FAILURE ANALYSIS OF PACKING PLATE IN A HYPERCOMPRESSOR AT A PETROCHEMICAL PLANT

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ABSTRACT

Cracks in one of the packing plates of a two stage multi-cylinder 250 MPa polymer hyper compressor at a petrochemical plant provoked a gas leaks and a plant stop. Fractographic and micrographic analyses and mechanical modelling revealed that fatigue cracks developed in both inner and outer discs of the fretted packing plate, First cracks initiated in the inner disc from pre-existing micro cracks in the wall of a 3 mm sealing oil channel, fatigue crack growth time was 70 days. Several small cracks were found in the surface of the oil channel, intergranular with few ramifications. These micro-cracks initiated by low cycle fatigue, after 1000 stop and run cycles. Microcracking in other packing plates in this and other similar compressors was found to be likely. The influence of excessive wear, and possible non destructive assessment techniques or replacement strategies, is discussed.

Key words failure analysis, fatigue, high pressure, polymer compressor

1.- INTRODUCTION

The purpose of the present study is the analysis of the causes of cracks that led to leaks in one of the packing plates of a polymer hyper compressor, located in a petrochemical plant, in order to define measures to minimize the probability of recurrence of the failure in other cylinders of the equipment [1]. The hyper compressor has two stages, with two cylinders in the first stage and four cylinders in the second stage. At the time of the failure was detected it had been in use for 25 years. **Figure 1** shows a sketch of the "packing" of one of the two cylinders of first stage of the hyper compressor. The first stage is formed by two opposed cylinders. Here the pressure of the compressed gas goes from 26 to 121 MPa, gas suction and discharge are through the valve in the cylinder head, with temperatures of 31 C and 90 C, respectively. Four pistons of second stage take the pressure to 250 MPa.

The cracked plate is the sixth plate in packing of cylinder 4, second stage, as indicated by the arrow in Figure 1. Packing is located inside the jacket, between they there is a small gap for refrigeration oil. Due to the high pressures generated in the gas, plates and cylinder are built by two fretted pieces. This is shown with two greys (1 and 2) in Fig. 1. Cylinders of first and second stage are similar, they differ in the inner diameter (smaller in second stage) [2].

Figure 2 shows the failed packing plate. The inner disk of each plate has polished surfaces and a small diameter hole (3 mm), where the packing lubrication oil circulates. This oil circulates at high pressure, comparable with that of the gas, and acts lubricating the brass packing rings, elements that are pressed in lodgings mechanized in each plate (as appreciated in Figure 2). Manufacturing data of materials and frettage loads in the cylinders and plates are:

- Shrunk liner material (3 in Fig. 1):	30CrNiMo8
- Packing plate material (1, 2 in Fig. 1):	Both rings 30CrNiMo8
- Pressure or interference between inner and outer cylinder:	Proprietary protected.

As for the fluids that circulate through the channels, data are:

- Cooling system: Pressure: 4-5 bar (0.5 MPa),
  Temperature: 40-45 C, Oil: Refrigerator 68 (YPF), Flow: 540 lts/min
- Packing lubrication: Pressure: 2600 Bar (260 MPa) Temperature: 45C,
- Oil: Poly Alkaline Glycol (PAG) [3].

It stands out that the pressures in both circuits only fall to zero when the compressor stops. In the 25 years of operation, some 45 stops per year are considered, what gives around 1080 stop-start cycles.

During normal operation of the plant a decrease of the level of oil was noticed. A visual inspection detected a small loss of oil in cylinder 4 (2nd. stage). It was decided to stop the machine and oil level recovered. After a new start, it was observed that the cooling oil was being emulsified. It was then decided to change the packing of the cylinder, since it was not sealing the gas, which passed to the system of cooling oil. During the disassembly it was noticed that the packing did not slip normally, but it was necessary to apply a larger force than normal. Finally plate number 6 was found broken.

2.- FRACTOGRAPHIC EXAMINATION

Figure 3 shows the appearance of the crack in the outer disk, this is radial and grows to both sides of one of the holes, the one with smaller ligament due to the outer cut for where the cooling oil circulates. The crack in the outer disk is through the thickness and width of the plate, while the crack in the inner disk is through the thickness and gets to the inner surface of the disk, but does not reach the interface with the outer disk. **Figure 4** shows the appearance of the crack in the inner surface of the inner disk (detail indicated in Fig. 2), after the polymer stains due to gas leak through the crack were eliminated and the brass hoop was extracted. Radial cuts were carried out for the separation of the fracture surfaces in both disks. Cracks' opening is similar in both faces of the plate. Note how the outer disk separated the inner disk in the area of the crack, see arrow in Figure 3. This shows a bending effect on the outer disk that allows speculating on the nature of the interaction between both disks during the failure.

