# A failure analysis study on the packing cups of a hyper compressor

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**Abstract**

Two packing cups of the second stage cylinders of the polyethylene hyper compressors failed after service life of about three months. In this paper, microstructural investigations and fracture surface studies are presented for failure analysis of the damaged parts. Moreover, the stress analysis is performed by using fatigue striations to evaluate the principal stress components of the lube oil ducts. It is shown that although the design of packing cup elements is very important, the quality of the finished surfaces, wear resistance and mechanical properties of the selected material must be considered to increase the fatigue life of critical parts of the hyper compressor.

***Keywords***: *Fatigue; Hyper compressor; Packing cups*

## 1. Introduction

High-pressure reciprocating compressors pressurize various gases to pressures ranging from 69 MPa to even greater than 345 MPa. The Hyper compressor is a machine for low density Polyethylene (LDPE) production that compresses Ethylene with discharge pressures up to 350 MPa (Fig. 1). The gas leakage must be controlled in order to obtain the desired discharge pressures [1]. Accordingly, the high pressure packing, which is composed of series of packing cups and rings (Fig. 2), is designed for this purpose. Packing cups consist of two disks (such as Fig. 3 in this case) which are assembled by shrink fitting or auto-frottage in order to prepare the pre-stressing in these components.

The high pressure packing works under cyclic stresses varying between suction and discharge steps. In this way, fatigue is the most common cause of the failure of the packing cups, due to these cyclic stresses and also the shear stress condition between the suction and discharge states [2]. In the design of the components, material selection is an important factor for increasing the wear resistant and fatigue life of machine parts. In the regard of materials selection, the fatigue strength of utilized metals is an important key to prevent the future damages.

Many investigations have been performed on the design of the packing cups to improve the reliability of hyper compressors due to the very high levels of load and pressure and gas involved. For example, Giacomelli *et al*. utilized advanced modeling and simulation methods to design such machines based on the purpose of the highest safety and reliability [3]. Reliability and safety also depends on the quality of the used materials. In order to increase the quality of the materials especially for elimination of defects, very large forgings are needed to develop the casting of the original ingot and its subsequent forging [4]. Also, other parameters such as quality of the finished surfaces play a critical role in enhancing the fatigue behavior of packing cups. The fatigue cracks usually initiate from the surface defects such as fretting and machine marks [2]. Maggi *et al*. showed that the typical failure modes of packing cups are tangential or radial [5].

The sensitivity to fracture increases when the surface defects are placed at critical points such as seal ring housing and lube oil ducts. Giacomelli *et al*. studied on the effect of influenced parameters on stress distribution at these points [6].

In this paper the failure causes of two fractured packing cups are investigated. These cups are the second and third packing cups from eight starting from head end.

## 2. Methods of Investigation

Magnetic particle test (MPT) was used to identify probable cracks in the disks. The fracture surface of one of the cracks was investigated by stereo microscope (SM) and scanning electron microscope (SEM). The microscopic investigations by the optical microscope (OM) were also carried out to study the microstructure and the metallurgical quality of the specimens. Mechanical properties of the material were studied according to the standard of ASTM A 723/723M-02 and especially to estimate the fatigue strength of the packing cups. Moreover, microscopic analyses were performed to inspect the surface quality of critical points of the packing cups. Additionally, the stress state of the lube oil ducts was calculated using both the fatigue striations and the Lame's equation.

## 3. Experimental results

### *3.1. Visual inspection and MPT results*

Different failure modes of the studied packing cups are shown in Fig. 4. As it can be seen, all of the failed points of the packing cups have been located in the internal disk. MPT results revealed some tangential and radial cracks on the internal disk of the packing cups that initiated from critical zones (Fig. 4). Figure 4a shows that the crack has been initiated from the surface groove. It seems that at the first, it propagated tangentially and then, the propagation path of the crack was changed. In the other words, the crack leaves the tangential mode to radial mode at bore profile.

In the other specimen, the radial cracks have been initiated from the lube oil ducts (Fig. 4b). The cause is the significance of the packing cup stress condition at the lube oil ducts. Therefore, optimization of the packing cup with emphasis on lube oil duct zones is essential [7]. According to the visual inspection and MPT results, all of the cracks placed on the internal disk. As a result, further experimental investigations and microscopic studies were focused on the internal disk.

