International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 6, June - 2013

Fatigue Failure Analysis Of Marine Engine Crankshaft

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Abstract

A case study of a catastrophic failure of a web marine crankshaft and a failure Analysis under bending and torsion applied to crankshafts are presented. A microscopy (eye seen) observation showed that the crack initiation started on the fillet of the crankpin by rotary bending and the propagation was a combination of cycle bending and steady torsion. The crack front profile approximately adopts a semi-elliptical shape with some istortion due to torsion and this study is supported by a previous research work already published by the authors. The number of cycles from crack initiation to final failure of his crankshaft was achieved by recording of the main engine operation on board, taking into account the beach marks left on the fatigue crack surface. The cycles calculated by the linear fracture mechanics approaches showed that the propagation was fast which means that the level of bending stress was relatively high when compared with total cycles of an engine in service. Microstructure defects or inclusion were not observed which can conclude that the failure was probably originated by an external cause and not due to an intrinsic latent defect. Possible effects of added torsional vibrations which induce stresses are also discussed. Some causes are analyzed and reported here but the origin of the fatigue fracture was not clearly determined.

Keywords: *crankshaft failure, rotating bending, steady torsion, fatigue crack growth*

1.INTRODUCTION

The fatigue phenomenon is a damage process caused by the growing of cracks due to cyclic stress that generate and aggregate micro cracks which can cause sudden catastrophic failures. In practice, 90% of all mechanical failure is due to fatigue which occurs under repeated application of a stress which is too small to cause failure in a single application in the elastic region. Now days the fatigue life prediction under multiaxial loadings has played a major role in structures and mechanical components design. Components in metal alloys subjected to cycling loading will fail by fatigue if an appropriate fatigue life criteria and a maintenance program were not implemented to prevent their fracture in service.

Fractures in crankshafts can occur by bending fatigue, by torsional fatigue or a combination of both. Misalignment raises bending loads on main journals fillets and can lead to bending fatigue fractures. All crankshaft fractures are generally fatigue fractures produced by bending loads on the fillets and or torsional loads on main journals. Bending and torsional fatigue cracks have similar features: flat smooth fracture faces with ductile final fractures and beach marks (arrest lines) radiating away from crack initiation site. Ratchets marks at the initiation site are arrest lines indicating multiple cracks started growing from severe stress. Bending fatigue cracks grow from fillet unless oil or lightening holes change their path. Torsional fatigue cracks start in journals and spiral around on about 45º angle. Crack initiation sites can be difficult to determine since several sets of arrest lines are often present. Usually, the origin is the point at which two sets of arrest lines radiate from each other on 45º angles.

1.1Approaches of fatigue life prediction

Two main approaches have been considered for fatigue life prediction: the crack nucleation approach and the crack growth approach. The first was proposed by Wohler [1] and it is still in use today. In the 30's of last century Gough et al [2] has performed an important research work concerned with fatigue of carbon-steels and cast irons under combinations of reversed bending and reversed torsional stresses, using a special testing machine, which gave a significant contribution for the understanding of multiaxial fatigue. The second approach considers that a crack preexists in the material and the fatigue life depends directly on the growth of this initial crack. The crack propagation approach can be used when the crack path is well identified as well as the mechanical parameters controlling the fatigue life.

Many examples of fatigue crack growth under mode I loading have shown that Linear Elastic Fracture Mechanics (LEFM) theory is increasingly being applied to the practical engineering problems, including material selection, design and analysis of engineering structures. It is a tool that can approximate the stresses surrounding a fracture to better explain damage occurrences, and is used when a defect, often a crack or corrosive attack, should be evaluated with regards to allowable dimensions. By altering the determined model parameters, the analyst can estimate the magnitude of the mechanical stress applied to a component at the time of failure.