Both disks in fact had two cracks, each one begun in opposed points of the surface of through holes. In **Figure 5** some initiation sites of the cracks in both sides of the hole of the outer disk are pointed by arrows. The only place of initiation in the smallest ligament (lower part of the picture) and two of the multiple initiation places in the biggest ligament are indicated. The beach marks on the fracture surface show that the cracks in both sides of the hole began in different ends of the disk.

Both cracks grew as semicircular cracks until reaching the outer and inner surfaces of the disk. As the outer ligament is much smaller, this crack continued growing longitudinally, as appreciated by the vertical beach marks advancing toward the right of the picture. The crack on the inner side of the disk advanced as a quarter-elliptic crack, when it had reached approximately half of the inner ligament it reached the opposite surface and continued advancing radially, as is appreciated in Fig. 5. The morphology of the fracture surfaces and their propagation are typical of a process of subcritical crack growth due to mechanical fatigue [4,5]. This is, the cracks grew due to cyclic stresses applied to the disks during the operation of the hyper compressor [6] **Figure 6** (X100) shows the surface of the crack in one of the initiation places, on the surface of the hole in the outer disk (arrows in Fig. 5). Small drilling surface defects are observed, and pores that acted as initiators of the fracture process. The way of propagation of the recently initiated cracks is transgranular by cleavage, this is, a brittle way of propagation, with indications of secondary cracking in grain boundaries. **Figure 7** (X200) shows an initiation place at 180º in the perimeter of the hole in the outer disk, its comparison with Figure 6 allows concluding that the initiation mechanisms starting from pores and other initiators are similar for the cracks in both sides of the hole. **Figure 8** (X2000) shows at large magnification the propagation of the same crack far from the initiation places. Here it is appreciated that the way of propagation of the cracks already developed is transgranular by micro void coalescence, this is, a ductile way of propagation [7].

Figure 9 shows one of the fracture surfaces in the inner disk. The places of initiation of the cracks are detailed in both sides of the hole. The numerous initiation places are separated by small vertical steps, all on the surface of the hole. Again, the soft morphology of the surface and the beach marks on the two fracture surfaces, show that the cracks in both sides of the hole grew as semicircular cracks due to fatigue. **Figure 10** (X25) shows the surface of the cracks and the initiation places on the surface of the 3 mm hole in the inner disk. Two darker bands are observed, between 0.1 and 0.15 mm wide, to each side of the hole. It is also observed that in that area the surface of the hole is rougher in the half area of the picture. **Figure 11** (X850) allows to see that this roughness is in fact small cracks parallel to the axis of the hole; in the dark band there are initiators of cleavage cracks [8].

3.- MICROGRAPHIC AND MATERIALS CHARACTERIZATIONS

The fractographic analysis has shown that the cracks in the inner disc propagated from longitudinal micro cracks in the oil channel, which form a dark band of about 0.12 mm. To verify the morphology of the micro cracks and their interaction with the microstructure of the material a traverse cut in the mid section of the channel was carried out, and etched with Nital 2%. **Figure 12** (X200) shows the micro cracks on one side of the channel. The trace of the main crack is observed to the right. This confirms the presence of several parallel micro cracks (white arrow indicates the path of the main crack)

The cracks present an intergranular morphology, with some indication of branching, and they grow in defined metalographic directions. The microstructure is very fine, of bainitic type, with banding in the same direction of the micro cracks. Few indications of non metallic inclusions were found. The morphology of the micro cracks would allow to justify mechanisms of damage by low cycle fatigue, hydrogen embrittlement or stress corrosion cracking.

The steel of the plate corresponds to DIN 30CrNiMo8, it is a high strength low alloy steel (HSLA) alloyed with Cr-Ni-Mo. Its resistance and toughness depend strongly on the thermal treatment [9]. **Table 1** shows typical mechanical properties for this steel, it has a yield strength of 690 MPa, and an ultimate stress of 1100 MPa. Hardness mapping revealed an average hardness of 350 Brinnell, with little variation in the thickness. According to the habitual relationship for ferritic pearlitic steels (of variable accuracy for bainitic steel) this corresponds to a strength of 1050 MPa.

Chemical composition of the plate is compared with specifications in table 2, the most important differences are a larger content of Ni and smaller content of Mo in the than nominal.

