High Speed Friction and Wear Measurements on Guide Rings for Reciprocating Compressors

Professor Dr.-Ing. Luigi Mazza

Dr.-Ing. Andrea Trivella

Dr.-Ing. Roberto Grassi

Department of Mechanical and Aerospace Engineering, Politecnico di Torino
Corso duca degli Abruzzi 24 10129 Torino ITALY

Abstract

The paper presents the results of a measurement campaign conducted on innovative polymers to be used in piston sealing and guide rings for reciprocating compressors. It is a part of a comprehensive research project named ISECOMP funded by Regione Piemonte. The target is to achieve good energetic performance in terms of low friction supported also by good wear resistance even without lubricating the barrel. The absence of lubrication introduces huge advantages in terms of quality of compressed air, cleanliness and safety. In order to reach the goal it is vital to proceed to an accurate evaluation campaign by measuring the friction coefficient and the wear properties of the candidate materials under the typical working condition they will encounter during the operational life. The test stand used in the campaign will be described in the paper and the data obtained by measuring the friction coefficient of two materials in different condition will be shown.

KEYWORDS: compressor, ring, friction, linear motor

1. Introduction

Modern compressors, no matter if they are reciprocating or rotary, depend on oil for their lubrication and in some cases for sealing. The result is that the compressed air they produce is saturated with oil which needs to be removed after the compression. In order to avoid or reduce the use of oil compressor manufacturers have developed a new generation of machines which are able to perform air compression with limited use of lubricant oil named oil-less. For particular applications (food and pharmaceutical) oil free compressors are required, complex machines where no lubricant is used in the parts which come in contact with air. Oil less compressors usually consist in reciprocating units where the rotating shaft is supported by grease loaded bearings and no lubrication is used for sliding the piston across the barrel. The performance of these machines and their reliability has been matter of deep research during times.

The state of the art concerning the study about contact characteristics, friction and wear in the cylinders between sealing, guide rings and barrel is full of applications. In some of the cases the study was carried out using specific case samples, in other cases specific testing machines were designed to investigate and measure the real component.

In /1/ the behaviour of guide ring – barrel contact is investigated with respect to the advantages obtained by the use of Laser Surface Texturing on the external surface of the ring. The test was conducted using samples which consist in a section of the ring (40° arc). An electric driven crank system provides reciprocating motion. The results showed a reduction of the friction about 25% with respect to an identical ring without texturing.

In /2/ is shown a test rig to evaluate wear phenomena between the piston ring and its housing on a piston from an hydraulic motor. Wear has been estimated from the mass reduction of the ring itself, from contact surface shape variations and from the roughness. Moreover the effects on the wear behaviour of some characteristic dimensions of the housing has been taken into account.

In /3/ the effects of lubrication on friction wear in the contact between piston and barrel of a diesel engine cylinder were studied. Annular guide rings and a flat testing surface to simulate the barrel were used. Tests were conducted with a standard test bench according to the ASTM normative. It allowed to measure the friction force and the wear under several pressure and temperature conditions and with different kinds of lubricants.

In /4/ the wear of guide rings and sealing elements for reciprocating compressors was studied. The rings were manufactured in PTFE with different additives: carbon, molybdenum disulphide, bronze and ceramic. Samples were tested in controlled environment (O_2 atmosphere, air and noble gas) and without lubrication. The test rig is a reciprocating compressor on which sensors and instruments were applied for the purpose.

In /5/ are represented the studies conducted to evaluate the friction coefficient and the wear on sealing rings from refrigerator gas compressors. Test were conducted without lubrication by using a "pin–on-disk" standard test bench. The "pin", manufactured in steel, represent the ring while the DLC (Diamond-Like Carbon) coated steel disk represents the barrel. Tests were conducted in controlled atmosphere and the results are shown in function of the type of cooling gas which was used for the test.

In /6/ a study for measuring the friction force in automotive engine guide rings. The test rig was obtained by modifying one of the four cylinders of a commercial engine and setting instrumentation on it. The barrel was modified to float axially then was connected to the frame with load cells. Said cells act as a support for the barrel and measure the friction force exchanged with the piston.During operation the cylinder is never pressurized. Tests can also be conducted at different temperatures by heating the barrel with an electric resistance. Friction is studied in function of the lubrication for different position of the piston in the barrel.

In /7/ an article that appeared on an italian scientific magazine and /8/ a paper presented at the Ecotrib conference in 2011 the authors describe the preliminary version of the test rig focusing in particular on some aspects which needed to be improved.