1.2 loading conditions

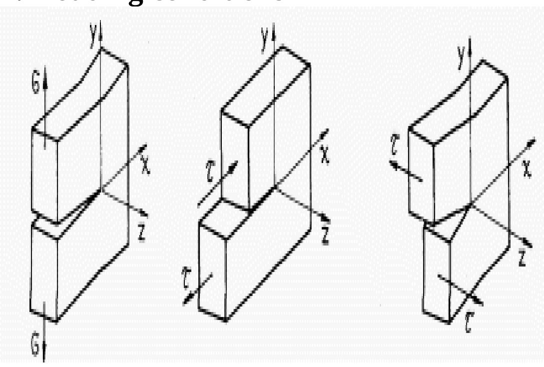


Fig1 loading modes

Often a defect discovered during routine, a non destructive testing can set of an alarm, leading to the close down of an installation or plant, and removal or repair the component. This is not always required, and this can be evaluated by performing calculations with parameter such as crack size, material properties, loading conditions, etc. Fatigue life prediction in metallic materials has been largely investigated over the past decades. Cracks in power shafts, such as crankshafts, generally start at surface and growth under mixed-mode (*_KI* + *KIII*): cycle bending, mode I (*_KI*), combined with steady torsion, mode III (*KIII*). This results from the cyclic bending stresses, due to the self-weight bending during the rotation of the crankshaft or possible misalignment between main journals and the steady torsion arises from the power transmitted by the shaft. However axial and torsional resonant vibrations can also appear under some particular operating conditions of the engine and therefore must also deserve special attention for determining the causes of damage.

2. Main Engine crankshaft

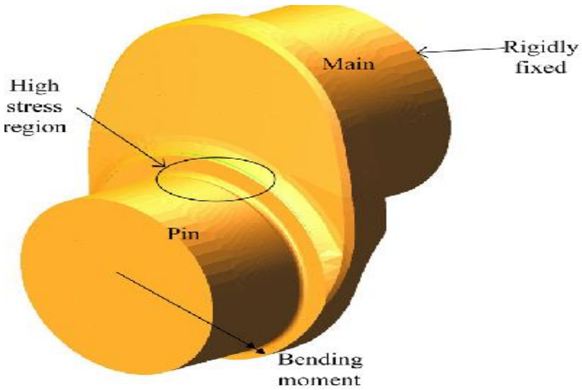


Figure 2 3-D full crank-throw model

Yang and Kuang [10] have studied the fatigue crack growth for a surface crack in round bars under multi-axial loading conditions and have shown the influence of the static compression/tension loading combined with cyclic torsion: the crack growth rate is dependent on the superimposed tension loading and the compression loading has not significant effect on the crack growth rate. Investigations in fracture mechanics in the last three decades could explain the effect of steady torsion when combined with rotary bending, and have shown that the Von Mises criterion cannot valid when applied to fatigue under multiaxial fatigue [11].

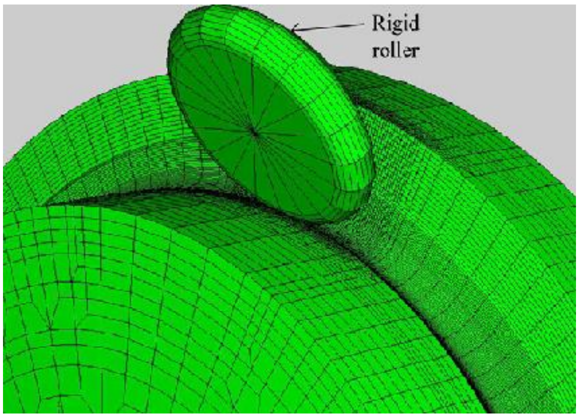


Figure 3 fillet model for residual stress

An important requirement for solid type crankshafts is the strength, and therefore some of them employ materials with strength as high as 800 MPa. Crankshafts were cold straightened after production, which causes internal residual stress. These stresses, in combination with the inclusions or other defects, can cause crack initiations. An exhaustive and important research work can be found in the literature by S. Archer [12]. One maintenance procedure with marine main engines is the strain measuring of static deflections of the crank webs.

These measurements are made at regular crank angles and historical limits have been defined, which relate observed deflation values to crack stress levels associated with once per revolution bending stresses. The effects of dynamic loads have largely been ignored. These loads, resulting from inertia and gas forces will add to the stress field generated by the static misalignment. Furthermore, the location of the rotating shaft in the bearing will affect the estimate of stress field based on the static web deflation measurements.