### *3.2. Chemical analysis*

Atomic absorption spectroscopy was used to determine the chemical composition of the internal disk material (Table 1). The selected nickel-chromium-molybdenum alloy steel is acceptable for high strength alloy steel forgings for pressure vessels.

### *3.3. Tensile test*

The tensile test results at room temperature are presented in Table 2. As can be seen, the materials satisfies the ASTM A 723/723M-02 Grade 3/ Class 3 standard.

*3.4. Microstructural investigation by OM*

Figure 5 illustrates the quenched and tempered microstructure of the internal disk. The investigation of the surface replication samples are shown in Figs. 6 and 7. It can be observed that the radial crack is transgranular. In addition to the main cracks (radial cracks), some defects and cracks were also observed on the cup surface. Figure 7 demonstrates two samples of these defects with several micro cracks that have been propagated from these defects. These defects can be caused by machining operation or fretting.

*3.4. SEM and SM investigations*

The SM micrograph from the fracture surface of the longer crack (shown in Fig. 4b), which is almost a through thickness crack, is shown in Fig. 8. It can be seen that the beach marks, as an indication of fatigue fracture, have been started from the lube oil duct. Moreover, fatigue striations can be observed on the fracture surface (studied by SEM in Fig. 9), demonstrating progression of this crack by fatigue.

The surface quality of the lube oil duct edges and some wear effects on theme are illustrated in Fig. 10. Fretting wear takes place on the edges of the holes due to high pressure of lube oil suction and discharge operations. Also, fretting wear happens on the surfaces of two close cups because of the difference in radial deformation in secondary compressor operation [8]. Therefore, the fatigue cracks could be initiated from the fretting defects. Figure 11 shows the probable initial crack that nucleated on lube oil duct edge.

Previous investigations exhibited that the variations of pressure in the first three cups are significantly high compared to the other ones. It has been stated that that the pressures of the cups are approximately the same after the third cup [8]. In addition, oil pressure in the lube oil ducts decreases in order from the first cup to the eighth. Consequently, the first to the third  cups are sensitive to fatigue fracture because of more wear and high lube oil pressures. Therefore, the fracture possibility of the first three cups is more than the other cups. Since the fracture has been occurred in the second and third cups, this fact can be observed in this case study.

## 4. Stress analysis and discussion

*4.1. Stress calculation by using fatigue striations and linear elastic fracture mechanics method*

As indicated above, it seems that the type of the fracture of all cracks is fatigue fracture in nature. According to the BS 7910–06 standard, stress intensity factor range ($\Delta K$) can be calculated from the crack growth rate ($da/dN$) by using the Paris equation:

$$da/dN = A(\Delta K)^m \tag{1}$$

where $A$ and $m$ are the materials constants of the Paris equation. The $da/dN$ values were calculated from the distances between the fatigue striations on the fracture surface by the use of SEM micrographs. For this purpose, after estimating the crack initial origin, the striation widths were calculated along two straight lines from the initiation zone to the final fracture [7–9]. By moving away from the origin, it was tried to find striations at different spacings (approximate range of 0.5 to 0.7 μm) from the initiation zone. In this regard, it has to be stated here that though each striation is produced by one stress cycle (and thus crack growth rate at that area can be calculated simply by measuring the striation width, if the striation is chosen appropriately), not all stress cycles would produce a striation. This point is so important in all fatigue calculations, especially for the case of estimating total cycles experienced by the material in the second stage of fatigue from counting fatigue striations, since the overall crack growth rate might be smaller than the locally measured value from the striations.

After determining the crack growth rates at different crack lengths, the stress intensity factor range can be calculated from Eq. 2 by assuming $A = 1.35\times10^{-10}$ mm/cycle and $m = 2.25$ [10], respectively, or alternatively by using $da/dN$ against $\Delta K$ curves, found in the literature for the same material. According to the beach marks length, the stress intensity range and average fatigue crack growth stress are computed to be about 38–44 MPa√m and 590 MPa, respectively.