4.- MECHANICAL ANALYSIS OF CRACK PROPAGATION

It has been shown that cracks initiate in the surfaces of the holes. These areas are critical due to service loads:

- Global circumferential stresses in the disks due to the inner pressure and the frettage interference.
- A concentration factor for circumferential stresses due to the holes, that is SCF = 3 for small holes in thick plates.
- Machining defects in holes surfaces.
- Local circumferential stresses in the hole of the inner disk due to lubrication oil pressure.
- Chemical species coming from the lubrication and/or refrigeration oils, or gas.

The propagation of fatigue cracks was studied for the plate material, using the tools of the linear elastic fracture mechanics (LEFM) [10]. The real value of the cyclic stresses applied in the area of crack initiation is of difficult quantification, in particular their variation once the cracks started to grow in the perimeter of the holes. According to the model, the maximum nominal circumferential stress in the outer disk is the sum of the static stress due to frettage, estimated in 270 MPa, and the cyclic stress due to the inner (gas) pressure, around 40 MPa. This gives a maximum circumferential stress of 310 MPa. The same analysis, carried out for the fatigue propagation of the micro cracks in the packing lubrication oil channel allows defining cyclic stresses of the order of 150 MPa. These stresses are nominal, and they do not include the effects of geometric concentration of stresses in the holes, neither the effect of the oil pressure. The SCF in a small hole is 3, for what the mentioned stresses should be multiplied by that value in the proximity of the lubrication channels [11].

In the channel of the outer disk, mineral oil circulates at a pressure of 5 bar, in the inner disk, lubrication oil circulates at a pressure of 2.600 bar. The inner pressure in the conduit generates a circumferential stress similar to the inner pressure. This stress, however, falls quickly and disappears at a distance of the order of the radius of the channel. If the crack opens to the conduit, it is probable that the fluid penetrates in the crack, so the pressure of the fluid on both faces of the crack generates an additional crack driving force. Therefore, the driving force for the propagation of a crack growing normal to the surface of the conduit is formed by the sum of the circumferential stresses in the material plus the inner pressure [12].

In summary, during the normal operation of the hyper compressor the maximum stresses in each channel of lubrication are those shown in **Table 1**. In each channel of lubrication we have the following amplitudes of cyclic circumferential stresses;

In the outer disk: 40 x 3 = 120 MPa   In the inner disk: 150 x 3 = 450 MPa

At distances of at least two diameters from each channel of lubrication, far from the stress raisers, we have the following nominal service cyclic stresses;

In the outer disk: 40 MPa   In the inner disk: 150 MPa

Note that these estimates are strongly influenced by frettage stress, which estimate is susceptible of appreciable errors. In general we can say that the maximum stresses are of the same order in the material bordering the lubrication holes in both disks. However, the amplitudes of the cyclic stresses are almost four times larger in the inner disk.

The integration of the Paris equation was carried out to calculate the necessary cycles to grow by fatigue a crack from an initial depth of 1 mm until a final of depth of 30 mm [13. 14]. Supposing a constant value of $\Delta K = \Delta Ko$ (fatigue threshold) along the whole propagation of a semielliptical crack, an estimate of 100 million cycles was obtained. These are the maximum possible propagation cycles. Carrying out the same analysis for a constant cyclic stress of 150 MPa (as it was defined in the previous paragraph), a fatigue propagation time of the order of 300.000 cycles is obtained. These are the minimum possible propagation times, because as the cracks grew in the inner disk, this disk was losing rigidity and the loads were being redistributed to the outer disk, for what the stresses in the area of the oil channel in the inner disk was decreasing as the crack advanced. It is for this reason that the cracks in the inner disk, although they began first, didn't end up encompassing completely the thickness of the disk, as did the cracks in the outer disk. A fatigue life of a million cycles, at a pumping frequency of 5 Hz, corresponds to a service time of 70 days.

With the results of the stress analysis and the experimental evidence it is possible to carry out a model of the evolution of the mechanical loads as the cracks in the inner disk were progressing. The bending suffered by the fractured section of the outer disk can be partly due to the relaxation of frettage stresses, however, the fractographic evidence and bibliographical experience indicate that frettage stresses have a very important membrane component. The observed bending is probably owed to the radial displacements suffered by the inner disk when losing rigidity with crack propagation. This radial displacement is indicated by arrows in the simplified sketch of **Figure 13**.