The vibrations are generally ignored for failure analysis but, indeed, they have an important role. Torsional vibration is the speed change of a rotating shaft within one rotating period. An engine crankshaft itself is deflecting (rotationally) forward and backward while it is operating, like a balance of a block. A crankshaft, like a plain torsion-bar, has mass and a torsional spring rate which causes the crankshaft system to have its own torsional resonant frequency. The torque peaks and valleys of the variation loading cause the engine crankshaft itself to deflect (rotationally) forward and backward, and when those pulses (excitations) are near the crankshaft resonance frequency, they can cause the crank to vibrate uncontrollably and eventually can lead to breaking. During the engine operation are also induced resonant axial and torsional vibrations (is the speed change of a rotating shaft within one rotating period) which can also contribute to an eventually catastrophic crankshaft failure. A vibration damper (absorber) can avoid such damages for protecting the engine. Therefore a torsional vibration measurement will made and will install a flywheel and a vibration damper accordingly. If the damper was not adequate (measuring torsional vibrations allows determinations of the proper damping required) or the regular maintenance was not done, crankshaft damage can occur during its normal expected crankshaft life. A vibration damper in poor conditions will have a reduced performance and high torsional stresses can occurs in the crankshaft.

2.1Deflection measurement

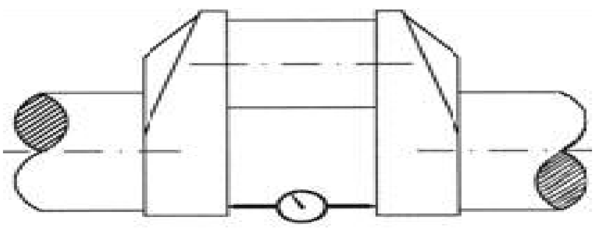


Figure 4 – Crank web deflection measurement

As it is well-known, all crankshaft bending failures are usually related with the misalignment, aggravated by deterioration of the foundation. The current industry approach to document crankshaft alignment is to measure static web deflections, see Figure 1. Deflection measurements at each crank web are until now an empirical process to assess and control the misalignment of crankshafts. Indeed this is a static and not a dynamic measurement. As a consequence of rotating bending and torsion generally also appear dynamic forces which can induce torsional or axial vibrations on crankshafts. Several observed catastrophic failures have shown that the crack initiation generally starts closed to the web crankpin where the stress bending is higher. These measurements are made at regular crank angles and historical limits have been defined, which relate observed deflection values to crack stress levels associated with once per revolution bending stresses.

However the effects of dynamic loads have largely been ignored but are also of the significant importance. In spite of the industry use of the deflection measurements as a Condition assessment tool, this measurement is less than satisfactory. It is difficult and uncomfortable to take and indeed doesn't reflect operating conditions of load or temperature. Cracks caused by bending generally start at the crankpin fillet and progress diagonally across. Sometimes abnormal bending forces are generated by main-bearing bore misalignment, improperly fitted bearings, loose main-bearing caps, unbalanced pulleys, or over tightened belts. The distribution of cracks caused by torsional (or twisting) forces is the same as for bending forces. All crankshafts have a natural period of torsional vibration which is influenced by the length/diameter ratio of the crank, the overlap between crankpins and main journals, as well as the material used

3. Experimental Procedure

3.1 Material and chemical composition

The crankshaft damaged was assembled in a main engine container ship, with controllable pitch propeller, diameter 3800 mm and 4 blades. The crankshaft material: 42 CrMo 4 + Ni + V (chemical composition, %: C=0.39; Si=0.27; Mn=0.79; P=0.015; S=.014; Cr=1.14; Mo=0.21; Ni=0.45; V=0.10); ReH=590 MPa and Rm=780 MPa; HB=285; grain flow forged, quenching and tempered. Main engine: 8 cylinders in line; 4-stroke; fire order: 1-3- 5-7-8-6-4-2. Rated power: 3520 kW, 600 rpm; crankshaft diameters: 280 mm (crankpin) and 300 mm (main journal). Counter weights: 12; flexible coupling and damper. Equipped with a reduction gearbox (ip =0.2683).