*4.2. Stress calculation by using the Lame's equation*

In order to investigate the stress state of the lube oil ducts, the Lame's equations were used [5]. Using Eqs. 2 and 3, $\sigma_r$ and $\sigma_\theta$ were obtained to be about -489 and 591 MPa, respectively.

$$\sigma_r = \frac{P_i a^2 - P_o b^2}{b^2 - a^2} - \frac{(P_i - P_o) a^2 b^2}{r^2 (b^2 - a^2)} \tag{2}$$

$$\sigma_\theta = \frac{P_i a^2 - P_o b^2}{b^2 - a^2} + \frac{(P_i - P_o) a^2 b^2}{r^2 (b^2 - a^2)} \tag{3}$$

where

$P_i$ (internal pressure) = 300 MPa

$b$ (outer diameter) = 225 mm

$a$ (inner diameter) = 106 mm

$r$ (distance of lube oil duct from center of internal disk) = 85.5

and the $P_0$ (external pressure) can be calculated as:

$$P_0 = \frac{F}{\pi b h}$$

where

$F$ (shrink fitting load) = 90 ton

$h$ (thickness of internal disk) = 47 mm

*4.3. Failure causes*

According to propagation mode of the radial cracks, the main cause of crack growth can be the hoop stresses. Obtained results from the fatigue striations also demonstrate this fact.

The fatigue limit of the used nickel-chromium-molybdenum alloy steel is about 500 MPa [10]. Although, the high strength alloy steel is selected for internal disk, it is not proper for this stress level. The stress analysis of lube oil hole indicates that a higher grade alloy steel, such as class 5 with minimum 1310 MPa of tensile strength, should be considered. Therefore, the consideration of stress state is very important for material selection, especially, considering the fact that the probability of failure increases with surface defects.

**Conclusions**

A failure analysis study was performed on two fractured packing cups of the second stage cylinders of the Polyethylene hyper compressors. According to the obtained results in this research, inappropriate material selection was the main cause of the failure. Low tensile strength of the chosen material together with existing surface defects resulted in growth of the fatigue cracks. All of the fatigue cracks had been located on the internal discs.

**ACKNOWLEDGMENTS**

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**Legends**

Fig. 1: Hyper Compressor for LDPE production.

Fig. 2: Schematic of the high pressure packing.

Fig. 3: Packing cup disks.

Fig. 4: Failure modes of the studied packing cups.

Fig. 5: quenched and tempered microstructure of internal disk.

Fig. 6: Cup surface replication from radial crack zone.

Fig. 7: Investigation of cup surface replication sample

Fig. 8: Beach marks extending from the lube oil duct edge surface toward through thickness.

Fig. 9: SEM micrograph of the fracture surface.

Fig. 10: Surface quality of lube oil ducts edge.

Fig. 11: Probable initial crack on the lube oil duct edge.

Table 1: Chemical composition of the internal disk

Table 2: Mechanical properties of internal disk

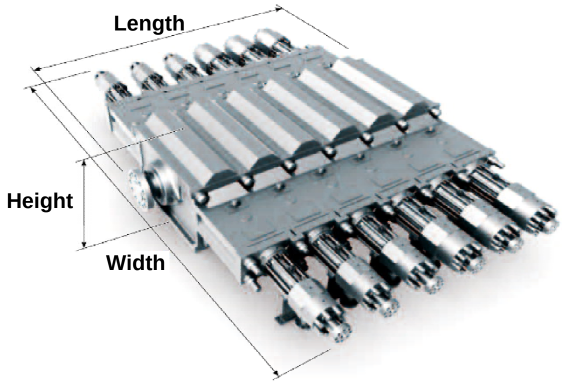



Fig. 1: Hyper Compressor for LDPE production.

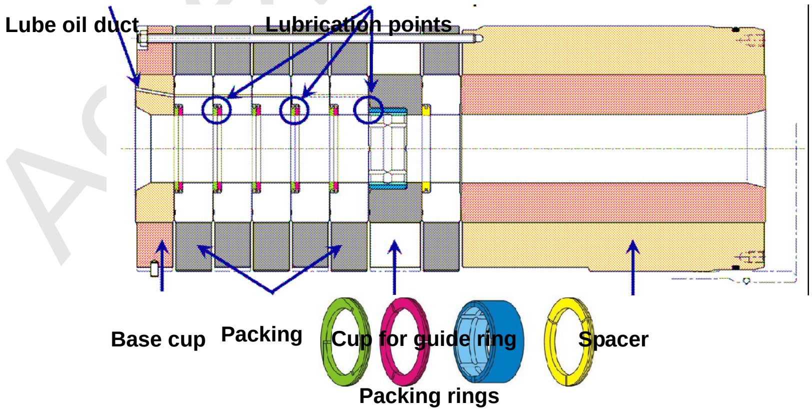



Fig. 2: Schematic of the high pressure packing.