5.- DISCUSSION OF RESULTS

The fractographic and micrographic analyses have shown that both the outer and the inner discs developed high cycle fatigue cracks during the normal operation of the hyper compressor. The time for in service crack propagation was estimated in 70 days. The cyclic nature of the loads in the backing plate generated cyclic mechanical stresses that caused fatigue crack propagation, from the geometric stress concentrations in the holes. The first cracks grew in the packing lubrication oil channel of the inner disk. The reduction of rigidity and increase of cyclic radial displacements of the inner disk, as the cracks grew, caused a gradual increase of the circumferencial stresses supported by the outer disk, which eventually ended up causing the initiation and propagation of fatigue cracks from the hole in the outer disk. One of the three packing bolts passes through this hole. The fractured section in the outer disk coincides with the smallest resistant section.

Besides the cracks that caused the failure of the plate, the metallographic study found other pre-existing micro-cracks, parallel to the previous ones. Their appearance allows a priori to classify them as possibly due to a mechanism of low cycle fatigue or to other mechanisms of damage, such as HIC or SCC. Their mechanical properties and chemical composition are reasonably similar to those specified, as shown in **Tables 2** and **3**. The most important differences of chemical composition are in a larger content of Ni and smaller content of Mo in the sample than in DIN 30CrNiMo8. The PAG packing lubrication oil [iii] is a synthetic oil broadly used as lubricant in engines and compressors, for heat treatment of metals and even in pharmaceutical applications. Antecedents of failures by HIC and SCC in steels are not reported.

The initiation and arrest of the parallel microcracks observed in the surface of the packing lubrication oil channel can be studied from the distribution of stresses in the material. Estimated maximum stresses in the surface of the lubrication oil channel in absence of cracks is the sum of the stress to the gas pressure affected by a SCF 3, that is 450 MPa, and the stress due to the oil pressure, that is 260 MPa. Under normal operation conditions oil pressure is constant, so that the cyclic stress amplitude is 450 MPa. This stress is somehow larger than 50% of the material yield stress (700 MPa), what would allow to justify the propagation of cracks by high number of cycles fatigue. However, in each stop-start cycle oil pressure falls to zero, in which case the total cyclic stress is 710 MPa, this is, the around material yield stress. Under these conditions the initiation of micro cracks by fatigue of low number of cycles is highly probable. In this way the nucleation of the micro-cracks is justified by the 1000 stop start cycles during the 24 years of life of the hyper compressor.

It is probable that most of the micro cracks stopped their propagation once their fronts left the most stressed area in the surface of the conduit. Another possible explanation for the arrest of the micro cracks, is the well-known phenomenon of “load shedding” [15, 16]. When a colony of parallel cracks separated a distance of the same order a their its depth, the cracks that are located in the ends of the colony or those that are for some reason deeper than the others shield the other cracks, this is, they reduce the stresses applied to the fronts of these. The traction stress that caused the cracking is horizontal in Fig. 12, 13. In absence of cracks, this stress is maximum at the surface of the hole. In a certain moment the main crack, which is vertical in the right part of Figure 12, had a depth of around 0.15 mm. Because the stress path at this time must avoid the tip of the crack, the isobars separate from the surface, with which the other cracks are in a field of lower stresses. If the cyclic stresses lower enough, the cyclic K descends below the fatigue threshold value for this material and the cracks stop growing.

The fatigue propagation of cracks is also controlled by partial crack closure due to plasticity and roughness in the crack surfaces, and interactions with microstructural interfaces that generate other more complex mechanisms of crack arrest. These phenomena are of maximum magnitude when the cracks have a depth of the order of the grain size. The micro cracks are between 10 and 100 times the average grain size of the material, for what it is concluded that this phenomenon had scarce significance in the process of arrest of the micro cracks. These results allow defining that the mechanism of initiation of the many micro-cracks that initiated in the surface of the packing lubrication oil conduit in the inner disk is low cycle fatigue. The micro-cracks were caused by cyclic stresses only developed in the stop start cycles, while the later cracks grew due to the operating cyclic stresses. These main cracks are observed to the right in Figure 12.

Oil pressure is another possible source of cyclic stresses. Pressure of lubrication oil is 260 Mpa, which is considered a source of constant stresses in the lubrication channel during the operation. However, this pressure is reached with a piston bomb, similar to those of diesel fuel injection. The hypercompessor has one bomb for each injection point (18 in total). Each injection point also has a check valve, before the oil inlet to the cylinder upstream the failed lubrication channel. Therefore, when the valve is closed pressure decays in this section due to the lubrication flow. When the bomb sends a new pulse oil pressure reaches its maximum value, which opens the injection valve and restarts the cycle. This effect would be increased in case of larger gaps than normal, for example due to excessive wear. The systems are designed to minimize the cyclic component of pressure if oil consumption is normal, but in abnormal conditions pressure pulses can greatly increase. When a check valve fails the compressor is quickly stopped. During the years of service there have been many failures of packing rings, but this is the first time that a plate fails this way.

