The Ball Piston Engine - Material Selection Testing Results

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INTRODUCTION

A series of tests to characterize friction and wear of various materials in a simulated ball piston engine/compressor were performed to aid in selection of production materials. Another goal of the tests was to explore the possibility that this machine could run without lubrication. If unlubricated operation was not possible, tests with instrumentation would be used to confirm the lubricated operation of the machine and the resulting internal loads. Two types of tests were performed. Simple drag sled static coefficient of friction tests were completed to evaluate sleeve materials and coatings. The materials with the lowest friction coefficient then became the focus of operational dynamic tests using a subscale tester.

TEST SETUP

The test setup was designed to simulate the conditions of a typical ball piston compressor. The key response parameters of interest for these tests were friction, wear, and leakage.

The test setup consisted of a test cylinder suspended on load cells, an electric motor driving an eccentric circular steel drive wheel with a simple ball track on the edge, a ball piston driven by the eccentric wheel, compressed air supplied to the cylinder, and a cylinder heater. The test cylinder had a removable sleeve so various material and coating combinations could be tested. The heater was used to change the sleeve temperature to partially simulate compressor thermal conditions and to adjust the ball piston clearance. A drip lubrication system for applying oil to the drive wheel track was fabricated to perform lubricated tests. This system deposited approximately five drops of 10 weight motor oil on to the drive wheel track per minute. A photograph of the test set up is shown in Figure 1.

The configuration of the eccentric drive wheel and its position relative to the cylinder axis results in simultaneous vertical oscillation and spinning of the ball within the cylinder and oscillating mechanical leverage angle that closely approximates the actual operation of a ball piston machine. Of greatest importance, given a cylinder internal pressure via supply air, ball/cylinder wall interaction forces (including sliding friction) are closely simulated.

Dynamic and static cylinder support loads, cylinder and tank pressure, and cylinder temperature were measured via a PC-based data acquisition system. The operating friction coefficient between ball piston and sleeve was indicated by correlation with one of the load cell signals. Leakage was calculated using tank pressure drop measurements over time. Wear was visually observed on the ball and sleeve after testing.

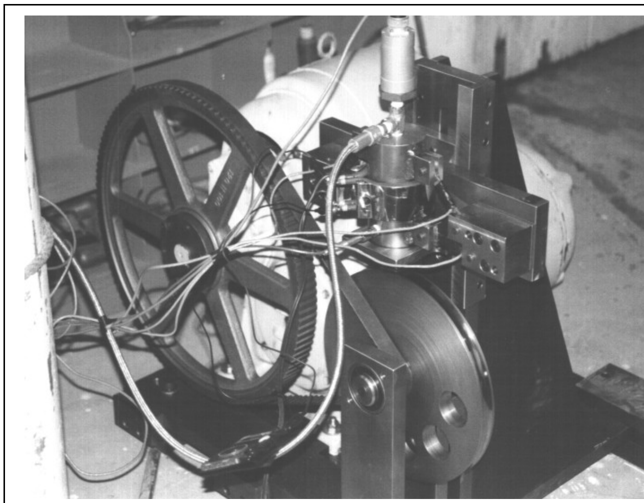

Figure 1. Tester assembly

TESTING

First, static friction tests were performed on uncoated steel, cadmium plated steel, steel coated with Alumide, steel coated with Chromide, and steel coated with TiN, TiCN, TiAlN, or TiAlCN ion deposition treatments. In addition, tests were done after polishing TiAlN and TiAlCN samples with fine grit lapping compound. The polished TiAlCN coating was selected as the best sleeve coating for sub scale testing. It exhibited the lowest friction coefficient against a silicon nitride ball, about 0.06, comparable with that of smooth plain steel. This was a welcomed result, showing that the hard ceramic-like coating did not adversely interact with the silicon nitride ceramic. Polishing was necessary to remove sputter residue that increased roughness. The tests indicated that using a highly polished surface would minimize friction coefficient in production.

Next, operational tests were performed with a wide variety of sleeves and several ball types. Mild steel, Chrome plated steel, plain M2 tool steel, and TiAlCN coated M2 tool steel sleeves were tested. Silicon nitride, Alumina, chromium steel, Teflon, and Nylon balls were used. In addition, cryogenically treated plain M2 and TiAlCN coated M2 tool steel sleeves were tried. This cryo treatment was purported to improve wear resistance.

RESULTS

First, the Teflon and Nylon balls were eliminated from consideration due to insufficient dimensional stability. They deformed enough just in storage to preclude fitting the cylinder.

