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Abstract

Modern tube-membrane-piston pump have a broad-banded operational area and are often used in mines, especially coal-mines. One pump was completely damaged during the operational run, which is an absolutely risk for operators, as the pump shaft is four meter in length with a weight of more than four tons and offers an high potential of kinetic energy. More over it is a financial problem for the manufacturer and an image problem for the producer. Therefore it is useful to analyse the damage and to find out the background details which lead to the breakdown of the pump. For the analysis some methods like visual testing, the mechanical-technology examinations, the bending fatigue strength test, optical and electron beam microscope investigations have to be performed. As the results show no deviations to the declared requirements of the material data, more investigations had to follow. Finally one micro cavity directly under the surface was found in the electron beam microscope. It was responsible for the start of the crack and its propagation. From that point on it was only a question of time, load and the number of cycles on the pump shaft that a fast fracture occurred. Based on this result the producer of the pump shaft changed the producing procedure and applied advanced non-destructive testing methods to detect these micro cavities directly under the surface. A repair of these located indications helps to improve the life time of these pumps shafts enormously.

Keywords:

Corresponding Author:

Introduction

Damage analysis on a defective part of a technical system which was leading to the total crash of the system is as thrilling like a murder case. Often there are investigative leads but sometimes some leads pursued by the examiner evaporate.

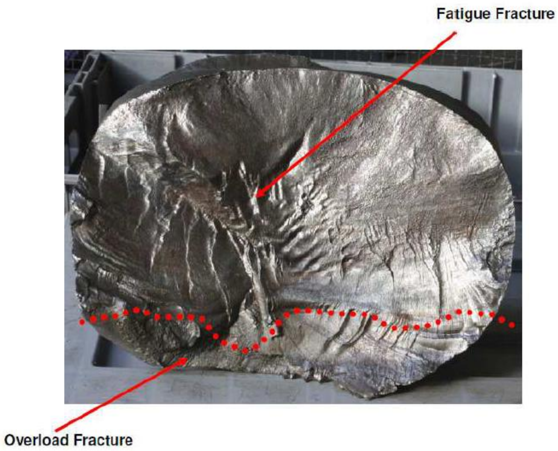
Figure 1. *Crack Surface of the Broken Shaft*

Fortunately in the present case there was no human victim which had to be inspected. We had to deal with a broken crank shaft of a high power tube-membrane-piston pump, figure 1. Anyhow the shaft had a weight of over 2,5 tons, a length of 3,5 meter and a diameter of 560 mm. The shaft rotated with 30 Hz, so enormous forces took effect on the shaft. The production of the shaft was in 2006 and afterwards delivered to China, used in coal-mines. After four years of use the critical damage occurred. Human loss could be precluded due to the construction of the pump. The economical trouble and in particular a possible loss of public image forces a producer to find out the reason why the system crashed. After the crash the broken parts of the shaft were transported back to the German producer. Before that the splotchy crack surfaces had been cleaned and the two parts including the crack surfaces were cut of, not to send the whole shaft on the way back. The constructional calculations flanked by a Finite Element Analysis had shown that the theoretical maximum load of about 205 MPa due to bending fatigue strength has not been reached. Therefore a failure in constructional calculations could not be the reason for the crash. First of all the Analyst of the damage had to collect all information. Asking the operator of the pump he noticed absolutely no striking features before appearance of the crash. An exact number of cycles was unknown. So the we had to check at first the material data. The crank shaft was produced of casting steel – 1.7221, G26CrMo4, heat treating level QT 1. The acceptance test certificate of the casting house attested all mechanical conditions, the chemical analysis as well as the results of the Ultrasonic Testing and the Magnetic

Particle Testing. According to DIN 1690 no indications had been found. All results in the certificate featured no deviations with regard to the fulfilling of the requirements. So the following methods had been used to look behind the curtain:

- optical investigations of the crack surfaces
- determination of the mechanical-technological data using the tensile test and notch impact test; parts of the broken shaft had been tested as well as new produced test specimen of the same material
- determination of the bending fatigue strength
- light microscope micrographs
- scanning electron beam micrographs including the EDX-Analysis