The project named ISECOMP, funded by Regione Piemonte, is the result of cooperation between a leading manufacturer of railway compressors, an industry specialized in plastic materials together with Politecnico di Torino . The mission of the ISECOMP team is to study the behaviour of a particular class of plastic materials to assess their use in reciprocating compressors. The idea is to use polymers for manufacturing the sliding elements of the piston taking advantage of the self lubricating properties of the mentioned in dry conditions.

On purpose of that project an innovative test bench has been developed for conducting measurement on sliding elements at high speed. It will provide a valid help in the design of new generations of piston sealing and guide rings for reciprocating compressors. The stand is designed in order to simulate the typical operating conditions for a compressor in order to evaluate the behaviour of the rings in terms of friction force and wear.

This paper presents the test stand in its definitive configuration, the tested samples and the materials that were used. The testing methodology and the measurement technique is also described with particular care attention to the PV factor, an important parameter for the study of friction and wear.

2. The PV factor

The friction coefficient of the materials which constitute the sliding elements has a strong influence on the behaviour of the compressor in terms of wasted power therefore it affects efficiency. The wear properties instead have influence on the MTBF, the quality of compressed air and the limits for the operating conditions.

Research and development in the field of innovative materials require deep testing sessions where the best compromise between wasted power and wear is sought. The most important parameter is the PV factor, the product between contact pressure and velocity. The PV factor proved to be the best suitable parameter for measuring the load to which a compressor is subjected because it takes into account both speed and friction load. It is important to stress that this factor considers pressure and not the normal force as used in the classic model. The classic formulation of friction according to the Coulomb model and Stribeck law consider as the most important parameter the translation speed and assume that the friction coefficient is not dependant on contact pressure.

It is therefore clear that friction coefficient tests shall be executed at comparable speed with the characteristics of the compressors while for wear testing the PV parameter should be considered. The standard testing methodologies for tribological studies do not reach half of the speed values typical of a reciprocating compressor and the PV factor that can be reproduced is even lower.

Moreover it is vital to be noted that standard friction testing is conducted with test samples with geometries and loading condition slightly different from what happens inside a compressor. Therefore a specific test bench has been developed in order to be able to test the real components in controlled working conditions.

3. Test stand and measurement technique

The bench is powered with a modern technology consisting in a couple of electric linear motors, propelling units able to reach excellent acceleration and speed performance. Such an extreme performance is needed to reach the operating values typical of a reciprocating piston compressor; the choice over that kind of motion was also due to the necessity of varying the parameters of the motion profile in order to perform life endurance tests.

The system in its actual configuration is designed for operating with compressor piston rings but the implements can easily be changed to reconfigure the apparatus for other sealing systems or friction testing purposes; it is visible in **Figure 1** in its definitive configuration.

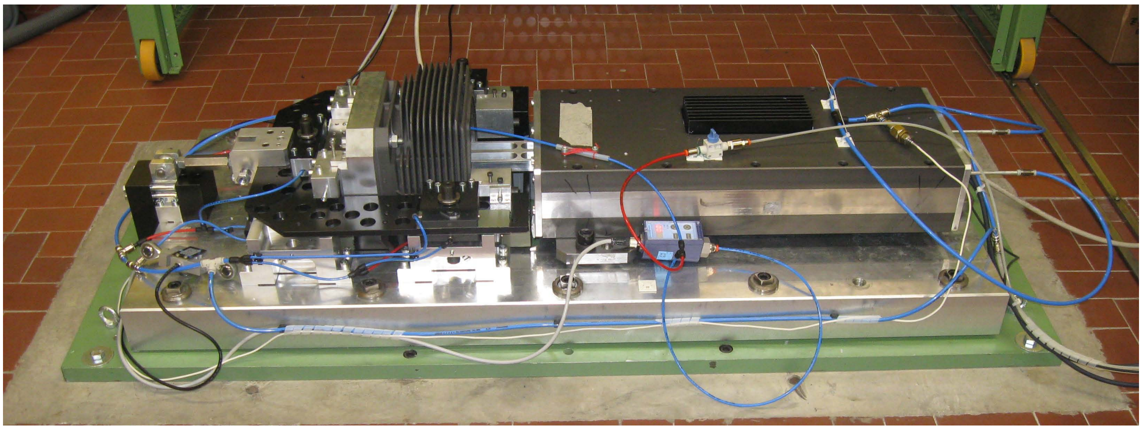

Figure 1: The test stand

With reference to the sketch design in **Figure 2** it consists in a linear motor (1) which carries a custom designed piston (**Figure 3**) which can house samples obtained from guide sealing rings shaped as a circumference arc. The linear motor drives the piston across a barrel (2) from a commercial compressor. The barrel is supported by a rigid plate (3) suspended on an air bearing system with negligible friction. The air bearing system guides the barrel-plate group across the direction of the friction force which is obviously the axis of the barrel itself. The mentioned force is then measured with a load cell (4) which connect the barrel-plate group to the fixed frame.

