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Research Article

Cause and Effect Assessment after a Complex Failure of a Trunk Piston in Oil Free Compressor

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Abstract

The premature piston failures in oil free reciprocating compressors working under different conditions have been investigated. The main cause for the failure is observed over a period in particular applications due to cooling system design and filtration system design of the machine. In order to identify the root cause of the failure, the QC (Quality Control) story is followed. The various failure modes are studied to find out the exact cause for the failure, it is validated, and solution implemented in the field running machines to improve its reliability and durability.

Keywords: Compressor, PTFE, trunk piston, Filtration system.

Introduction

Conventionally oil lubricants are commonly used in oil flooded reciprocating compressors, however, in compression of clean and speciality gases as well as in refrigeration systems the presence of oil is a common problem. In medical applications or any other applications where high pureness of the compressed media is required, the oil must be excluded. Oil free or oil less compressors are used for an application in which, there is no oil in the compression chambers.

In this oil free design, self lubricated dry lubricant materials used for piston materials and hard anodizing is done as surface coating inside the cylinder bore capable of functioning under stringent frictional sliding operating conditions. The major challenges in oil free compressors are designing of the compression system and transmission system without oil lubricant to meet the lifetime and reliability requirement.

In process gas and petrochemical industries reliable oil-free compressors are vital, because of the extremely high downtime costs. The majority of the oil-free compressors used in these industries are of the horizontal reciprocating type, but in case of lower range trunk piston compressor needs more reliability of the pistons being fitted with compression and bearer rings made from PTFE (Polytetrafluoroethylene) filled with various inorganic fillers such as carbon, glass fibre, and molybdenum disulphide, or combinations of these. In addition, there exist composite materials consisting of PTFE, carbon, molybdenum disulphide, compounded with epoxy binders, as well as alternative filled plastics such as polyamides and polyphenylene sulphides. The compression rings are normally self-actuating and act as sealing elements between the piston and the cylinder. The bearer rings support the weight of the piston and act to prevent the piston contacting the cylinder wall. In this design, instead of bearer rings, PTFE laminated piston, it is a gapless enclosure of the piston skirt made from aluminium with PTFE film as shown in figure 1.

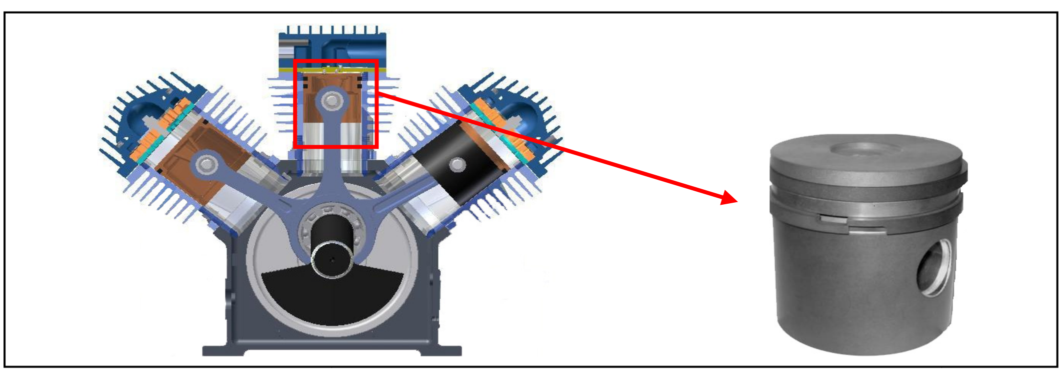

Figure-1
Compressor configuration and PTFE piston

Piston ring sealing was the key technology of high-pressure oil-free piston compressors[2]. In order to seal high-pressure difference, several piston rings were used on a piston. In ideal condition, the pressure difference on each ring should be the same, so that the frictions and wears on each ring were also similar and the life of the entire piston rings group could be the longest. However, the actual life of the rings was much shorter than that in ideal condition, and generally, some certain rings were damaged firstly. The reason for this was that the loads on the certain rings were much greater, and this was caused by the non-uniform pressure distributions. Different authors did not make consistent conclusion about the pressure distributions between piston rings[2].

