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Hard particle contamination in reciprocating compressors

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1. Summary

The reliability of process gas compressors has never been more in the focus of plant managers and process equipment engineers. Often, the presence of gas contaminants in the form of abrasive particles is not taken into consideration during the design stage. The sign of accelerated wear due to hard particle contamination is only usually observed after an unscheduled process gas compressor shutdown. In many cases, condition based monitoring is a valuable aid in detecting early signs of accelerated wear. During operation, problems due to hard particle contamination are most often indicated indirectly by valve failure. Once the process gas compressor is shutdown, in order to understand the failure root cause and bring the process gas compressor reliability to acceptable levels, in a first step, it is required that a detailed forensic investigation to be conducted on sealing rings, guide rings, packings and cylinder liners. As a second step, corrective actions are required to be implemented. In such cases, the investigation brings the entire process gas compressor and process under scrutiny. The relation between the compressor OEM and End User/Operator becomes extremely strained. The potential corrective actions are in many instances limited as the plant has already completed the engineering stage and plant managers want to focus on production. The cost of such gas contamination, both in compressor downtime and material costs can in many instances exceed several thousands of euros. The origin of such gas contamination can be various, such as materials used as adsorbents in pressure swing adsorption (PSA), which is a technique used as gas dryer and purifier. The lack of piping cleanliness after welding and fitting, the absence of rust inhibitors during hydro testing are potential sources for contamination. The material selection on the gas compressor can be made in order to counteract the accelerated wear created by the foreign particle ingress. The cause/effect understanding of hard particle contamination is critical for a reliable compressor operation and for drafting of maintenance schedules. Thermally sprayed tungsten carbide coatings or other ceramic based materials have seen successfully used in mitigating the consequences of abrasive particle ingress. This paper will provide an overview of such investigated cases; it will disclose effects of two body and three body abrasion found on cylinder liners and piston rings. The paper will disclose potential repair and protection measures required for trouble free compressor operation.



2. Introduction

Process gas compressors under API 618 are designed to a minimum of 20 years lifetime and a minimum of three years of continuous operation [1]. Most operators have their own maintenance schedule and their mean time between overhaul (MTBO) varies greatly. Upon the occurrence of a major breakdown it is inevitable that maintenance and repairs are immediately required. The cost of such failures remains difficult to quantify, but it can incur in to the 6 digits sums. Also cylinder liners are critical compressor parts with long leads times. It has been reported in literature [2] that 8.8% of failures can be related to process related problems. In the same survey, the top causes for unscheduled reciprocating compressor shutdown were compressor valves (36%), pressure packings (17.8%). Within the failures related to process related problems, it is not possible to find exactly the ratio between process-related liquids in the gas stream and debris entering the compressor cylinders, or its impact to valves and piston rod packings. It is well accepted as one of the main parameters for reciprocating compressor reliability is the cleanness of the gas [2]. Possible parts affected by gas contaminations in a reciprocating process gas compressor, to name a few, and represented in Figure 1:

- Cylinder Liners
- Piston rings & Rider bands
- Packings
- Compressor Valves

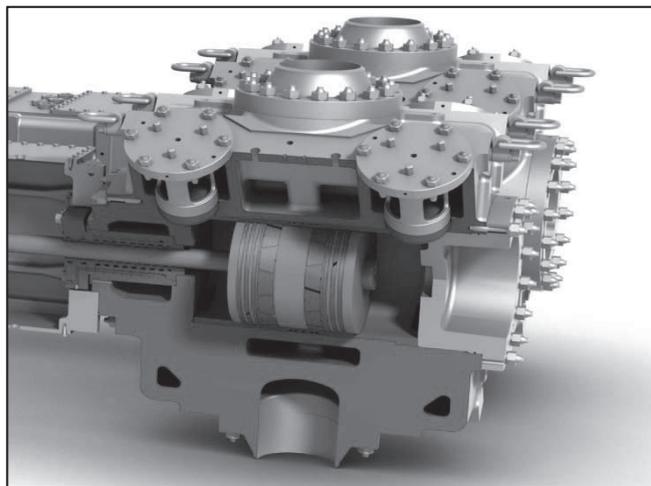


Figure 1 – Process gas compressor cylinder cross section

Considering the parts affected, the occurrence of such event can have disastrous effects. The time of which these occur is usually within the first year of operation (8000 hours). Some failures have occurred in periods less than 500 hours. Critical equipment can be delivered with online monitoring system and the information required is collected and evaluated. Process operation conditions, vibration, dynamic pressures, temperature and rod position are typical monitored parameters. The performance of piston rings and valves can be monitored by dynamic pressure curve measurement, pressure/volume diagram, (pV diagram). Rod position can give a very good insight on the condition of the rider band wear condition, as they carry the piston weight. The location of the wear band should be in a position which is protected from direct contact with the process gas, i.e between the two piston ring packs – for a double acting piston. This translates to an increased reliance on the pV diagrams to detect blow-by, by a shift in the pV diagrams, crossing the theoretical curve for both chambers. If compressor valves begin to leak, one of the immediate reactions is the increase of the gas temperature.

In some cases crankshaft bearings can modify the effective load angle of the piston resulting in increased surface pressure in the cylinder, hence the frame vibration is also important to monitor.

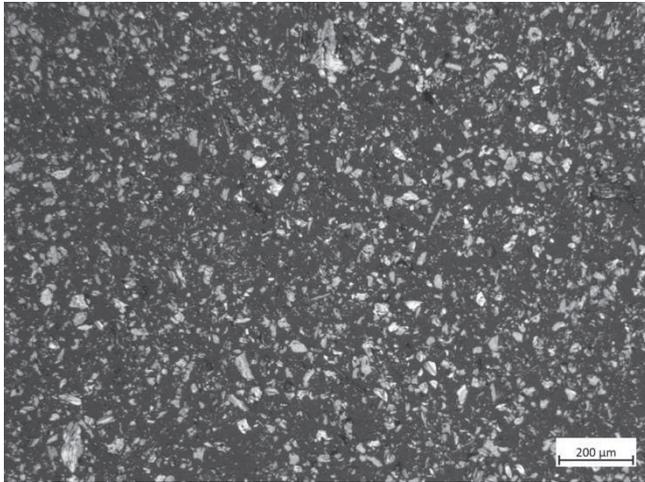


Figure 2 –Microstructure of carbon/ graphite-filled PTFE.

3. Compressor parts – Piston rings and Cylinder liners

For many years Polytetrafluoroethylene (PTFE) based materials are used for both sealing rings and rider bands in the compressor industry. The most commonly used fillers are carbon/graphite which are known to be soft and ductile. PTFE, Figure 2, is known for poor abrasion resistance due to the lack of mechanical resistance in an unfilled state. Graphite and carbon fillers are added in defined quantities to improve wear resistance. The cold flow/creep limit of filled PTFE depends of a number of factors, intrinsic to the operational window and depending on material properties and piston ring design. During the design stages, some operational parameters have to be known, such as, temperature, pressure difference, piston ring geometry and joint sealing to name a few. This is linked with the operational performance of filled PTFE based materials which begin to creep, therefore reducing the sealing efficiency and lifetime of piston rings. With proprietary PTFE processing and careful piston ring pack design, in some cases the pressure limit can be extended further than 250 bar. High temperature polymers, e.g. Polyether ether ketone (PEEK), in combination with PTFE, graphite and carbon fiber is known to have low scuffing resistance and sliding and micro abrasive wear resistance when compared to its pure state [3]. PEEK is recommended to be used at heavy duty applications.