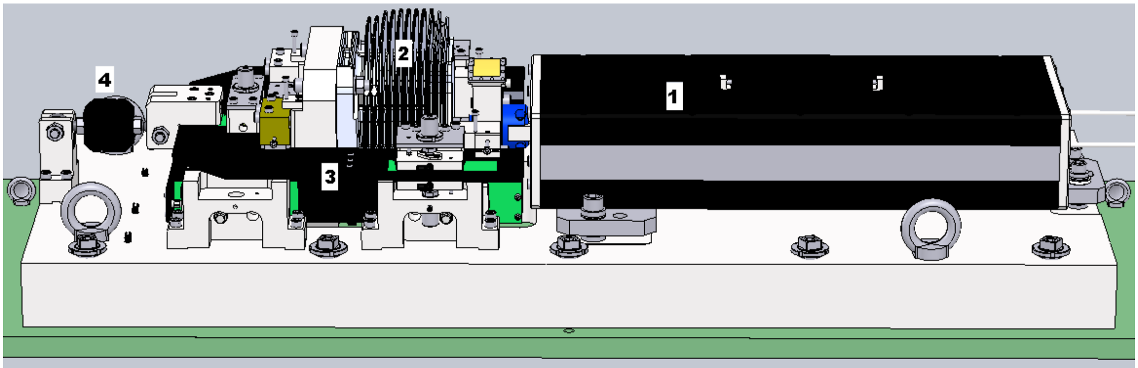

Figure 2: Sketch view of the test stand

The friction force generated in the contact between ring samples and barrel is transmitted to the load cell and therefore measured. The piston is designed to press radially the sample against the barrel internal surface to simulate the radial load applied on the sealing rings and reproduce the contact pressure between ring and barrel. The samples, each in form of a circumferential are subjected to air pressure by means of a membrane made of rubber coated nylon fabric.

The sample support is designed to house two sliding elements in the same condition they would encounter when mounted on a compressor piston. By regulating the pressure under the membrane it is possible to vary the radial load between sample and barrel. The sample is therefore loaded with a normal force which can be set to the same value of the force that a piston exerts on the barrel by mean of its sliding element.

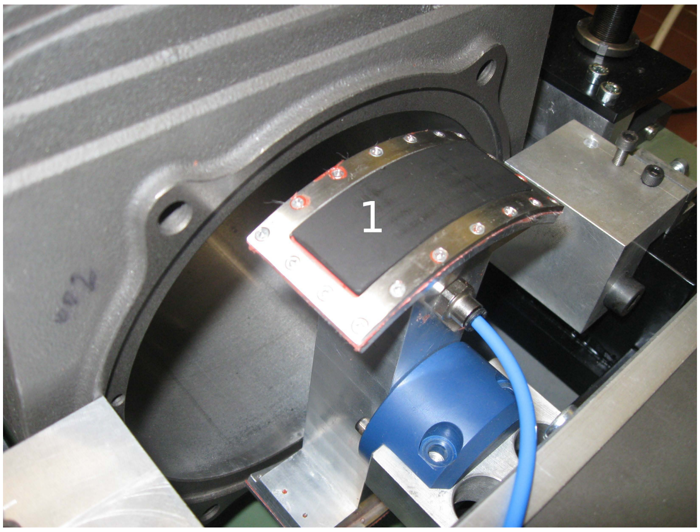

Figure 3: The piston with a sample of the Black polymer (1) loaded into the holder

An interesting aspect of the sample carrier is that it can accept also samples manufactured as in **Figure 4** (2) which are designed for multiplying the contact pressure.