3.2 Experimental Procedure

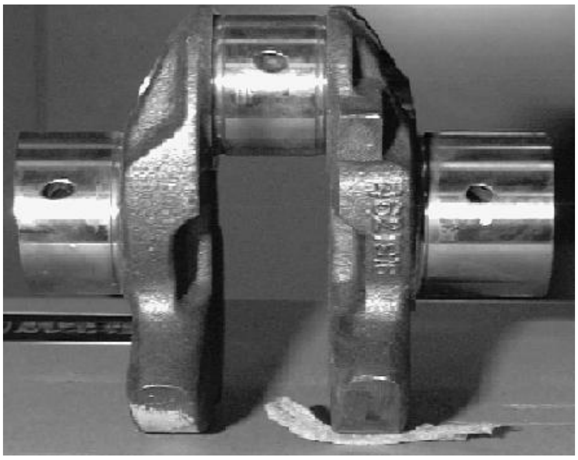


Figure 5 Test sample cut from a crankshaft

The focus of this study was on a rolled, ductile crankshaft. Crankshaft test samples were coupons cut from main to main, as shown in Figure 5. The symmetry of the mains allowed for resonant ending fatigue testing since the masses that would be in resonance could be centered to each main. The orientation of the bending moment to crankshaft sections was across the cheek from main to pin journals. This resulted in the highest stress concentration points in the fillet region.

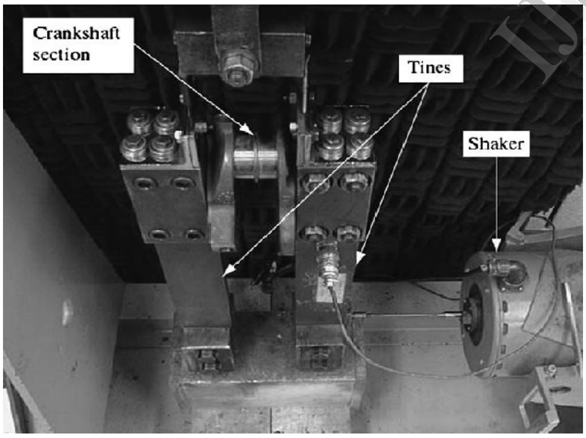


Figure 6 Crankshaft resonant bending fatigue test apparatus

Figure 6 showed a crankshaft resonant bending fatigue test fixture for testing. This was the same fixture used in previous fatigue strength studies [1] using the surface crack failure criterion. This fixture had an adjustable function generator for a drive load and a pair of every tine attached to the crankshaft section and instrumented with a bending load cell or a feedback. The assembly was excited at its resonant frequency through the function enervator attached to one of the tines. The resonant frequency of the assembly would continue to decrease because of the change in stiffness from cracks. The constant upper vision of a technician was needed to oversee the resonance frequency of the assembly, the drive loads, and the feedback loads during testing so that bending fatigue testing could be preserved at a resonant frequency and at the targeted load. An updated bending resonance of the assembly was determined by the peak feedback load after sweeping through the frequencies of +/_0.5 Hz from the previous resonant frequency. After the new resonance was attained, the function generator would be adjusted until the feedback load matched the targeted load.

4. Results

4.1 System and failure description

The crankshaft of the main engine has damaged. The crank web nº4 has broken. The facts:

1)The crankshaft failed after over 32,834 hours in service. It has broken on the web Crankpin nº4, in the transition to the main journal nº5.

2)The main journal bearing shells were changed by new ones after 29,952 hours according the maintenance plain.

3)Deflection measurements, before and after the bearing shells change, were in satisfactory conditions.

4)Deflection measurements were also obtained after 31,687 hours, i.e. 1,147 hours before damage and were in accordance with the allowable mean values.

5)All shell bearings were in normal wear after damage, except the shell bearing of the crankpin nº 4 because the some material was desegregated in consequence of the fracture.

6)The crack initiation started in the fillet of the crank web nº4.

7)The fatigue crack surface shown the beach marks or arrest lines left from the last voyages and could be identified through the voyage book on board.

8)In vibration damper a significant number of springs were found broken or damaged, and many of the pockets for the spring packs showed unusual high wear rates.

4.2 Fractographic features and visual inspection

Figure 7 – General view of crankshaft with the fatigue fracture section at junction of nº4crankpin and forward web

Figure 7 shows a failed marine web crankshaft. The catastrophic failure happened after more than 32,000 operating hours (1.15x10^9 cycles) on the crank web nº4, at the middle of the crankshaft. The bearing shells were found in good conditions after damage and only the crankpin bearing caps were changed nine months before, according to the maintenance plan. The alignment of bedplate was checked and the measured values were under standard recommended by the engine builders. Measurements of crank web deflections were available 1,147 hours before and no anomaly was found. In a first approach, the fatigue fracture seems to be as a consequence of high bending moments on the crank web nº4.

