material removal. Tests were continued for a maximum duration of 30 minutes and severe erosion was observed as shown in fig. 2 and 3. Material removal was largely due to the formation of pits resulting from grain pull outs. In later stages, pits joined together and appeared to be larger ones. This resulted in huge loss of material. These experiments are vital for understanding the erosion behaviour in the new test method. Moreover, this erosion test system was satisfactory to be utilized for this study.

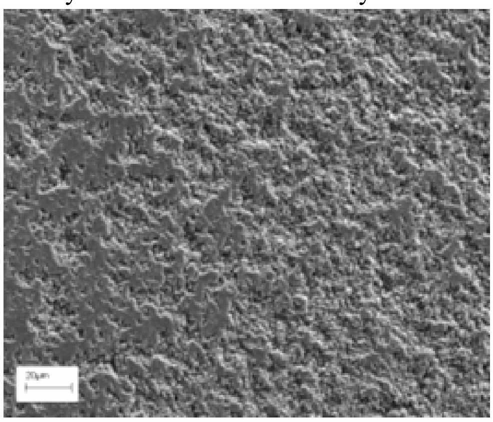

Fig.2. *SEM image of eroded surface*

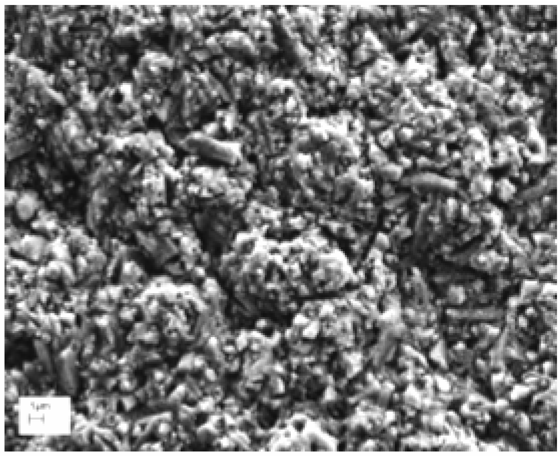

Fig.3. *High magnification of erosion*

2.2. Mechano-Erosion testing

The four-ball machine presented in this paper is a TE92 Microprocessor Controlled Rotary Tribometer. Advanced control and instrumentation in this machine makes it possible to conduct tests in a wide range of speeds and loads. The test chamber consists of a steel cup, oil bath, lower balls, and an upper ball for applying load and transferring motion effectively as shown in fig.4. The cup, lower three balls and the upper ball represents the outer, rolling elements and inner race of a bearing respectively. This test chamber simulates an angular contact ball bearing configuration.

This test machine is very useful for rolling contact fatigue study of materials under different conditions [5-7, 12–13] and hence selected for this work.

The upper ball is fixed to a drive spindle and its accurate positing is achieved by two rigid vertical columns of the machine. Load is applied by a pneumatic actuator; this actuator assembly includes an in-line force transducer to get the direct feedback control. Direct friction and torque measurements are also possible by a strain gauge transducer attached to the test adapters, which are mounted on a cross beam, guided by linear bearings on the machine columns. Tests can be conducted at high temperatures up to 200 ^{0}C which is continuously monitored by a thermocouple attached to the test chamber. A computer connected to the machine, provides a graphical user interface to run, control and record tests. A test is a set of series of steps, each with load, speed and temperature, data recording and alarm information. In order to combine erosion testing to this rotary tribometer, the four ball machine test chamber had to be modified. The best way to achieve this is to include the erosion setup in the test chamber as shown in fig 4. From the erosion bench testing, it was found that the rate of erosion was proportional to the distance between the transducer horn and the sample. The closer the horn tip to the test specimen would increase the erosion rate and therefore reduce the test time.