Figure 3 shows a bearing grade PEEK microstructure. The cylinder liner material can be made out of 34CrAlNi7, in Gas nitrided condition. Gas Nitriding is a ferritic thermochemical treatment in which nitrogen is diffused into a steel surface at a temperature between 480-570 °C. After nitriding, a thin compound layer known as white layer is formed at the surface, which is composed of iron nitrides. The thickness of the white layer is typically between 5-30 μm. This formation of this layer is actively controlled by heat treatment process. To prevent the white layer from spalling during operation, the white layer needs to be mechanically removed [4]. The motivation to nitride cylinder liners is mainly to improve the surface hardness and wear resistance, with a reduced risk of scuffing and galling. A typical micrograph of nitride surface is shown in Figure 4.

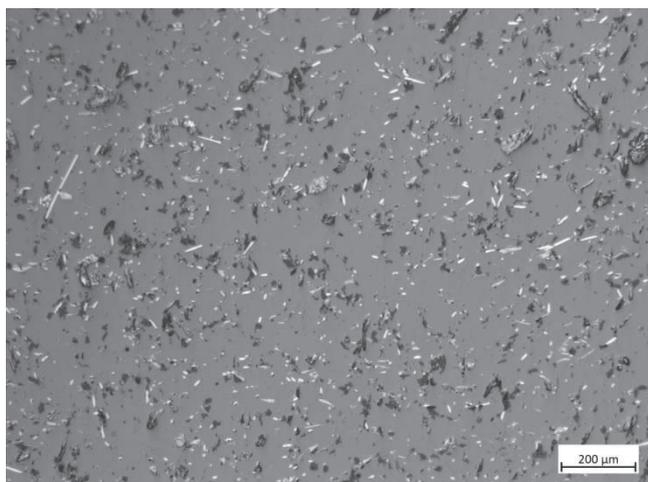


Figure 3 –Microstructure of bearing grade PEEK

For all cylinder liners the white layer is removed by a further honing operation, using diamond impregnated honing stones. This results in typical surface hardness values between 900-1100 HV [4]. Soft cylinder liner materials such as Cast iron and Ni resist can also be used in compressors but their matrix is recommended to be run against PTFE based materials and in cases of particle free process gas. The expected wear rate of a good performing lubricated process gas compressor cylinder liner wear rates tends to be lower than 0.1 mm/1000 hours operation. Piston rings and rider bands which are considered being a consumable, have wear rates ranging between 0.1-0.3 mm/1000 hours, for lubricated service, further depending on other process conditions and after careful selection of the material type for the specific service.

4. Cases

The situation of external particle contamination remains a “taboo” subject within the compressor industry. Many processing plants receive the process gas from other gas providers; hence the contamination origin cannot always be ascertained. The occurrence of such events is rare but extreme troublesome. In some cases cylinder wear rates could be extremely high, as 6 mm/1000 hours of operation and piston ring wear rates higher than 15 mm/1000 hours. Occasionally, it has occurred that operators have several older process gas compressors machines in operation and use increased capacity of the most recently engineered process gas compressor, as the base load equipment and the older equipment becomes peak load equipment. In some cases even though for the other machines it had ordered more than 30 cylinder liners in the last 25 years. One aspect that remains unanswered is the fact that lower stages of process gas compressors are not affected. This can be attributed several factors: a) lower pressure difference, b) softer polymer ring, PTFE (60-70Shore A) vs PEEK (80-85ShoreA) and c) tribology pairing between a soft cylinder liner, e.g cast iron, which has a graphite open structure being capable of embedding particles.

Figure 5 shows a piston ring from a hydrocarbon compressor, which suffered from extreme cylinder liner wear with clear metal particles embedded. Using scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM/EDX) it was possible to determine the chemical composition of the particles embedded on the ring surface (Figure 6) which was Al_2O_3 .