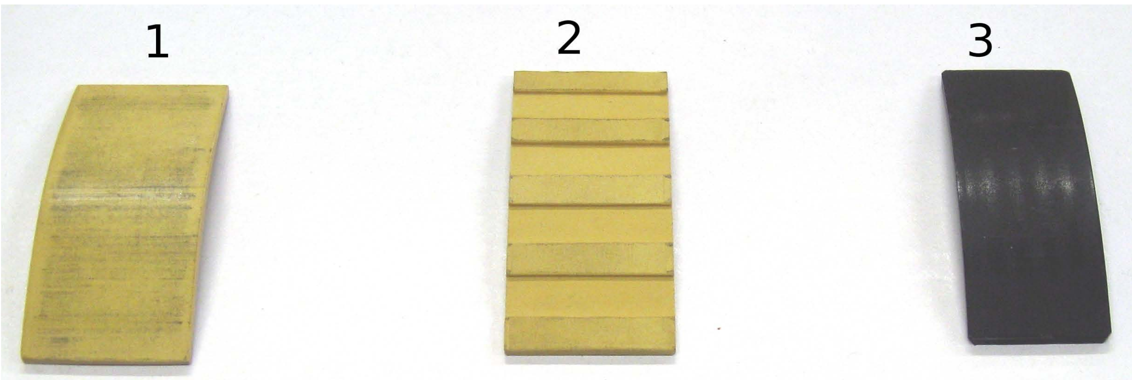

Figure 4: The samples of Yellow (1,2) and Black (3) polymer, in (2) the machined Yellow sample for the purpose of increasing the contact pressure

The side located on the membrane has a full contact surface therefore is subjected to the full pressure transmitted by the membrane. On the other hand the side in contact with the barrel, i.e. the contact surface, has been machined in order to be in contact only for a fraction of the original surface. It means that with this artifice it is possible to perform tests with a contact pressure which can be a multiple of the loading pressure and the same normal force. With this solution it is possible to increase the contact pressure without exceeding the limits of the linear motors in term of generated force.The exact composition of the materials will be omitted for confidentiality reasons and they will be addressed as Yellow and Black. Both of them are PTFE based materials with addition of poly-immide in the yellow and graphite in the black.

The measurement of the friction coefficient is carried out by performing a series of velocity sweeps each done at a different pressure keeping the pressure constant for each sweep. The results are evaluated in different ways, the first one is the presentation of the averaged friction coefficient obtained at the same speed for different values of the pressure. A standard deviation of this result is calculated in order to have an index of the accuracy of the measurement. The second way of analysing the data is to plot the friction coefficient function of the PV parameter and it is the one which allows to assess the results for being used by the compressor technicians.

4. Experimental results

The results here presented are a selection of the data obtained during a testing campaign which had the purpose of assessing the potentiality of the hardware and evaluating a first series of sample. They will be presented in a comparative way in order to stress on the differences between the two materials

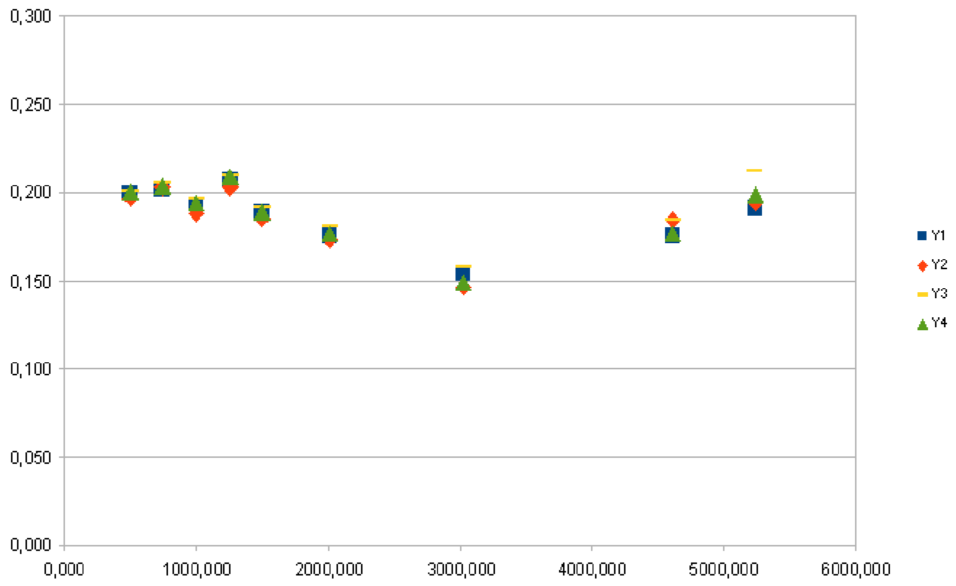

Figure 5: Friction coefficient plotted versus speed for different samples of Yellow polymer, speed in [mm/s]

The two materials present a different value of the friction coefficient and their behaviour, with respect to the velocity is slightly constant.