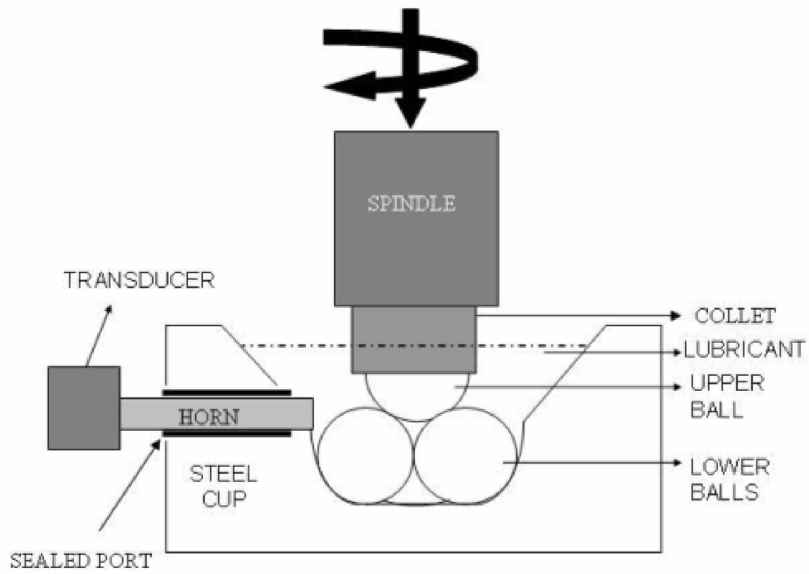

Fig. 4. *Schematic of Mechano-erosion test configuration*

A port had to be designed and made in the steel test cup to fix the piezoelectric transducer. The location of the port was carefully designed to allow the horn tip to be held close to the rolling elements and ensured no disturbance to their dynamics by contact. A high carbide drill bit was used to create the port of 6 mm diameter on the steel cup. Major challenge rose when a proper sealant had to be found to seal the transducer in the port. The purposes of the sealant are as follows:

1. To hold the piezoelectric transducer in the test chamber
2. To seal off the port to prevent any lubrication leakage
3. To allow the transducer horn to vibrate freely without constraining, and thereby eliminating any heat generation due to sliding contact.

This eliminates the possibility of using any mechanical seals. A high temperature adhesive sealant was selected for this purpose. The female part or the port on the steel cup was filled with this sealant and was allowed to set for a time period of 24 hrs. The centre point of the port was carefully marked and a hole of 4 mm was drilled. This helped the piezoelectric transducer to fit tight enough into the port as shown in fig. 4. The distance between horn tip and the rolling elements was fixed for all tests. One other important design alteration was to create a support for the piezoelectric transducer in the rotary tribometer. This is because when testing starts, the two rigid vertical columns guide the test chamber to move vertically upwards to apply load and rotation by the drive spindle. When test specimen fails eventually, the test chamber moves back to its initial position. Any external support to hold the transducer in the test chamber would cause damage to the transducer and break the sealing during this test cycle. An aluminium block with a conical cut at the middle was clamped with the tribometer test chamber beam. This conical cut ensured a safe design to fix the transducer, and moreover this whole setup can be moved horizontally giving more freedom for increasing or decreasing the distance between the horn tip and the rolling elements. Test chamber was cleaned with acetone before each test to ensure no debris presence to avoid any abrasion. For preliminary tests, a low viscosity paraffinic hydrocarbon lubricant was used mainly to increase the erosion rate. These tests were carried out at different speeds and loads as shown in the table 1. Tests were run for a specified duration of time to understand the erosive wear progression at different stages of material wear under this condition. All the test samples were smooth silicon nitride balls of 12.67 mm diameter. A forced air cooling system was employed to cool the transducer horn. After each test, samples were cleaned in acetone for 20 minutes in an ultrasonic bath and then dried using a dryer before set for surface analysis. A light and a scanning electron microscope were utilized for this purpose.

4. Preliminary results and discussion

For testing, the piezoelectric transducer was inserted in the test chamber of the high speed tribometer as mentioned in the testing method. The test specimen, silicon nitride smooth ball was held by means of a collet in the drive spindle. The average surface roughness of the test specimens was 0.01 um. For hybrid contacts, lower balls of carbon chromium steel was used, which are of same diameter of the test specimen. Hardness of silicon nitride and lower balls was 1650 and 840 Hv. The transducer was excited at the maximum power, and amplitude of 60 µm peak-to- peak.

Table 1 *Preliminary experiments test programme*

Test	Contact stress (GPa)	Shaft speed (Rpm)	Lubricant $2.4\ mm^2/s$ at 40^0C	Vibration Amplitude (µm)	Stress cycles	Test time (Hrs)
A	3	2000	Macron 110	60	2.53×10^5	2
B	3	3000	Macron 110	60	7.63×10^5	4
C	5.1	2000	Macron 110	60	5.07×10^5	4
D	5.1	5000	Macron 110	60	1.17×10^6	4
E	5.1	5000	Macron 110	60	1.76×10^6	6

3.1 Surface Analysis

Results obtained from these tests are promising. Erosion was formed on the contact track in a short duration of time of 30 minutes at a speed of 5000 rpm. Rolling contact fatigue testing for few hours under similar loads and speeds with same lubricant was also examined.

No sign of material damage was noticed.

A light microscope image of the contact track with erosion pits is shown in fig 5.