Figure 2. *Overview Screen of the Crack Surface*



Examination and Results

First visual testing inspections showed the tendency due to a fatigue crack, which was underlined by finding numerous lines of rest. The part of the fatigue fracture zone was up to 90 % of the whole crack surface. Therefore the nominal stress was assumable low. The crack started from the top, figure 2, the relatively marginal zone of the overload fracture can be seen at the bottom. The crack went through the cross sectional area under unidirectional bending force. The area of fracture was hammered by the cyclic opening and closing of the growing crack. Therefore important advises had been destroyed. So we had been forced to comprehend first the test results of the casting house if the material data of the G 26CrMo4 are correct. For it some parts of the broken shaft had been extracted and test specimen for the tensile test had been produced. Overall the casting house sent us test specimen of the same material which went through the same heat treatment like the original material for comparing results. The results pointed out that all data coming from the tensile test corresponds to the data for casting steel according to DIN EN 10293, heat treating level QT1 for a thickness over 250 mm, figure 3. The results coming from the new produced casting steel showed higher values in tensile strength, data of elongation were nearly the same. Talking to the casting house to find out the reason for the difference of the tensile test results – although the requirements according to the standard had been fulfilled in both cases – we recovered the main cause. The casting house cut out the specimen directly from the surface. Our specimen had been cut out from the internal part of the broken shaft. So in our examinations we performed the tests with specimen having a ferritic-perlitic microstructure, the casting house with specimen having a bainitic microstructure. The evaluation of the fracture areas of the tensile specimen showed some silvery spots. By help of a stereo microscope we detected in the centre of the silvery spots in each case a blowhole, figure 4.

Figure 3. *Tensile Test Diagram*

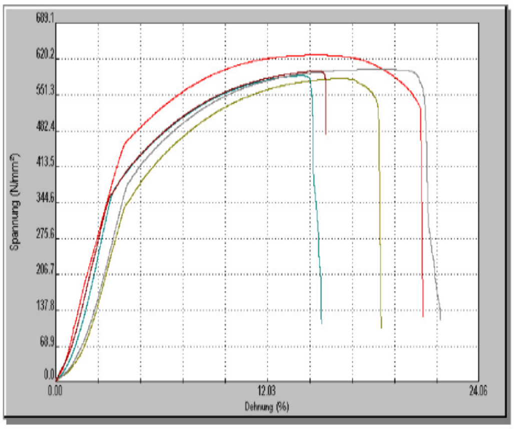
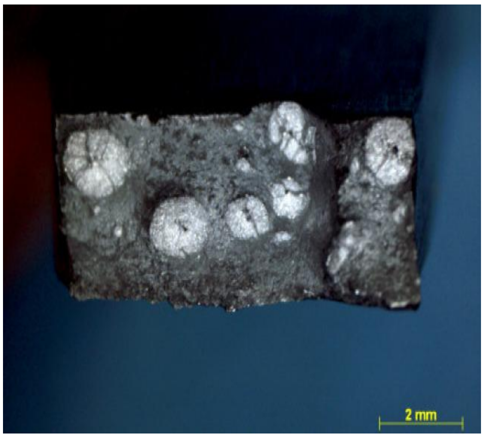


Figure 4. Fracture Area of One of the Flat bar Tension Specimen



Apparently we found more blowhole spots, having in their periphery some phosphoric and sulphuric segregations. For a casting steel it is not unusual featuring some blow holes, but their frequency of occurrence was disproportionally high. Thereupon some more specimen had been cut out of the core of the shaft as well as from the boundary area for microstructure investigations. Within a ferritic-perlitic basic structure one can recognize the blowholes surrounded by segregations containing phosphoric, sulphuric and carbide accumulations. The perlitic structure was extremely small banded (portions of sorbite and troostite) and contained some relics of bainitic areas. The partially rodded bainitic structure also contains some areas of Widmannstatten patterns, figure 5. The ferritic percentage in the boundary area of the shaft was much lower compared to the core area. In consequence of the higher ferritic and lower bainitic level of the core of the shaft due to strength was lower, the boundary area due to strength higher. More over it was stated that more blowholes surrounded by segregations can be found in the core. Also examinations performed by notch impact test produce results had been acceptable with regard to the standard.