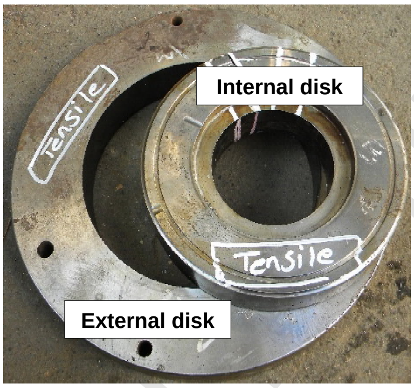



Fig. 3: Packing cup disks.

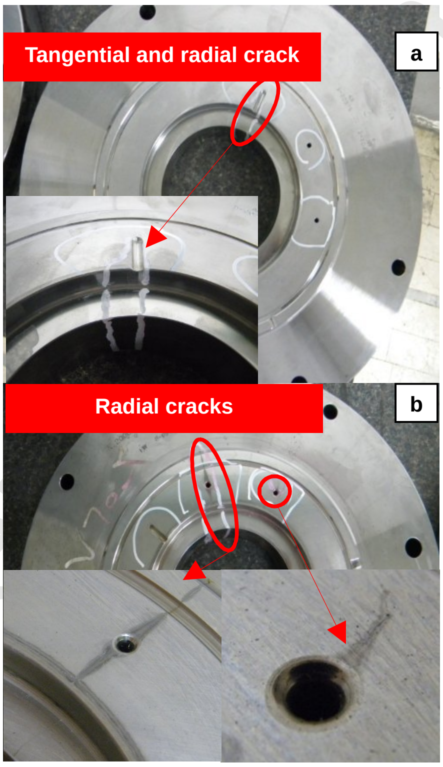



Fig. 4: Failure modes of the studied packing cups.

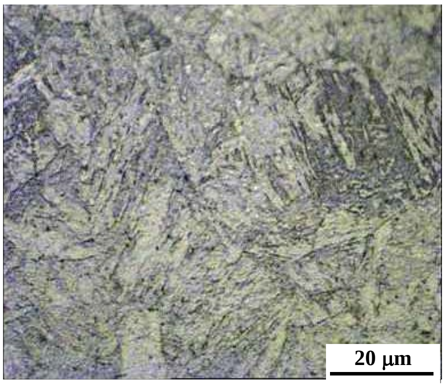



Fig. 5: quenched and tempered microstructure of internal disk.

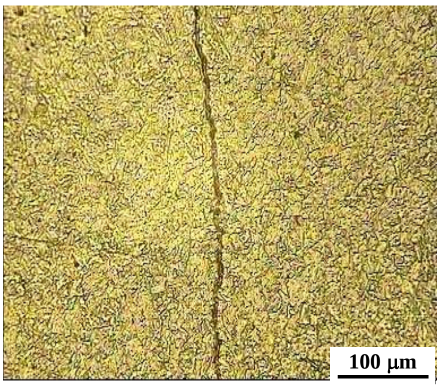



Fig. 6: Cup surface replication from radial crack zone.