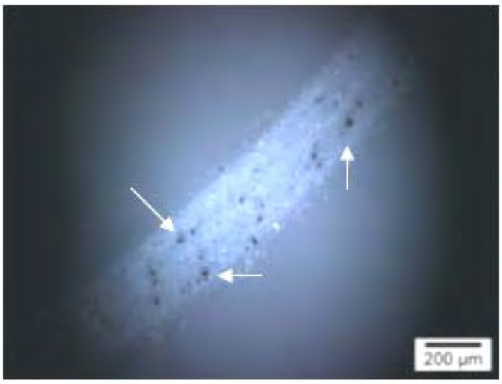

Fig.5. *Light Microscope image of the ball showing erosion pits on track.*

This is test A, with a maximum contact pressure of 3 GPa and with the spindle speed of 2000 rpm. Apart from the tiny pits, few number of large erosion pits were noted on this test specimen. The surface away from the contact track remained smooth as before the test. This is very much evident that both cavitation erosion and rolling contact fatigue played a role in material wear process under this testing condition.

The initial stage of material wear showed increase in surface roughness on the contact track, which became the primary factor for erosion acceleration. As the roughness of the test balls increased during the course of testing, it formed a more favourable condition for bubble nucleation. This helped in rapid cavity growth and collapse; this violent collapse increased the erosion rate. This initial stage was then followed by formation of tiny erosion pits. These pits were formed by removal of material which was encapsulated by a weakened boundary due to erosion as shown in fig 6. This was observed in the test B. Because of rolling with contact stresses these pits appeared with a unique geometry in a crescent shape as in fig 7. This is of test C with a maximum contact pressure of 5.1GPa and a spindle speed of 2000 rpm.

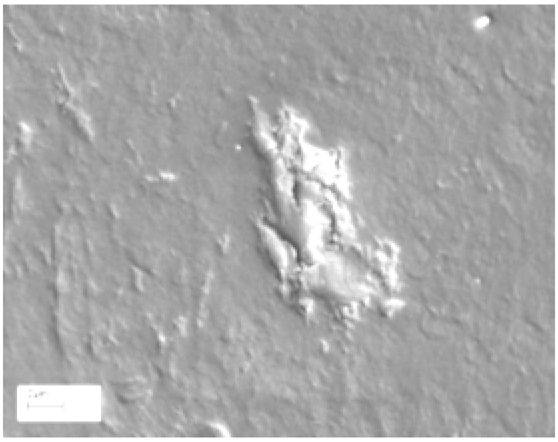

Fig.6. *Erosion pit initiation from roughened surface*

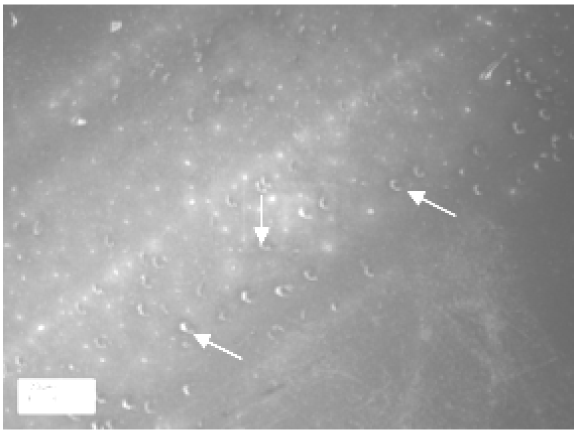

Fig.7. *Crescent shaped erosion pits*

These crescent shaped pits enlarged further by opening up their mouth during the course of wear process, which is shown in fig 8. This part of the wear needs further investigation.

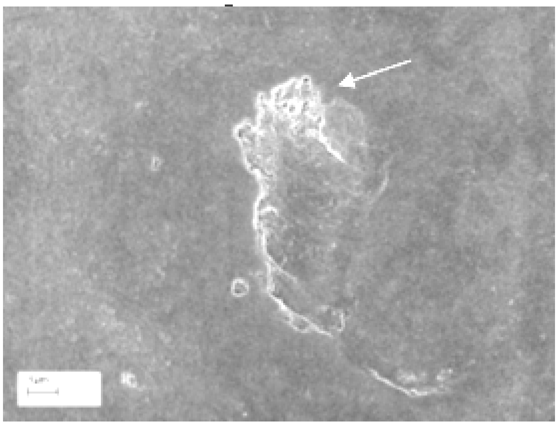

Fig.8. *Close up of crescent pit showing mouth opening*

When both load and speed were increased as in test D, a maximum contact pressure of 5.1 GPa and 5000 rpm. Erosion pits showed clear directionality in their growth and were joined together with the adjacent pits in a process called pit bridging as shown in fig 9.

