Failure investigation of an industrial crankshaft made of ductile iron

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Received 28 February 2017; Accepted 22 May 2017; Available online 6 June 2017

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ABSTRACT

The design against fatigue of materials and components in rotary equipments is critical and attractive, as number of industrial rotary components failed by fatigue increased over the years in petroleum sector. Novelty of fine grain practice micro structure engineering and surface modification significantly increases the fatigue strength of industrial components. Root cause analysis of fatigue failure is conducted with possible outcome to prevent the failures. The high cycle fatigue life design of crankshaft approaches safe life design philosophy. In the present investigation, failure analysis of the crankshaft was analyzed to determine the cause of failure. Visual examinations reveals the brittle fracture with beach marks and metallographic examinations reveals the crack initiation at Type I graphite sharp boundaries in pearlitic matrix and crack propagated & accelerated till broken in to two pieces of crankshaft.

KEYWORDS: High cycle fatigue, Ductile iron casting, Type I Graphite, Fracture and Fatigue, Metallography

INTRODUCTION

The ductile iron is solid solution strengthened constituents of spheroidal graphite in ferritic, pearlitic or ferritic pearlitic matrix. Because of high toughness, high strength, high damping capacity and low cost ductile iron are used widely in many crankshafts, camshafts, gears, wheels, sprockets, chain links, and axles of many rotary industrial types of equipment. The performance of components made from ductile iron is dependent of mechanical properties like tensile strength, yield strength, fatigue strength which in turn depends on microstructure. The casting and solidification quality is utmost important for fatigue component design. Although matrix structure can be altered by subsequent heat treatment, however formation of graphite is only controlled during casting and solidification. The controlled rate of spheroidal graphite growth during solidification determines the notch toughness of material during fatigue applications. The spheroidal graphite distribution wholly or partially on matrix depends on type of component application like axial stress, bending stress, reverse bending stress or torsional stress determines the life of component. The magnesium or magnesium contain ferrosilicons are used as nodulizing agent during casting of ductile iron. The fatigue design of an industrial components based on two major design philosophies. The stress or strain life approach is called safe life design; crack length approach is called damage tolerant design. The crankshaft fatigue design is based safe life design; crack length approach is called damage tolerant design. The crankshaft fatigue design is based on the assumption that the crack will initiate at the spheroidal graphite nodules. The crack path will follow the spheroidal graphite nodules. The fatigue limit of ductile iron is significantly lower than that of tool steel. However, ductile iron offers a number of advantages over tool steel due to its lower cost, ease of fabrication, and superior wear and fatigue properties.
In the present study failed crank material ASTM A536 GR 80-55-06 has been analyzed and examined. The crankshaft is solid metal bar transmit power or motion in axial direction. The failed crankshaft was used in water injection pump operated for last fourteen years. Before installation chemical analysis of heat & crankshaft, mechanical properties, dimensional check, non destructive examinations like dye penetrant, magnetic particle and ultrasonic inspection were conducted. No significant indications were obtained before installation. The crankshaft was failed after running of 100000 hrs into catastrophic in nature. The design life is 150000 hrs under ideal operating conditions. On dismantling and inspection, the crankpin of the second plunger of the crank shaft was found to have sheared off. A frequent crankshaft failure in operating pumps leads an un-planned shutdown and causes major revenue losses.

MATERIALS AND METHODS

The crankshaft material was made from ASTM A536 GR 80-55-06 casting and machined to final dimension. The American society of testing materials was specified mechanical properties of crankshaft. The ASTM specifies ultimate tensile strength lies in range 551 MPa to 685 MPa and average tensile strength should be 620 MPa [3]. The Hardness should be in the range from 179 HB to 248 HB [1] [3]. Fatigue endurance strength is expected in the range between 268 MPa to 275 MPa for un-notched specimens and 144 MPa to 165 MPa for notched specimens [3][1]. For un-notched specimens, endurance limit and impact energy was specified as 275 MPa and 20 Joules to 88 Joules, respectively. For 45° V notch specimens, endurance limit and impact energy was specified as 165 MPa and in between 2.5 Joules to 7 Joules respectively [1].

![S-N curve for ferrous and non ferrous materials](image)

**Experimental procedure:**

The failed sections of crankshaft were inspected visually and macroscopically. The failed portion was subjected to photo documentation; metallography samples were prepared using Struers fine cutting and Buehler polishing machine, metallographic samples were analyzed using optical microscopy of Zeiss Axio Vert.A1 model, and hardness tested using diamond pyramid indenter of MIC 201A GE. The Chemical Composition of crank pin material was analyzed using positive material identification x-ray fluorescence technique using Oxford instrumentation X-Met 7500 model.

RESULTS AND DISCUSSION

The visual observation of crank shaft reveals that shaft broken into two pieces whereas corrosion, wear, distortion and surface marks are not observed. The chemical composition measured from failed section of crankshaft shown in table1.