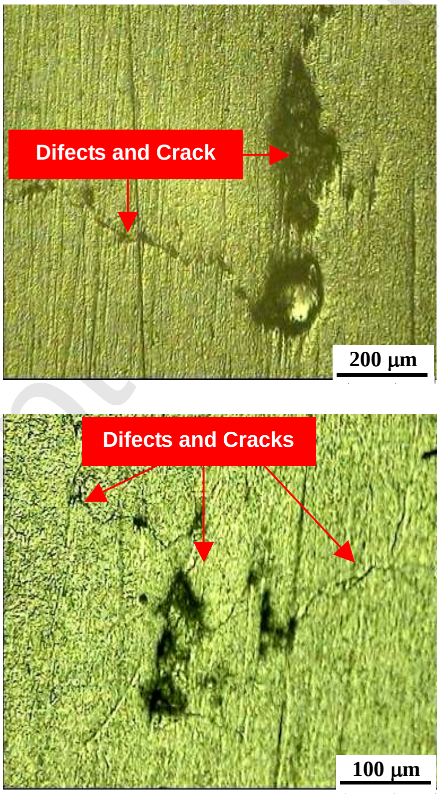



Fig. 7: Investigation of cup surface replication sample

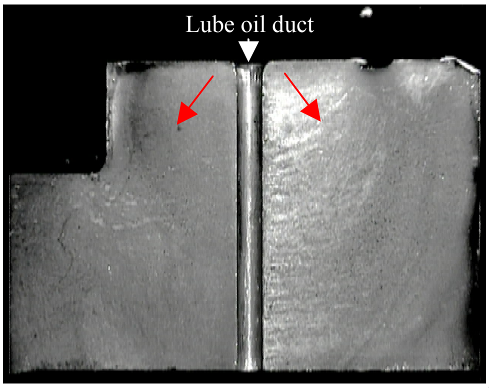



Fig. 8: Beach marks extending from the lube oil duct edge surface toward through thickness.

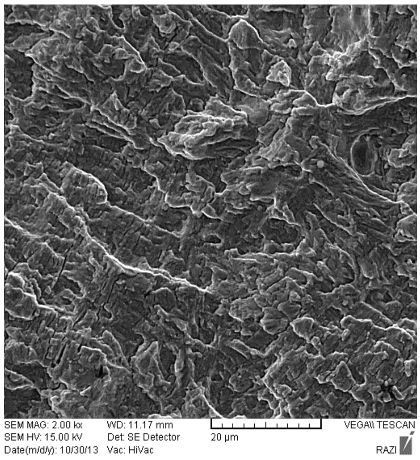
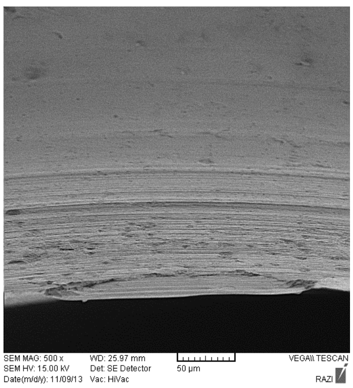



Fig. 9: SEM micrograph of the fracture surface.





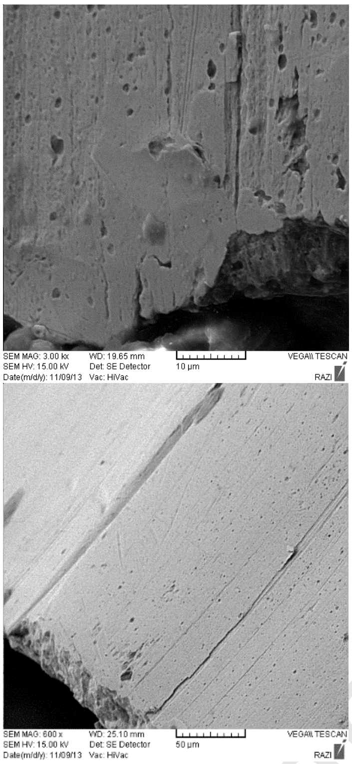



Fig. 10: Surface quality of lube oil ducts edge.

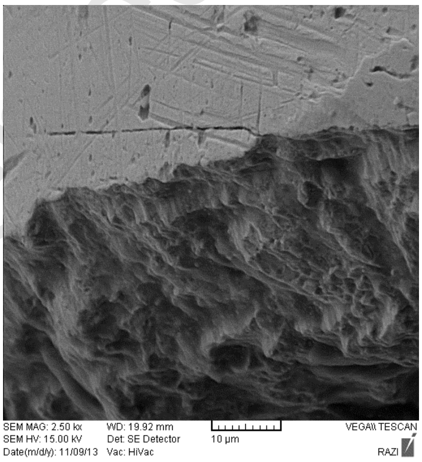



Fig. 11: Probable initial crack on the lube oil duct edge.

Table 1: Chemical composition of the internal disk

| C | Si | Mn | Cr | Mo | Ni | P | S | Fe |
|---|---|---|---|---|---|---|---|---|
| 0.18 | 0.21 | 0.48 | 0.92 | 0.54 | 3.60 | 0.006 | 0.003 | Base |

Table 2: Mechanical properties of internal disk

| $R_t$ Tensile stress (MPa) | $R_m$ Yeild stress (MPa) | $\%A_{50}$ |
|---|---|---|
| 1153 | 1050 | 19 |