The results allow concluding that the first indication of fatigue cracks is the presence of longitudinal defects in the surface of the lubrication oil channel. It is probable that other plates of the hyper compressor already developed micro cracks in the 3 mm diameter oil channel. Due to the small diameter of the channel it is difficult to verify by NDT methods. Mappings by ultrasonic techniques with angular probes around the channels of lubrication oil could be used to assess cracking in the rest of the packing plates. Taking into account that once the cracks grow the time of survival is of few days, it is required to replace the plates that present micro cracks. In the event of not being able to develop a reliable method for early detection of the micro-cracks, a chronogram of substitution of the plates is necessary.

6.- CONCLUSIONS

Cracks in one of the packing plates of a two stage multi-cylinder 250 MPa polymer hyper compressor at a petrochemical plant provoked gas leaks and a plant stop. In order to define root causes and to minimize the probability of recurrence of failure in other cylinders of the equipment, fractographic and micrographic analyses and mechanical modelling of the failure were carried out. Fatigue cracks developed in both inner and outer discs of the fretted packing plate, due to cyclic operating loads. In service fatigue crack growth time was estimated in 70 days.

First cracks were found to have appeared in the inner disc from pre-existing micro cracks in the wall of a 3 mm sealing oil channel. When cracks were half way through their propagation in the inner disk, a large part of load was transferred to the outer disk. Then cracks began to grow in the outer disk and those that had begun first eventually stopped. Several cracks, parallel to the cracks that initiated the failure, were found in the surface of the oil channel. Their appearance is intergranular with few ramifications. These micro-cracks initiated by low cycle fatigue, after a service life that included about 1000 stop and run cycles, each of them involving a 260 MPa stress cycle in the affected region. Most of the cracks arrested at a depth of around 0.1 mm, due to mechanisms of load shedding, plasticity and roughness induced crack closure, and interaction with microstructural barriers.

This work concluded that the presence of micro cracks in oil channels of other packing plates in this compressor was likely. However, further non destructive inspection in these regions in the rest of the packing plates did not detect any other cracks. Note that once propagation occurs remaining life is short. Two possible sources for high amplitude pressure pulses of lubrication oil generated by the injection valve were identified:

- Larger than normal gaps, due for instance to excessive wear.
- Interruptions in the oil supply, due for instance to blockage in the oil circuit or defective pump or valves.

It was therefore recommended to evaluate both alternative sources of cyclic stresses. Further investigations allowed finding an anomaly in the oil pressurization system. A reduction in section in the oil intake circuit allowed gas to get into the oil pump. Once this problem was solved, with a very low cost, no further failures were reported.

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FIGURA CAPTION

Figure 1 Sketch of the packing of one of the two cylinders of first stage.

Figure 2 Failed packing plate.

Figure 3 Crack in the outer disk.

Figure 4 Crack in the inner surface of the inner disk.

Figure 5 Initiation sites of the cracks in both sides of the hole of the outer disk.

Figure 6 (X100) Surface of the crack in one of the initiation places, hole surface in the outer disk.

Figure 7 (X200) Initiation place at 180º in the perimeter of the hole in the outer disk.

Figure 8 (X2000) Propagation of crack far from the initiation places.

Figure 9 Fracture surfaces in the inner disk.

Figure 10 (X25) Surface of the cracks and the initiation places on the surface of the 3 mm hole in the inner disk.

Figure 11 (X850) Small cracks parallel to the axis of the hole.

Figure 12 (X200) Micro cracks on one side of the channel, inner disk.

Figure 13 Sketch of displacement between disks.

	In absence of cracks:	In presence of cracks:
In the outer disk	310 x 3 + 0.5 = 930 MPa	930 + 2 x 0.5 = 931 MPa
In the inner disk	150 x 3 + 260 = 710 MPa	450 + 2 x 260 = 970 MPa

Table 1: Maximum stresses in each channel of lubrication

	Yield strength ($Rp0.2, N/mm^2$)	Tensile strength (N/mm^2)	Elongation (Lo=5 x do, %)	Reduction of area (%)	Impact strength (J)
Nominal	700	900-1100	12	50	50
Plate		1050			

Table 2: Tensile properties of plate material, nominal and estimated from hardness

	C	Si	Mn	Cr	Mo	Ni	V	W	Others
Nominal	0.30	0.20	0.45	2.00	0.40	2.00	-	-	-
Plate	0,38	0.33	0.16	1.81	0.53	3.70			

Table 3: Chemical composition of packing plate