Figure 8 – Failure surface

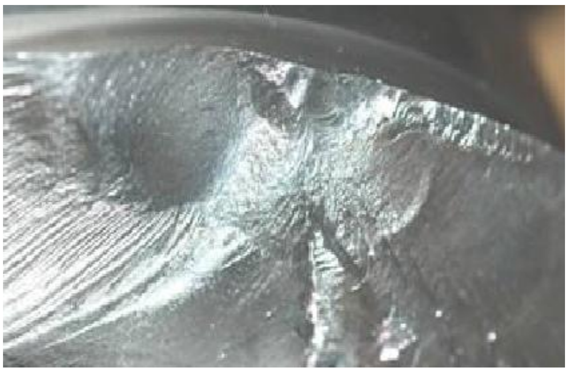
Figure 8.a - Parallel to the axis (final fracture)

According to the Figure 8, it is possible to observe the region where the crack was initiated, starting from the elliptical lines (but distorted because the effect of steady torsion) and then to find the origin or the focus. Observing the fatigue crack surface, the fatigue crack initiation was by rotating bending and the crack propagation was by rotating bending combined with torsion. The cause of failure will be analyzed in the following.

The morphology of the failure surface shows that the fracture presents two different surfaces: one almost perpendicular (with some deviation) to the crankpin section and other in a horizontal plan with the crankshaft axis. The latter one, the second, is the residual surface and corresponds to the final fracture, because the remaining section over the limit of material strength for that load, and therefore it is a ductile fracture. The first one shows a typical fatigue fracture characterized by a circular/semi-elliptical crack front profile starting from a point where the crack was nucleated, perpendicular to the crankshaft axis and another showing some deviation from the perpendicular plane.

Observing this zone with more amplification, as shown in Figure 9, it is clearly seen that crack initiation occurred through the growth of three parallel cracks that linked together at a certain depth. It is also observed lines known as beach marks which correspond to the engine stopping or changes of loading in service. These lines are helpful to calculate the number of cycles among different stops or changes of load which allows reconstruct the history of the crack propagation. A crack with a configuration perpendicular to the shaft axis is generally associated to rotating bending. Here it seems to be clear that the fatigue surface is due to a high bending moment on the crank web. However in this case the fatigue surface there is some inclination which results of a combination of rotating bending with steady torsion, typical situation of the power shafts [4]. Observing the crack path since the crack initiation zone until final fracture, it is possible to see the beach marks with a semi-elliptical front profile with some distortion which is typical of the fatigue by bending combined with steady torsion. These beach marks are centered in a focus which is generally associated to the crack initiation

Figure 9– Crack initiation zone



5. Failure characterization

5.1 Hardness test

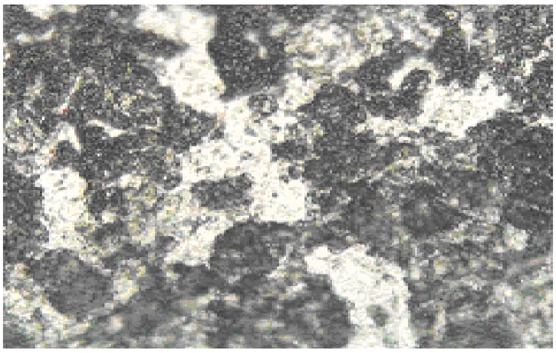


Figure 10 – Micrographs of the material

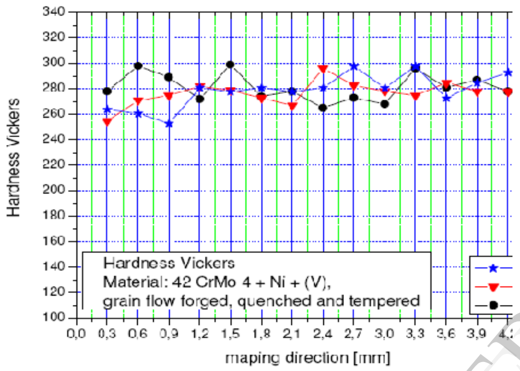


Figure 11 – The Vickers hardening in the first millimeters from surface

The material closed the crack initiation was analyzed at the laboratory and shown a bainitic structure, Figure 10 and the hardness Vickers was about 285, Figure 11, which is according to the standard values for this type of steel and delivered by the manufactory and confirmed by the class certificate.