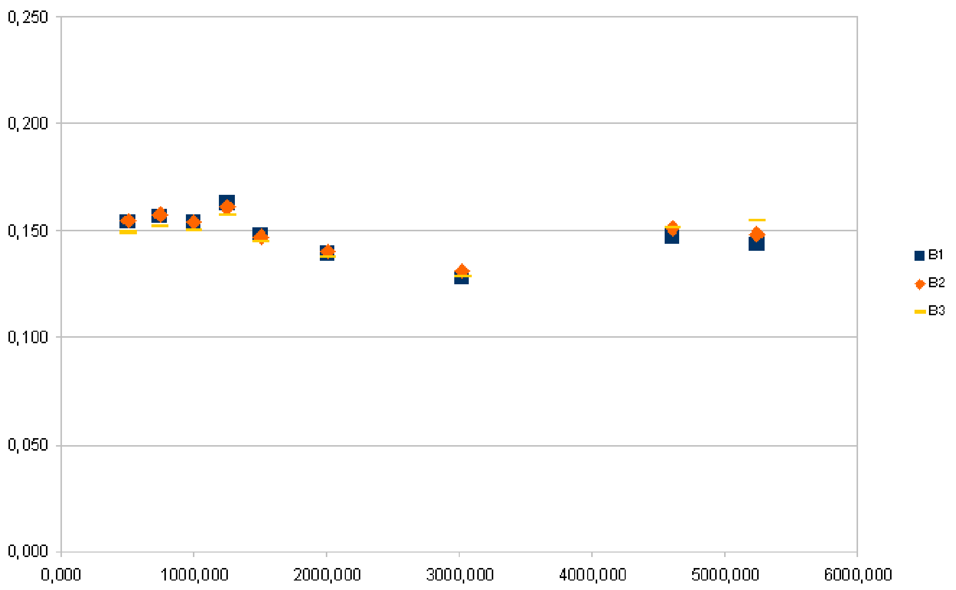

Figure 6: Friction coefficient plotted versus speed for different samples of Black polymer, speed in [mm/s]

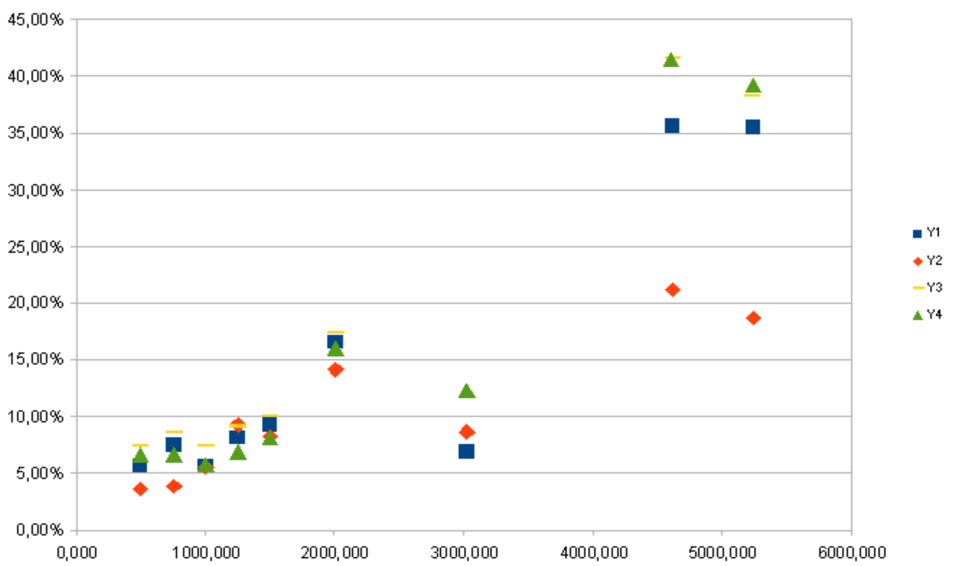

Figure 7: Standard deviation of the friction coefficient plotted versus speed for different samples of Yellow polymer, speed in [mm/s]

There is a slight oscillation around a value which is due to the difficulty of extracting the force data. The values here presented are obtained by averaging the friction coefficient evaluated for each run at each testing pressure and plotted in a separate series for each of the samples that were tested. For assessing the quality of the measurement a study on its repeatability have been conducted and the data are expressed in the next two graphs in the form of a standard deviation.

It is the deviation from the average values presented before and it is used to evaluate if there is any influence of pressure on the friction coefficient different from the conventional behaviour based on Coulomb friction theory.