<table>
<thead>
<tr>
<th>Table 1: Chemical composition of crankpin</th>
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<tbody>
<tr>
<td>Carbon</td>
<td>3.50-3.90%</td>
</tr>
<tr>
<td>Silicon</td>
<td>2.25-3.00%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.15-0.35%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.025% max</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.05% max</td>
</tr>
</tbody>
</table>
The hardness was measured on surface and cross section (post fracture surface) of crankshaft shown in figure 2. The hardness measured found well within ASTM standard on surface, however it shows higher hardness on the cross sectional area (Beach marks area) of crankshaft due to slip band intrusions/extrusions processing during fatigue crack growth propagation simultaneously [2]. The macroscopic view confirms low nominal stress under reversed bending as primary source of failure and not due to rotating-bending fatigue (mostly occurs) as crack initiated at only one point on surface A. The center part of crank shaft also experiences zero torsion force and the torsion increases radially towards the outer surface reached maximum on surface (periphery). The beach marks/striations on both sides of the shaft from figure 3 were confirmed the material experiences fatigue and failed accordingly. The initial rough region shows shaft failed due to a notch which could not carryover the low nominal stress during the service. The root notch was found at portion A where severe stress concentration occurred with low nominal stress and progressive advancement of crack towards the outside diameter of the component as shown in figure 3. The initial stress concentration factor is expected to increases abruptly with combination of bending-torsion & localized stress near crack root tip at surface A as shown in figure 3. Crack started growing by cyclic loading after crack depth reaches the critical crack length. The B region in fig 3 shows brittle fracture with no gross deformation and observed to be fast fracture region. Type I graphite particle edge initiated the crack and growth leads to brittle fracture is clearly illustrated in figure 4a and figure 4b. This figure also confirms that nodular graphite has neither influenced crack initiation nor crack growth. This failure has followed the normal fatigue pattern of chevron marks for failed crankshaft under rotary service condition. The large fast fracture cross sectional area very near to surface confirms defects (surface cracks) which increases stress concentration and failure by brittle fracture as shown in figure 3. The surface and sub-surface Type I graphite with sharp boundaries as shown in figure 4a and figure 4b is primary cause for this failure. The sharp Type I graphite boundaries could have originated during solidification of casting which leads fatigue crack initiation on surface and subsequently component failure during the service.

Fig. 2: Hardness measured by diamond Indenter of crankpin on surface and cross sectional area

[Fatigue failure with brittle fracture shown as A and B while C indicated as beach marks]
Fig. 3: Macroscopic view of crank pin failed with different zones viz. A-crack initiated region; B-crack propagated region through rubbing; C-ring pattern beach marks

Figure 6 shows smooth rubbing marks which follow the direction of rotation clearly indicating torsion-bending fatigue failure has taken place [2]. Also figure 6 reveals that the load applied during operation of the rotary component (pump) was not fluctuated as load intensity is same/alternating stress has not varied and shows absence of beach marks at macro level at portion B in figure 3. Figure 7 shows primary nodular graphite nucleated in pearlitic phase while flake graphite nucleated in ferrite phase during solidification after casting [3] [4]. The Type I nodular graphites and Type II flake graphites were uniformly dispersed throughout the material but some nodular graphites were not grown fully as nodular structure instead grown as non-uniform sharp graphites during solidification after casting. The uniform distribution of graphites was also observed as seen from figure 6, figure 7 & figure 8 [1] [3] [4].

Fig. 4a & 4b: Un-etched 100X surface: Pentagon primary graphite particles with severe stress concentrated brittle fracture initiated at the notch section A of Figure 3
The analysis of crank shaft failure reveals a crack at surface originated due to sharp boundaries of primary type I graphite nucleated in pearlitic matrix may be the root cause of fatigue failure based on the fractography analysis [2]. The defect of above classification is manufacturing defect during solidification which aggravated & accelerated the fatigue failure of the crank shaft due to reduced fatigue notch toughness [3]. The stress intensity factor reached critical fracture toughness was failed eventually under ideal operating condition of shaft.
Conclusion:
X-ray florescence, hardness and metallographic examinations were concluded that failed crankshaft is ASTM A536 GR 80-55-06 ductile cast iron. Although surface inspection and magnetic particle examinations were satisfied the crankshaft surface quality after casting, the metallography revealed failure occurred due to sharp boundaries of primary type I graphite nucleated in pearlitic matrix. The sufficient quantity of inoculants like magnesium or magnesium based ferrosilicon addition in hot metal should be ensured before pouring in cast mould to form nodular graphitic structure throughout the cast section to avoid fatigue failure [5] [6]. The sharp boundaries of primary type I graphite nucleated in pearlitic matrix drastically reduces the notch toughness of material and prematurely failed against safe life stress based design philosophy under fatigue limit. The higher hardness on failed cross sectional area reveals cyclic hardening during fatigue crack propagation.

REFERENCES