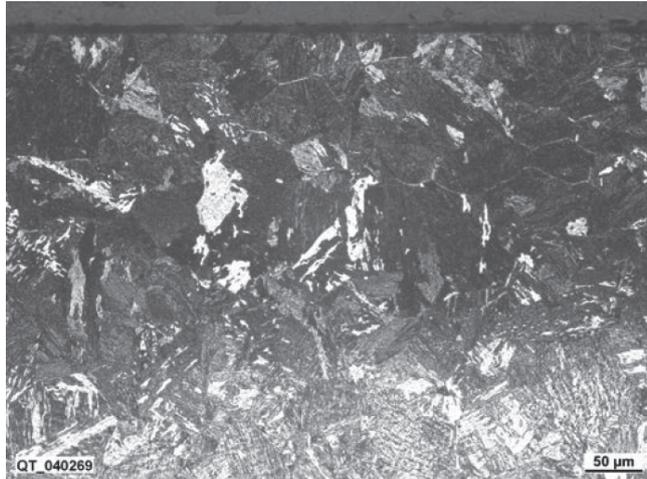


Figure 4 – Typical microstructure of 34CrAlN7 – etched condition.

The piston ring during operation is a very dynamic component. During the compression stroke the ring flank is compressed against the piston ring groove. As the rings are relatively soft, metal particles coming from the process gas or even wear particles from the cylinder liner wall can be embedded on the piston ring flank, creating wear on the piston ring groove as seen in Figure 7. The cylinder liner can present heavy scoring marks, as shown in Figure 8. These marks will be in the sliding direction and with ploughing, only visible under SEM. The wear mechanisms will be further detailed in section 6. There are cases where fine filtration systems are fitted in upstream of compressor.

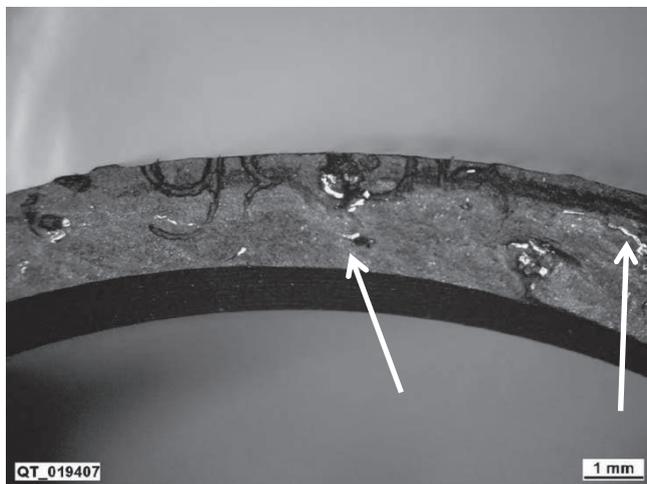


Figure 5 – Piston ring with embedded metal particles.

However, some operator startup procedures include operation with the filter in bypass mode, due to their experience of fast filter clogging. This means that particles could ingress the compressor until the filter is put into operation. Once the filter is in operation the cylinder liner wear rate is expected to decrease to acceptable levels.

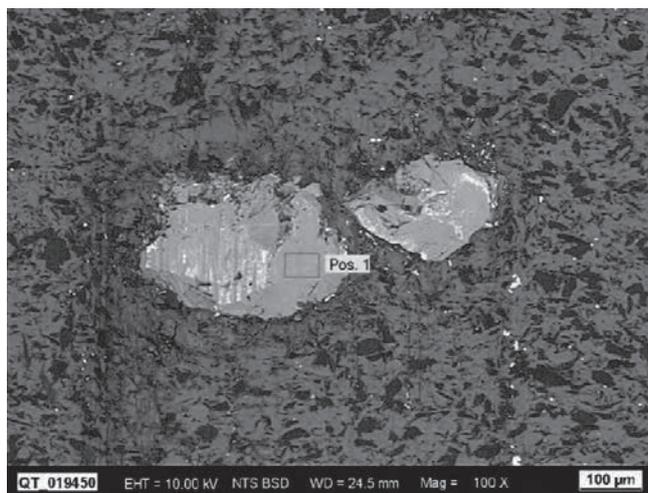


Figure 6 – SEM micrograph of Al_2O_3 particles embedded in piston ring.