5.2 Micro-Fractography

Looking at the initiation site with good lighting and magnification, revels no inclusions, precracks, or other abnormal stress raisers. One should conclude as a first impression that the damage was caused by a latent defect of the material. However, the experience has shown that a crankshaft after an operation time of more than 32,000 hours at 600 rpm, more than 1,15x10^9 cycles such a flaw can by no means have the causative factor of the damage, and therefore a crankshaft has long proved its endurance strength.

The fatigue surface after the region where the crack (or cracks) began presents not a flat surface but an oblique surface is within 2 to 3 mm depth from the origin. The reason is because, in the beginning, the crack initiation starts from three short parallel cracks nucleated by rotating bending, that were linked, after some millimeters of depth, by the effect of torsion. After this joining, the crack propagation goes on with a typical helical surface due to the effect of torsion [4]. The propagation observed from a perpendicular direction to the crankshaft axis shows a crack path in zigzag, typical from the crack growth under bending combined with steady torsion [4,5], and see Figures 8 and 9. The crack length on the surface grows faster for one side than the other side which is understood because the direction of applied torque [5] and this is clearly seen with a more distance among the elliptical fatigue lines during the propagation. Close to the final fracture, the distortion or warping of fatigue crack surface is more significant than that observed in the beginning of propagation because the effect of torsion is predominant regarding to the bending. After an accurate observation of the fatigue surface and material close to the crack initiation, after micrographs and material examinations carried out at the laboratory, if there is no evidence of a latent defect, it is necessary to find the causative factors in other sources namely the operations conditions of the last months.

The crack arrest lines on the pictures of the fatigue surface, known as the beach marks, identified with the last voyages of the ship, provides a clear information about the number of cycles to failure between the crack initiation and the catastrophic failure.

On board there is on board book a record of the each voyage (all events and time in hours from starting until stopping the main engine). The history of fatigue crack growth is written on the fatigue failure surface through the so called beach marks or arrest lines. It is not possible to know how many fatigue cycles were done during the crack nucleation process and in the first millimeters after nucleation as well, but statistically a value of 80 to 90% of total life is spent in the crack nucleation process.

5.3 Fatigue crack growth analysis and prediction of fatigue life

The stress calculation and the number of cycles to failure were obtained using the fracture mechanics approaches and compared with the cycles obtained from the record on board. The Stress Intensity Factors used for the equation of Paris law were obtained from another previous work [4, 5]. The calculations were carried out into two stages: first, the remote stress level was calculated taking into account the length of crack growth between beach marks and the records on board. Second, the number of cycles obtained from the final fracture until a certain crack depth considered as the start of crack growth after crack initiation was calculated.

The number of cycles to failure of this crankshaft was achieved by recording of the main engine operation on board, taking into account the *beach marks* left on the fatigue crack surface. Through the beach marks (stopping or starting of the machine) left on the fatigue crack surface, observed on Figure 12 it is possible obtain a correlation between a certain crack length and the time spent during the corresponding voyage of the ship. Using the crack growth equation which gives the number of cycles by integrating the Paris Law for a considered crack length, it is possible to estimate the applied remote stress ($\Delta\sigma$) for R=-1 (reversed bending).