The association of aluminium oxide and PTFE offers a possibility to avoid lubrication in cylinder of a compressor and to discharge gas free of lubricant[3]. Large wearing of PTFE noticed in such case at the initial period of working sliding becomes slowly smaller with the further laps of time and after 100 to 200 or so hours stabilizes and becomes insignificant. Next the basic period comes which is characteristic for operation time of a compressor and can last up to dozen or so thousands hours as it was established in our investigations up to now. Constant reduction of wearing of the solid sliding aluminium oxide layer was observed during this period till to almost complete disappearance. Sliding association comes then into condition with substantial traces of wearing both of aluminium oxide surface and of PTFE piston rings together with the lowest value of friction factor

Compressed gases are utilized in various processes including large industrial food installations or medical applications[4]. Specific examples are refrigeration systems including also cryocoolers. In refrigeration systems, the piston compressor used to compress and circulate the working gas is a critical component. The compressor performance controls the degree of cooling and efficiency achieved in the system. Conventionally, the compressor's sliding surfaces are oil lubricated to reduce friction and wear. However, in compression of clean and speciality gases as well as in refrigeration systems the presence of an oil lubricant is a common problem. In medical applications or any other where high pureness of the compressed media is required, the oil must be excluded. In the compressors used in cryogenic systems the carryover of an oil to the working fluid must be limited to avoid contamination and hence deterioration of the gas quality and cooling performance. Without the presence of an oil lubricant the compressed medium will remain clean. This, however, necessitates developing advanced surface treatments and coatings, capable of functioning under stringent frictional sliding operating conditions. Alternatively, a different piston lubrication concept can be worked out where frictional sliding is avoided In general, piston compressors must fulfil specific requirements due to their inherent use. First, lifetime and reliability requirements which are mainly related to material wear and the compressor design. A major challenge in the design is to reduce the potential of material wear in the critical components. The second requirement is an energy efficient gas compression. One of the main contributions to energy losses during compression stems from sliding friction. Another factor determining compression efficiency is the piston/cylinder clearance. The clearance must be minimized in order to prevent gas leakage out of the compression space.

The aim of this research is to develop novel design of high performance piston compressors for the application to railway braking systems excluding oil lubricant. The lifetime and reliability are identified as the most important aspects, which are mainly attributed to the piston surface wear and premature failures in critical applications.

Failure Observation

This design works satisfactorily in some of the industrial design with different cooling system. This compressor is modified to suit the railway braking system application. The major modification is on the transmission and cooling system to meet the overall dimension with direct drive arrangement, temperature requirements of the railway application. There were three machines are sent for field validation after successful completion as per the test plan. The one machine is tested for 550 hours continuously with full load and is tested for 100 hours with an ambient temperature of 60°C. There is no failure observed in in-house endurance testing.

There are two failures happened in the field within a period of four months. The following are failure observations from the field. The duty cycle of the compressor is about 60 % on and 40% off condition and runs for about 8 hours per day with the above duty cycle. The first stage piston found with more scoring marks on the piston skirt and second stage piston is in fully damaged condition as shown in figure 2.

All small end connecting rod bearings and grease inside the gudgeon pin found normal. The connecting rod big end bearings are intact condition while disassembling the compressor. There are more aluminium particles, grease and carbon powder is observed inside the crankcase. Both low-pressure piston and cylinder bore found with scoring marks. Second PTFE ring in the high-pressure side piston totally damaged in one compressor and premature wear on the top rings on both compressors observed. There is no abnormality in all valves and cylinder head. The rust particles are observed inside the header of intercooler, low-pressure delivery manifold and intercoolers drain. The vibration level in the locomotive application is also high, but the compressor is tested with severe vibration test as per the standard. Optical investigation shows more aluminium particles along with PTFE layer in the piston skirt as sown in figure 3.

Figure-2
Failed piston

Figure-3
Optical investigation of failed piston

Root Cause Analysis

Failure analysis is considered examination of the characteristics and causes of equipment or component failure. In most cases, this involves the consideration of physical evidence and the use of engineering and scientific principles and analytical tools. The principles of root-cause analysis may be applied to ensure that the root cause is understood and appropriate corrective actions may be identified. Systematic analysis of equipment failures reveals physical root causes that fall into one of four fundamental categories like Design deficiencies, Material defects, Manufacturing/installation defects, Service life anomalies.

To perform the root cause analysis, some of the following tools is used like Fault tree analysis, Fish borne diagram and why why analysis. In this work, fishbone diagram is used to list all possible causes. All possible causes are verified as listed in the table -1.