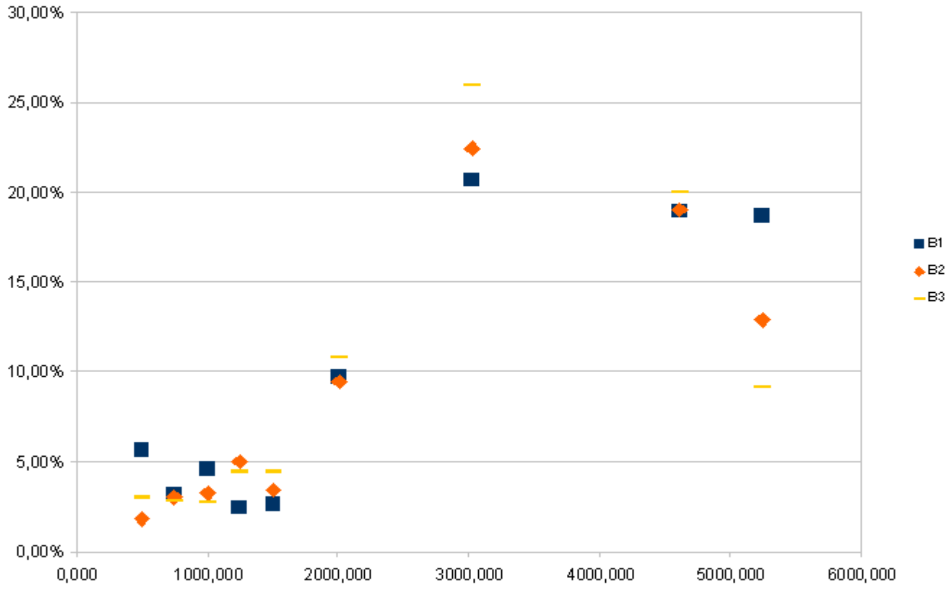

Figure 8: Standard deviation of the friction coefficient plotted versus speed for different samples of Black polymer, speed in [mm/s]

Figure 7 and 8 show that the standard deviation for measurements conducted at variable pressures does not exceed the 10% up to 3 m/s with a spike located at 2 m/s. It means that at high speed there is a sort of disturbance which affects the repeatability of the test at different pressures. It has been noticed that this phenomena has more relevance for lower pressure measurements.

The last form of representing and interpreting the data is to show the behaviour of the friction coefficient versus the PV factor. It is a particular analysis of the friction parameters which is used in the compressor technique because it can be easily correlated with the wear data while the PV is assumed as a “load index” of the sliding pair.The measurement errors are visible as in the other plots and the dispersion of the data suggests that high speed is more likely to generate errors.

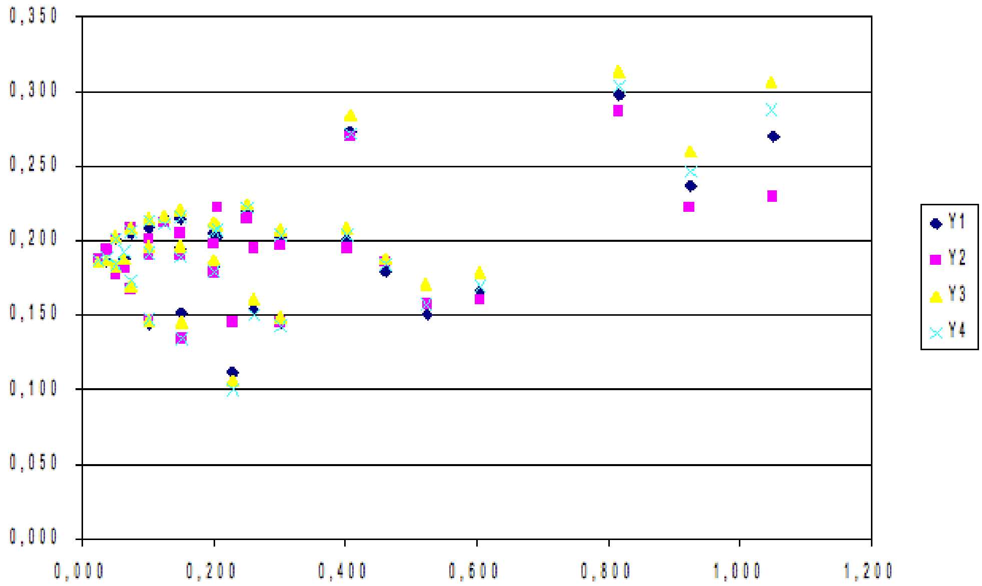

Figure 9: Friction coefficient plotted versus PV factor for different samples of Yellow polymer, PV factor in [MPa*m/s]