Although some of the remaining materials and coatings worked better than others, none of the unlubricated tests were successful. The heat generated at the ball piston/test sleeve interface, despite reasonable Hertzian stress levels, caused “smearing” failure of the sleeve wall shortly after the tests were started. Material was actually removed from the cylinder walls and redeposited. A distinct wear pattern was visible on the sleeve and most tests were stopped because the ball seized in the sleeve on the built-up material.

Lubrication solved the problem. The silicon nitride ball ran smoothly in the M2 tool steel sleeve. Test durations of 100 minutes at 200 psi and 800 RPM and 60 minutes at 400 psi and 800 RPM were achieved with no visible wear on sleeve or ball. Figure 2 shows the sleeve bore after the test. In addition, leakage was greatly reduced.

An Alumina ball was successfully run for 10 minutes at 400 psi and 800 RPM as well in a lubricated M2 tool steel sleeve. The sleeve and ball showed minimal signs of wear. Alumina is heavier than silicon nitride, but is much less expensive, and is a viable option for compressor, pump, and motor applications.

A 20 minute test at 400 psi and 800 RPM was run with a chrome steel ball on a lubricated M2 tool steel sleeve. The test was successful but indications of wear were observed. It is likely that the lower modulus of steel caused more deformation of the ball, resulting in a wider contact area, and some cylinder wear indicated as “fogging” of the shiny M2 sleeve surface. The ball also showed fine scratching in a directional pattern, and steel removed from the ball was seen in the lube oil. It is clear that the steel ball would not be acceptable for long term operation.

CONCLUSIONS

After this series of tests it is clear that lubrication must be used for the design to work as a compressor or engine with conventional materials. Without lubrication of some kind, the localized heat at the rubbing contact is too great even for high temperature resistant metals and coatings. It may be possible, for compressor/motor/pump applications, to use a ball piston made of some “high-tech” self-lubricating material, such as graphite-impregnated metal or a dimensionally stable and lubricious plastic. These materials may be investigated in the future. For an engine, however, the higher temperature requirements would preclude such materials, and oil lubrication is likely to be the best approach.

It was also found that oil lubrication can greatly improve machine efficiency by virtually eliminating rubbing friction and reducing leakage. Lubrication increases mechanical efficiency from approximately 85% to approximately 97%. Most of this improvement is due to friction reduction. Results indicate that the lube oil produces a hydrodynamic bearing layer at the contact region, resulting in negligible friction coefficient. If this is true, cylinder surface hardness is no longer a great concern, and special coatings and treatments are unnecessary.

Using a stiff ceramic ball with lubrication should work well in a compressor or an engine as long as the lubrication system is properly designed. High speed engines will require a silicon nitride ball to minimize centrifugal loads at high speeds. It is likely that materials other than M2 tool steel could be used as a cylinder material with proper lubrication, such as conventional cast iron and chrome plated iron or steel.

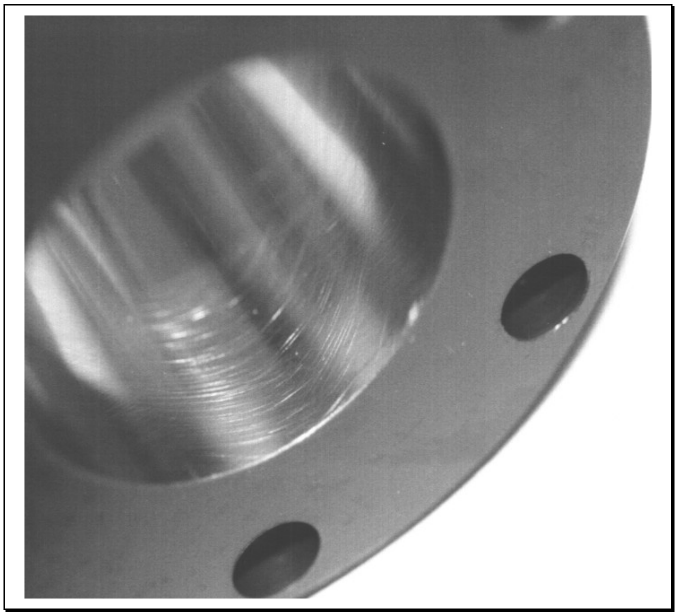

Figure 2. M2 tool steel sleeve bore after lubricated test with silicon nitride ball. Original hone marks are still visible, and no wear is observed.