Table-1

Possible Causes	Verification	Root cause (Yes/No)
Clearance between piston and cylinder	Cylinder Honing size: Dia 90 +0.00/-0.01 Piston Dimension: OD:90.85 +0.00-0.04 Clearance of 14 to 19 microns available as per supplier recommendation	No
Shelf life of PTFE coating	No restricted Shelf life for PTFE pistons.	No
Finish of Cylinder bore	Finish verified and found as per specification (Rz< 3 Microns)	No
Grease reaction with PTFE piston	Grease will not react with PTFE.Confirmed with piston coating supplier and grease suppliers	No
Hardness of cylinder	Verified the hardness and found as per specification of 90 BHN	No
Finish and geometry of Gudgeon pin	Finish and geometry verified and found as per specification	No
Fatigue life of reed	In-house testing completed for 1750 hours at 60°C.Approximately the reed crossed $8.1x10^7$ Cycles. No abnormality observed.	No
Anodizing thickness in piston	Verified and found as per specification. (30 microns per side)	No
Connecting rod geometry	Part assembled as per approved drawing and its geometry verified	No
Rust formation in intercooler	Intercooler headers are of MS material. Possibility to get corrosion is high. Small amount of rust observed in field failed unit	Yes
Filteration rating of the filter / Fine particle entry into the system	Existing filter element rating (20 microns). For railway applications it is recommended to use filter with high filtration (10 Microns)	Yes
High temperature of operation	Verified and no abnormality found after 1750 hrs of running at 60°C. Simulated the reed failure condition and observed high temperature in LP outlet and Low temperature in HP outlet. Hence there is no relation to temperature with respect to high wear of HP piston	No
Forgien particule presence Inside piston surfaces Optical	Optical investigations made to ensure the foreign particles presence in the piston skirt surfaces	Yes
Duty cycle of operation	Railway duty cycle is simulated and verified at in-house for 1300 hours with ON time :2 min 30 sec/ OFF time: 2 Min	No
Grease residue from main and connecting rod bearings	No grease residue observed in failed units.	No
Grease residue from small end bearings	No external leak observed in the failed parts from small end bearings.	No
Weld spatter from Intercooler	No weld spatter observed in the failed unit.	No
Weld spatter from LP delivery manifold	No weld spatter observed in the failed unit.	No
Relative thermal expansion of piston due to high ambient inside the loco	High environment test carried out at in-house with ambient of 60°C and observed no abnormality after 1300 hours	No

From the above table, it is observed that filtration rating of the filter and rust formation inside the intercooler are the root causes for the more wear and in turn, it leads to damage on the piston and cylinder. The design modified to eliminate the above root causes to avoid the same nature of failure.

Discussion

From the analysis, it is found that the rust formation inside the interconnecting manifolds and Intercooler headers. The cooling system with mild steel manifold and cooper coolers with mild steel headers are well suited for oil-flooded compressors. However, in case of oil free design, during stoppage of the machines, the moisture content in the air is trapped inside the low-pressure delivery manifold and Intercooler leads to rust formation of the internal surfaces the Mild steel headers and manifolds. The rust particles lead to more wear in the second stage PTFE piston. The axial running marks in the piston outside surfaces and rings. The contamination mainly consists of PTFE particles and rust particles.

There are more aluminium particles, grease and carbon powder is observed inside the crankcase. As consequential damage on the small end, bearing lip seals due to more temperature during rubbing of piston with cylinder with more clearance after scoring happened in the piston.

The PTFE piston failure is eliminated with by changing interconnecting second stage manifolds from mild steel to copper and copper cooler is replaced with aluminum cooler to avoid rust formation inside the intercooler. The performance test and temperature tests were carried out with modified cooling system and it is meeting the requirement.

As per PTFE piston manufacture recommendation, less than 10 micron filtration rating is used for railway application. Second stage inlet air contains any particles of size above ten microns induces more wear of PTFE coatings on the piston and it leads to complete worn out within short period of operation. The compressor has run for 50 hours internally to check the performance and found that temperature and free air delivery limits are well within the limits. The modification is carried out in the field units and it has crossed 7 months duration in railroad application.

Conclusion

Root cause analysis shows that, the filtration rating of the filter and rust formation inside the intercooler are the main cause for the failures. The filtration system improved from 20 microns to 10 microns to prevent the dust particles, which reduces the wear on piston. The cooling system is design is modified to eliminate the rust formation in airflow path to avoid the similar failures in this application. The performances of the modified units are found good after seven months of running.

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