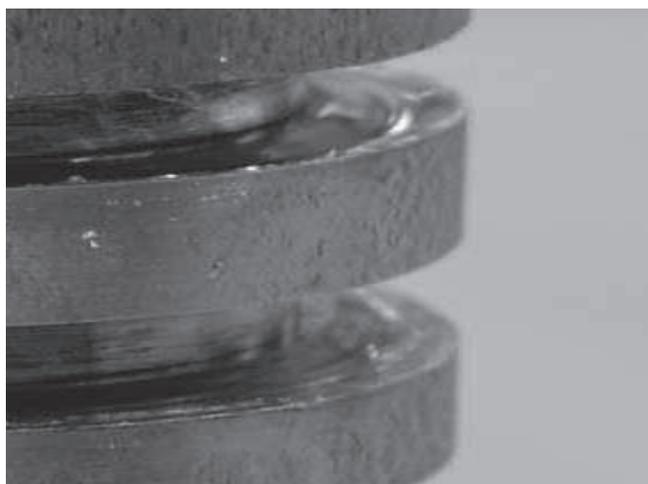


Figure 7 – Piston ring groove wear

5. Contamination Origin

The source of contamination can arise from multiple sources. Outside of the compressor OEM battery limits, there is usually little or no information is exchanged. Some factors have to be taken into consideration depending whether the plant is new or already for some years in operation, i.e new process gas compressor in old pipes. In some occasions during welding/fitting some debris can remain, after the hydro testing the absence of rust inhibitors in some cases combination with aggressive process gases might lead to pipe corrosion. Iron oxide based particles are the most prolific in this case. Table 1 summarizes the hardness values of possible contaminants. Certainly these types of contamination would create limited compressor damage. However, if the process gas contamination level remains high and constant immediate measures have to be taken. Such measures include gas treatment/conditioning, by means of filtration systems and a careful revision of the materials used. In order to obtain purified process gas, pressure swing adsorption (PSA) is a well-established gas separation, gas drying and hydrogen purification technique. In general it is used to separate some gas species from a mixture of gases, according to their characteristics and affinity for an adsorbent material. Typical

adsorbents can be activated carbon, silica gel and zeolites. The PSA process is based on a physical method to cage the bigger water molecules by holding them in porous material.



Figure 8 – Dry running H_2 Compressor

Therefore huge columns are built and filled with corresponding material, in order to provide good flow distribution across the adsorbent bed. Some of these materials are based aluminosilicate minerals, Ca_x , Na_x , Al_xO_x and SiO_x . The hardness values of such materials are summarized in Table 1. The composition of such materials can vary widely depending on the application.

	Hardness Scale	
	Vickers (HV)	Mohs scale
Aluminosilicate minerals		3.5 - 4.5
Iron oxides (Fe_xO_x)	~600	4.5 – 5.5
Silicon Oxide (SiO_2)	~1200	7-8
Aluminum oxide (Al_2O_3)	~2000	9

Table 1 – Hardness values of possible compressor contaminants.

The cleaning process of such columns is based on the back flow process. By introducing dry and hot gas, to the cleaning process this can cause damage to the adsorbent material. Small broken parts of ceramic nature will then travel with the process gas flow into the compressor equipment. The backflow process is assured by a network of valves; in the case of PSA dusting, the valves are subjected to excessive wear. During the first few hours of operation, it is also practiced to bypass the filter to prevent excessive fouling and clogging the filter within the first few hours of operation. Some other cases due to economic constraints the filter bypass line does not have any filtration. Also, improper filter design can result in the same effect as no filtration at all. In addition it is also possible that remains from the construction period are still in the system. Due to the fact that dirt will reduce over the time assuming that the process gas is fairly clean, the effect of rapid wearing cylinder liners will decrease. In any case it's of the utmost importance a properly designed filter