Figure 4. *Micrograph, etched, 50:1*

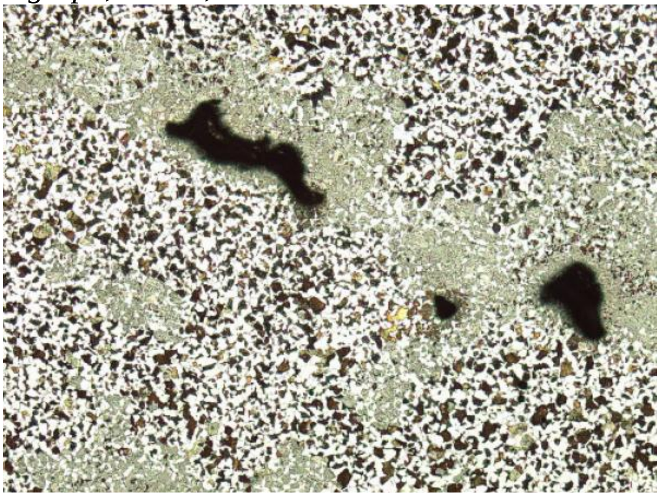


Figure 5. *Micrograph of Boundary Area, etched, 500:1*

At that point of the investigations it was clear that mechanical properties of the material cannot be responsible for the crash. In hope of getting more information we started to perform bending vibration stress tests. So more specimen had been cut out of the shaft, both from boundary area and from the core. The results also were disappointed as the amplitude of bending vibration stress was about 225 MPa, figure 6. The Finite Element Analysis calculated with about 100 MPa at its maximum. One remarkable fact was: no respectively a low number of segregations had been found within the specimen. It seemed to be that segregations in the core of the specimen had no influence with regard to the strength of the material. But otherwise we found one specimen which failed at a low amplitude of less than 100 MPa. And in that case we detected a segregation directly under the surface within the fracture area. The output was clear and is manifested in many publications. Segregations directly under the surface have a strong influence on the bending fatigue strength. So we started again to examine the fracture area of the shaft with regard to some imponderabilia. And fortunately we found a location directly under the surface, figure 7. So we cut out this spot and put it under scanning beam electron microscope.

Figure 6. *Wöhler Diagram for Bending Vibration Tests*

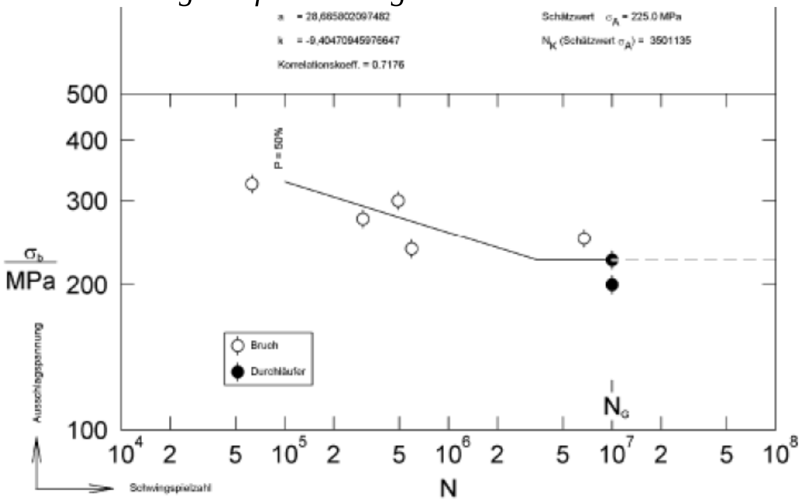


Figure 7. *Section of the Boundary Area of the Shaft*

The fracture area was totally hammered by the opening and closing mechanism of the premature crack. Therefore no vibration or crack propagation lines had been found. After a long period of scanning the whole surface of the specimen we found the malefactor – a micro blowhole which was situated 2 mm under the surface having a dimension of 1 mm. That micro blowhole could be allocated to the spot which was pointed out in figure 7 by the arrow. So we assume that effectively the crack started at the micro blowhole, propagated to the surface of the shaft and grew further until the shaft crashed. Furthermore we found some polishing tracks which caused some micro notches on the surface. In combination with the micro blowhole under the surface it was only a matter of time until the crack started its propagation.