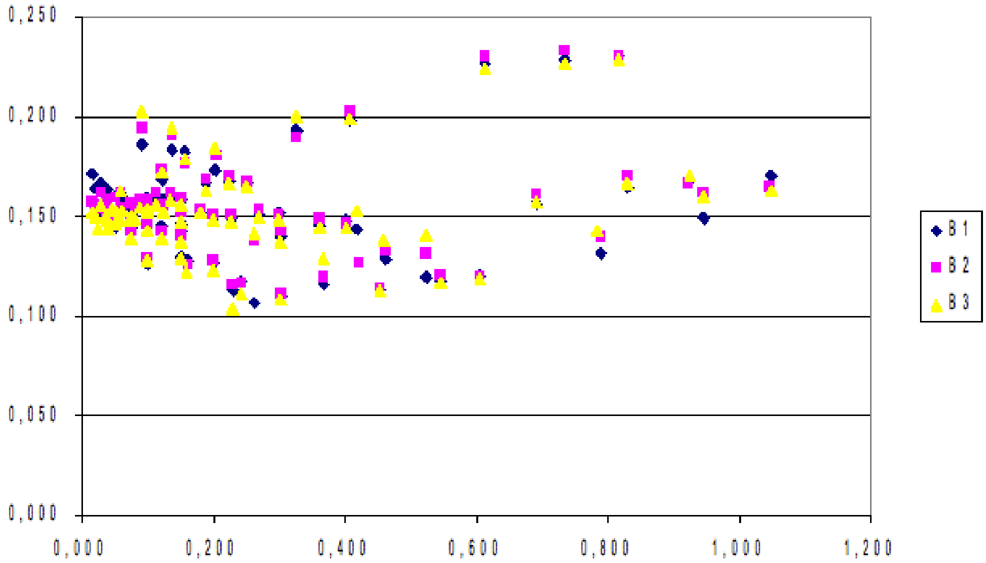

Figure 10: Friction coefficient plotted versus PV factor for different samples of Black polymer, PV factor in [MPa*m/s]

5. Overview

The results here shown have been obtained with an innovative test bench which is able to test the materials in the real operating conditions encountered in reciprocating compressors. The test rig allows to perform tribological measurements during which the friction characteristics are evaluated referring to specific samples which are obtained by machining a real slide ring of a compressor.

The materials have proved to have different friction coefficients i.e. 0,15 for the Black polymer and 0,20 for the Yellow one. The results are repeatable with an adequate error factor in a velocity range up to 3 m/s while for greater speed the data present a slight dispersion. The first assessment campaign proved the reliability of the whole system even if affected by dynamic problems.The difficulties of extracting the datas had been discussed in /8/ where it is said they are due to the dynamics of the whole measurement chain. Some aspects of the dynamics cited in /8/ have been improved but there is still the need of performing a deeper analysis of the data. Evidence suggests that there is a need for further analysis of the high speed data to determine if there is any sort of disturbance which affects the readings. By comparing the standard deviation figures with the average figures it is clear that the repeatability of the same measurement for different samples is really high. While analysing the measurements conducted at the same speed with the variation of pressure it should be expected that the friction coefficient remains almost constant with the pressure. What is measured is a strong variation of that value which rises with the speed.

By analysing the last plot, i.e. the friction coefficient versus the PV factor it is to be noticed that there is a sort of tendency to increase the coefficient with the PV factor. A linear tendency line is represented in the two following figures and shows a monotone rising behaviour which if confirmed could explain the errors encountered at high speed and mentioned in the previous section.

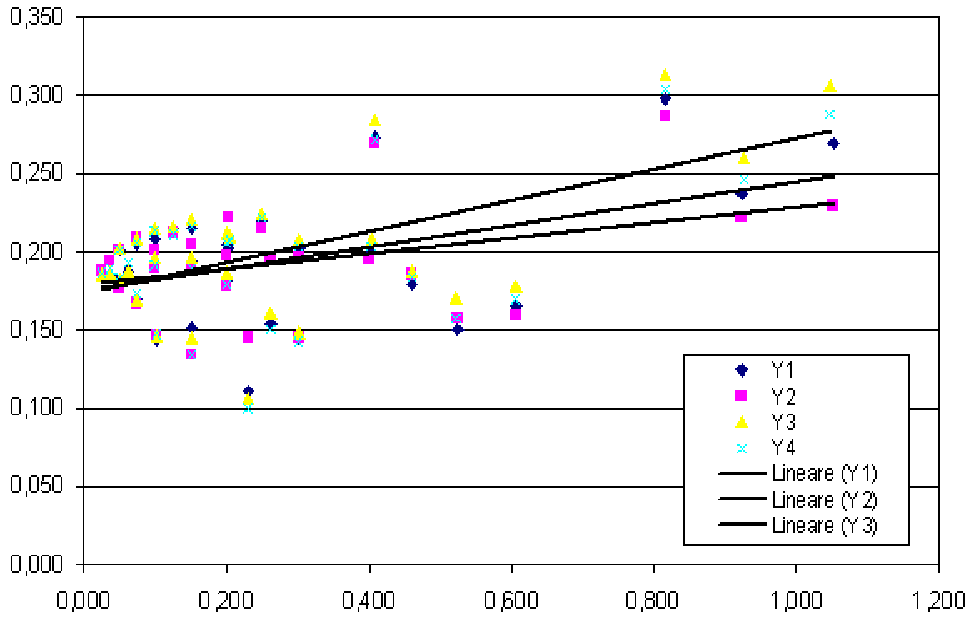

Figure 11: Tendency line of the friction coefficient versus PV factor. Yellow polymer, PV factor in [MPa*m/s]