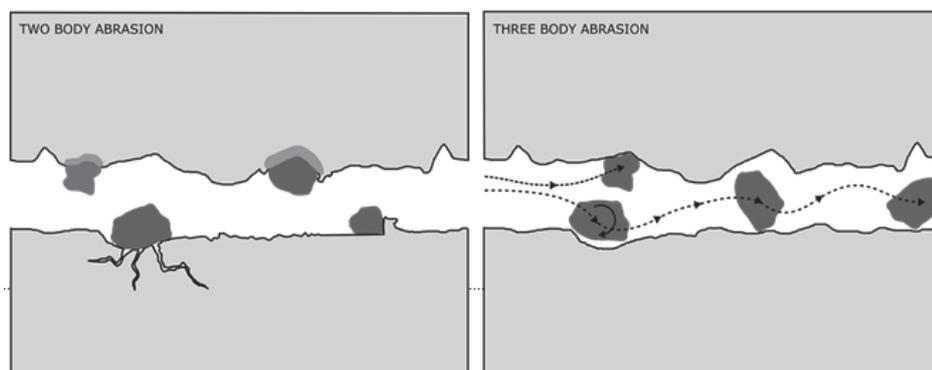


Figure 9 – Two and Three-body abrasion wear.

6. Wear Mechanisms

Abrasive wear is a general term which requires to be analyzed with great care. For an in depth comprehension of the abrasive wear mechanism a few insights into abrasion theory are given. In order to wear occur by abrasion, relative contact between two surfaces with a given load is required and obviously knowledge of the material properties in question. Some abrasive wear mechanisms are [5]: micro-cutting, fracture, fatigue and grain pull-out.

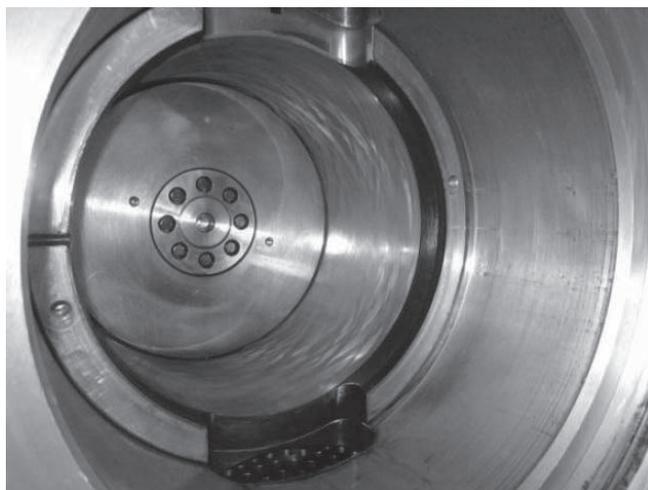
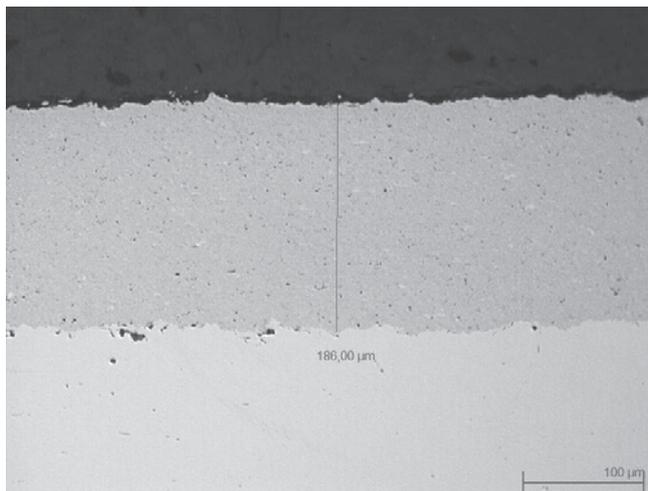