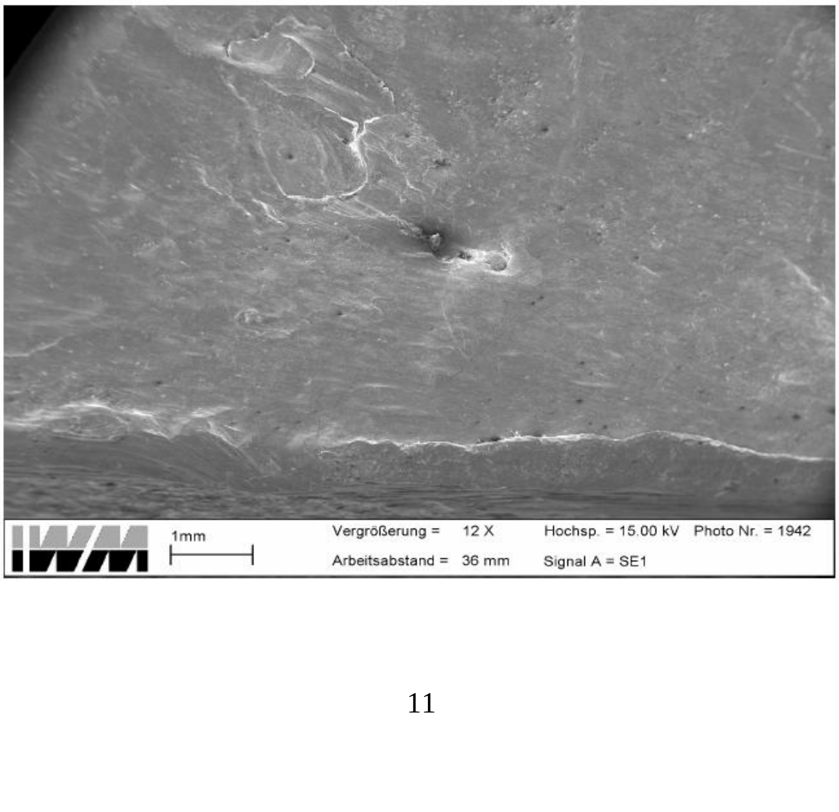
Conclusions

Under technical conditions the fatigue breakage starts generally from the surface of the component. The crack formation is strongly dependent by the state of the surface. The causes generally are:

- heterogeneous load (bending, torsion, notches)
- concentration of stress in consequence of near-surface defects (small inclusions) or localized sliding (sliding marks)
- environmental effects

According to experience inclusions of about 2 mm range are relevant. The critical value of fracture toughness is basically adverse influenced by strange phases (non-metallic inclusions), rough inclusions, accumulation of trace elements at internal boundary surfaces (segregations at grain boundaries) and strain hardening. Procedures to improve the surface condition for higher vibration strength have positive effects due to crack start, however barely on crack propagation.

Figure 8. *Scanning Beam Microscopic Image of a Blowhole near the Surface*



The surface quality factor of a component under operational conditions is of enormously importance for fatigue behaviour. Duration of life of technical constructions can be prolonged by avoiding small radius of curvature and treatment of the surface. Within the existing case it was a matter of fatigue breakage showing a minor ratio of overload fracture. Finally not the mechanical-technological properties determined the crash of the shaft. On the one hand the surface treatment - the incorrect polishing - , on the other hand blowholes directly under the surface lead to initiate crack start. Starting from the blowhole the crack propagated radiant, also in the direction of the component surface. From that point of time the crack propagation and finally the overload breakage war only a question of time correspondent to the number of cycles of flexural fatigue stress. To validate these results more vibration fatigue tests had been performed having blowholes near or directly on the surface. These specimen failed at a relatively low number of stress cycles. The extracted experiences coming out of the damage analysis had been integrated in the production of the next generation of pump shafts. First the polishing of the surfaces was optimized by creating new quality procedures, finally the application of high technology ultrasonic methods for the detection of small blowholes under the surface was implemented.

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