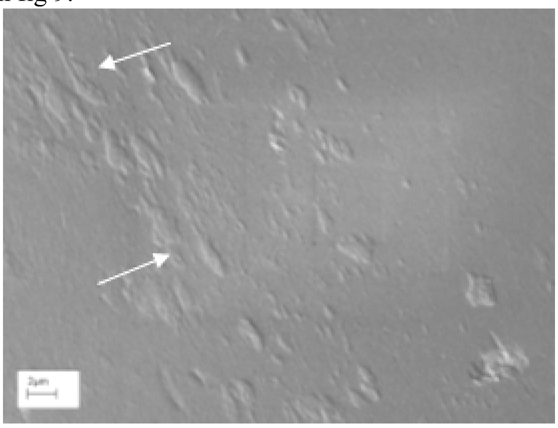

Fig.9. *Directionality of erosion pit growth*

The closer look of an erosion pit is shown in fig 10 which was from the same test D. Almost all erosion pits appeared in the similar shape and size. Erosion pits didn’t grow deeper, because of lubricant squeezing into the pits and acting as a cushion for any further cavity collapse. This will also retard the rate of erosion, but will result in a minimum loss of material as the process continues. The final stages of this wear process ended up with the signs of more erosion on the contact track. As more pits formation leads to a dense area of pits on the track, the test specimen will eventually fail due to spalling. Test E with more test time of 6 hrs at a maximum contact pressure of 5.1 GPa and a spindle speed of 5000 rpm resulted in enormous density of erosion pits and is shown in fig. 11.

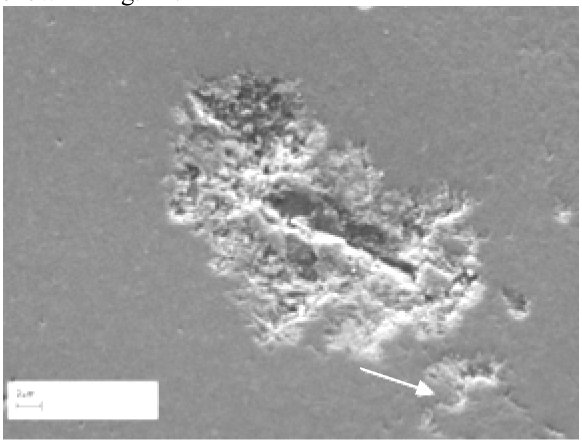

Fig.10. *Large erosion pit surrounded by tiny pits bridging*

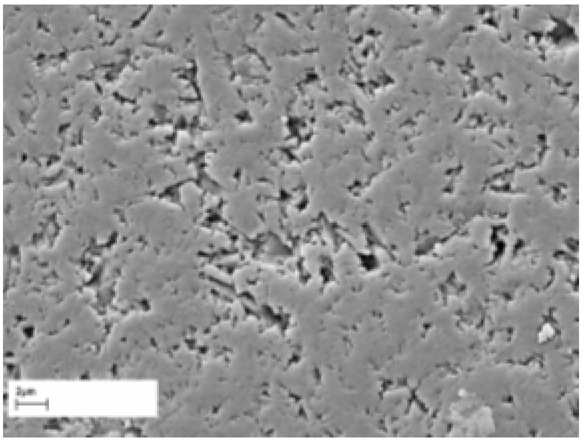

Fig.11. *Final stage of wear – showing high concentration of erosion pits on track*

Most of the tests conducted were Ceramic balls with steel contacts, that is upper ball was silicon nitride and the lower three balls were steel. Ceramic to ceramic contact was also investigated for initial study. The rate of material removal was found to be faster in ceramic to ceramic contact than steel contact. This is mainly because of bearing steel provides high resistant to erosion compared to ceramics.

4. Conclusions

The primary aim of this work is to accelerate erosion in rolling contact experiments, which was achieved using this test methodology. Modifications made to a rotary tribometer were successful in controlling the level of turbulence or pressure drop in the lubricating medium. The preliminary results obtained from this testing were presented. Erosion was created on the contact track and was monitored at different stages to understand the wear mechanism. Increase in contact stresses resulted in crescent shaped pits, which were not noted at low loads. Furthermore, at high loads, pit growth was dominated by widening than deepening. Due to increase in the number of stress cycles corresponding to higher spindle speeds, pits concentration were higher than at low speeds of 2000 rpm. Laboratory testing of material wear which involves both erosion and rolling contact fatigue can be studied using this test method. The liquid/gas phase changes and its influence on the wear mechanism are important and often considered to be difficult for experimental study. This work addressed this problem by presenting a novel testing methodology.

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