Figure 10 –WC coated liner after 6000hrs of operation

The nature of abrasive wear is given by the interaction between the external particle and the surface, i.e two-body and three-body abrasive wear. In simple terms for the case of polymer based piston ring vs a metal cylinder liner. The rigid external particles are held by the soft polymeric matrix acting in a similar manner as a cutting tool, as shown in Figure 9, left side. In a three-body the external particles are not held on the polymeric matrix and are free to roll and slide over the surface, Figure 9, right side. The abrasion is mainly dependent of the hardness ratio between the particle and the surface. If the ratio is higher than 1.2, then plastic indentations are produced on the surface, hence hard, fast abrasion. If the hardness ratio is below 1.2 there is no plastic indentation on the surface [5]. The shape and size of abrasive particles is also of great importance. Angular particles cause much more severe wear then rounded particles. Furthermore, particles with sharp edges cause more abrasion than round particles. Large particles can produce high values of abrasive wear. For high wear rates, a constant flow of hard particles needs to be introduced in order to create such amount of wear in

a short time frame. In the case of hydrodynamic lubricated parts such as piston rings, abrasive damage only occurs if the particle size overcomes the fluid film thickness, and the highest amount of wear concentrates on the mixed lubrication areas (TDC and BDC). Hence the appearance of such cylinder liners is close to a double trumpet shape – in case of a double acting compressor. From experience it has shown the critical size for particle damage ranges between 10-100 μm . This is within the expected range for the fluid film thickness.



*Figure 11 – Micrograph from WC coating.
Courtesy of RHEIN-RUHR Beschichtungs-Service GmbH.*

7. Solutions – Path Forward

If a process gas compressor is being fitted to a new or existing plant good working practice would be to evaluate the equipment upstream of the compressor and evaluate the risk of hard particles ingress. Also special attention should be taken to the piping. During the upstream piping fabrication and hydro test, appropriate cleaning and passivation should always be practiced. If particles are detected during or after commissioning it may be required to bite the bullet and chemically clean, flush and passivate the system. Additional measures to protect the compressor cylinder liner can be taken even after the commissioning. A revision of the cylinder liner materials is the most common approach. Cermet's comprising of 88% Tungsten Carbide (WC) and 12% Cobalt (Co) present hardness values between 1200 HV and 1400 HV. The heterogeneous structure sintered composites of hard carbides (WC-Co – 2300 HV) in a soft metal matrix has proven to be wear resistance even in the presence of very hard gas impurities such as SiO_2 and Al_2O_3 . The microstructure of such coating is shown in Figure 11.

Figure 10 shows a cylinder liner coated with WC-Co after 6000 hours in operation. Other sprayed coatings can be used such as Cr_xO_x and other ceramic ternary alloys [6]. The state of the art solution considered is proprietary bi-metal hot isostatic process of the cylinder liner with diameters smaller than 200 mm. This implies a solid base body encapsulated (outer surface) and inner body (powder form) to be processed by hot isostatic press. This combines the benefit of different material properties with a high quality uniform microstructure with a diffusion type bonding without segregations. In the case of suspicion of a particle contamination has occurred proactive and open communication between OEM and End user/operator is required. In such cases focus on well documented information is crucial. The material investigations should be properly structured using experienced certified laboratories according to ISO/IEC 17025.



8. Conclusions

The subject of gas contaminations is far from over. These situations will continue to occur in the future. Hence it is of vital importance to understand the equipment upstream of the process gas compressor and evaluate the risk of occurrence for each project. It remains a critical issue to be addressed as early as possible, ideally during the contracting stages. The OEM should be prepared with guidelines for maximum contamination values and with appropriate countermeasures. In the event of high occurrence risk, the OEM should take the lead, with the support of the end user in an open and fair manner in order to understand and resolve the situation as swiftly as possible. From the end user side, the system cleanliness and filtration should be taken seriously. From the OEM perspective, the process gas compressor materials should be appropriately selected in order to assure smooth compressor operation.

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