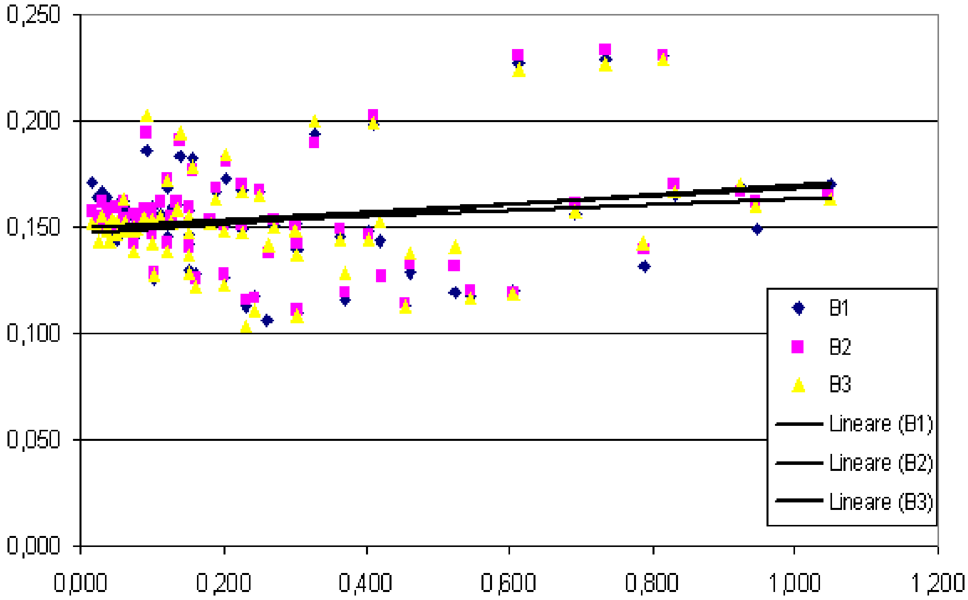

Figure 12: Tendency line of the friction coefficient versus PV factor. Black polymer, PV factor in [MPa*m/s]

This part of the work is only a tentative consideration which will be discussed in a following paper when all the analysis will have been carried out.

6. Acknowledgements

This paper refers to a comprehensive research project named ISECOMP funded by Regione Piemonte aimed to evaluate the environmental issues concerned with the use of low friction materials in air compression.

The authors are pleased to thank the italian branch of Faiveley Transport International and PIEFFE Srl for the endorsement of the project and the cooperation.

7. Bibliographical References

/1/ G. Ryk, I. Etsion. Testing piston rings with partial laser surface texturing for friction reduction. Wear 261 (2006) 792–796.

/2/ U.I. Sjodin, U.L.-O. Olofsson. Experimental study of wear interaction between piston ring and piston groove in a radial piston hydraulic motor. Wear 257 (2004) 1281–1287.

/3/ J.J. Truhan, J.Qu, P.Blau. A test rig to measure friction and wear of heavy duty diesel engine piston rings and cylinder liners using realistic lubricants.

Tribology International 38 (2005), 211-218.

/4/ By Dr Chris Radcliffe – Hoerbiger Rings & Packings Ltd. Sealing material developments for reciprocating gas compressors. Sealing Technology November 2005, 7-11.

/5/ J.D.B. De Mello, R. Binder, N.G. Demas, A.A. Polycarpou. Effect of the actual environment present in hermetic compressors on the tribological behaviour of a Si-rich multifunctional DLC coating. Wear 267 (2009) 907–915.

/6/ Sung-Woo Cho, Sang-Min Choi, Choong-Sik Bae. Frictional modes of barrel shaped piston rings under flooded lubrication. Tribology International 33 (2000) 545–551.

/7/ R.Grassi, S.Impera, L.Mazza, A.Trivella: Compressione eco sostenibile dell aria Oleodinamica & Pneumatica Dic 2010 pp 54-59

/8/ R. Grassi, L. Mazza, A. Trivella: Friction testing equipment for piston sealings actuated with electric linear motors. European Conference on Tribology, ECOTRIB '11. Jun 2011, Vienna, Austria