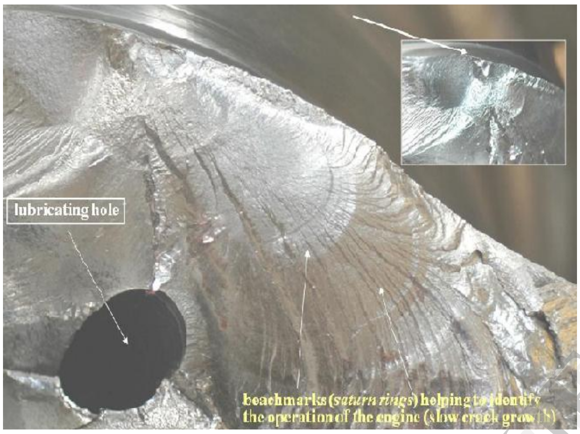


Figure 12 – Crack initiation site and beach marks of crack growth

The **Paris-Erdogan** law states that:

$da/dN \quad = C\,(\Delta K)\,^{\wedge}m$

Where C = 2x10^-12 and m = 3

$\Delta K = Y \cdot \Delta\sigma \cdot \sqrt{\pi a}$

Where Y = (b/a, b/r, φ□) ≈ 0.5

by integrating this equation between an initial and final crack depth, for example af=55 mm, ai=32 mm, that can be related to the onboard records, a stress level of $\Delta\sigma \approx 30$ MPa can be estimated.

It is now possible to estimate the life spent to grow the crack between an initial small crack and final fracture, by integrating the same equation with the applied stress of $\Delta\sigma \approx 30$ MPa, between af=55 mm, ai=2.5 mm, therefore 2400 hours were estimated which corresponds to approximately to a time less than the time spent since the scheduled change in the journal bearings.

5.4 Failure analysis discussion

The fatigue fracture appears in two distinct surfaces: a smooth almost to perpendicular to the crankshaft and a second one in a horizontal plane with the crankshaft, with transition zones between two surfaces, according to Figure 8. This confirms a typical fracture by fatigue, characterized by propagation with a crack front profile approximately elliptical from the crack initiation point until the fast final fracture. The beach marks show several stops of the main engine which permits to obtain the history of the fatigue crack growth Process associated to the vessel voyages. A fracture surface configuration perpendicular to the crankpin axis is generally associated to the loading bending in shafts. However a helical surface observed in this fracture clear shows a mixed-mode fatigue, i.e., a combination of rotating bending with steady torsion, and found in the literature [4, 5]. Consulting the main engine book on board, it is possible identify the beach mark zones of the fatigue fracture with the last voyages of the vessel (visited ports), starting from the fast fracture (catastrophic failure) towards the crack initiation point. The total estimated hours found were about 2400, computed from the catastrophic failure until the crack region of the nucleation. It is not possible to know the number of cycles of the nucleation process, but the experience has shown that is about 80-90 % of the total life time (≈16000 hours). It seems evident that the catastrophic failure has resulted of a fast fatigue crack growth rate. The local microstructure and the microscope observation close to the crack initiation zone didn't reveal any defect of the material. The experience has also shown that a crankshaft, after more than 30000 operating hours, an inclusion/flaw or a latent defect in the material, cannot be the root cause of damage.

On top of a list of possible causes the damaged vibration damper can probably be as a main cause of the failure. The vibration damper presented a significant number of springs broken or damaged and many pockets for the spring packs showed unusual high wear rates. A vibration damper in such conditions will have a reduced performance which will lead to a higher torsional stresses in the crankshaft. However as can be seen by the crack initiation the nucleation is by rotating bending and with more than one crack developing on the same local which usually occurs on stress concentration zones or higher stress levels. Operational irregularities which may include firing pressure deviations and engine overload can also origin overstress on the main journals.

6. Conclusions

The catastrophic fracture of this marine crankshaft was by fatigue, a combination of rotating bending with steady torsion. It was possible to identify the crack initiation due to the elliptical arrest lines, which happened in the zone between the crankpin and main journal. The hardness obtained for this material close to the zone of crack initiation is adequate for this type of steel. It was not found any material defect or inclusion and the manufacturing and material of crankshaft was supervised and certificated by a Register of Shipping Society and the resonant frequencies found were not significant. The number of cycles to failure obtained by the record on board and the calculated by the linear fracture mechanics approaches showed that the propagation was fast which mean that the level of bending stress was relatively high. After the crack initiation by rotating bending the effect of the steady torsion became itself significant. Having to account for the arrest lines and the last identified voyages of the ship, indicates that the crack growth was relatively fast when compared with the total number of hours of the main engine and crankshaft, which confirms that the catastrophicfailure was not due to a progressive wear of the crankshaft. The origin of the fatigue fracture it is not still determined. The research and the monitoring of the new crankshaft are going on because eventually it may happen again.

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