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The Analysis of Light-duty Truck Diesel Engine Crankshaft Failure

K. Aliakbari*

Mechanical Engineering Department, Faculty of Montazeri, Khorasan Razavi Branch, Technical and Vocational University (TVU), Mashhad, Iran.

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Abstract

In this study, crankshaft failure of four-cylinder light-duty truck diesel engine was examined. The failure occurred by fatigue crack growth which was initiated from a surface defect after about 95000 km on the second crankpin from the crankpin-web fillet where the stress concentration was at the highest level. To evaluate the mechanical properties, some hardness and tensile tests were conducted and spectrometry analysis was used for studying the chemical composition of the crankshaft material. Additionally, for considering and evaluating the microstructure, microcracks, fracture surface, and the cause of failure, optical microscopy (OM) and scanning electron microscopy (SEM) equipped with energy dispersive spectrometry (EDS) were used. The morphology of the fracture surface showed a smooth and flat crack initiation with the beach marks and ratchet marks and second crack propagation zone with beach marks and fast final fracture zone near the end. The results of EDS observations indicated that inclusions of non-metallic aren't distributed throughout on the steel and in some places leads to the formation of the microcrack clusters.

1. Introduction

Mobility is one of the major necessities of population living in industrial and non-industrial countries. This achievement requires light and heavy, private and public transportation vehicles to be available. Continuous transportation is possible when all the automotive engine components, power transmission systems, and steering and control systems function properly and get damaged after a long time. The engine motive components are: crankshaft, flywheel, pistons, connecting rods, camshaft, oil pump, and water pump. Crankshaft is the most important motive part of engine whose components are shown in Fig. 1 [1-2].

Crankshaft is the shaft in the internal combustion engine that converts the linear motion of piston into rotational motion. Most of crankshafts are made of steel with medium carbon or its alloy in combination with chrome and nickel metals using forging or casting techniques and they have remarkable mechanical strengths. Crankshaft must be strong enough to hold on the pulses that enters piston during the combustion process without exerting too much pressure. In addition, crankshaft has to be balanced so carefully that is prevented from vibrations caused by the off-center masses. However, for balancing the crankshaft, counterweights are added to the crankshaft for every crank. The power that piston gives to the crankshaft is not uniform and this action causes the decrease or increase in crankshaft speed. Of course, the relatively heavy flywheel connected to the end of crankshaft overcomes this limitation. Flywheel inertia tends to make it rotate at a constant speed, so that the flywheel gets the power when the crankshaft speed increases and gives

*Corresponding author: K. Aliakbari (Assistant Professor)
E-mail address: karim.aliakbari@gmail.com
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it back when crankshaft speed decreases [4-5].

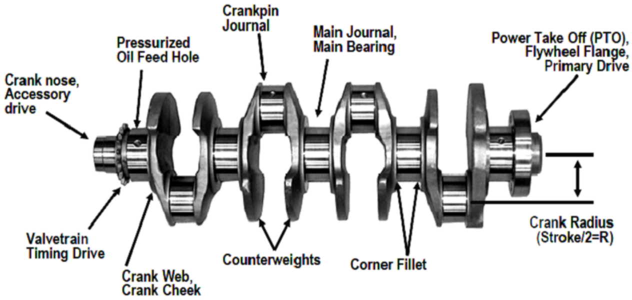

Fig. 1. Engine crankshaft terminology [3].

Most of crankshaft failures of internal combustion engines related to fatigue failure are the result of bending and torsional loads. The main source of loads is related to high pressure gases of the combustion process that this is applied to the crankpin through the connecting rod. Other factors affecting the fatigue life are: high torsional oscillations due to the imbalance of crankshaft or lack of crankshaft balancer, insufficient oil between main journal and crankpin bearings, high pressure resulting from combustion inside the cylinder and the existence of cracks resulting from manufacturing especially between the crankpin-web fillets, or on main journal fillets. Surface cracks related to rotating bending start to form when there are non-finishing of the manufacturing process or the insufficient oil between main journal and crankpin bearings [6-7].

Font et al. [8] considered the analysis of failure for two diesel engine crankshafts of the mini backhoe and the automobile vehicle. The first crankshaft failed after 1100 hours on the third crankpin and the second one failed after 105000km being in service. Crack growth in both crankshafts were related to crankpin-web fillet and the forms of cracks that were semi-elliptical and symmetrical. This fact approves the effect of mode I. In another article, Font et al. [9] analyzed the fracture of engine crankshaft of diesel vehicle with 90Hp and 180Nm of torque in revolution 2500rev/min. Failure in this crankshaft happened twice on the crankpin no. 2. The first failure was after three years and the second one happened after 30000km. The fatigue crack initiation, in both cases, formed from the center of crankpin and eventually led to the fracture. Crack front profile in this crankshaft was symmetric semi-elliptical that showed the effect of fracture mode I under alternating bending load. Alfares et al. [10] considered the crankshaft failure analysis of six-cylinder in-line diesel engine of public bus after 300000km in service. Crack growth had extended between the fillets of the main journal, across the web to the crankpin fillet. It was concluded that the removal of partial layer of nitration decreased the fatigue strength in both crankpin and main journal of crankshaft and resulted in the growth of crack. The semi-elliptical form of cracks approved the effect of fracture mode I. Farrahi et al. [11] evaluated the fracture analysis of some crankshafts of four-cylinder diesel engine. FEM results revealed that the most vulnerable point of fracture is on the fillet of the last crankpin (closest to the flywheel). Silva [12] examined the failure of the two crankshafts of diesel engines. The grinding operation on the crankshafts were performed after 300000km and after reassembling the crankshafts of the engine, the crankshafts broke down after traveling about 1000km. The analysis of the results showed that the initiation of small thermal fatigue cracks, because of the improper grinding operation, caused the damage of the crankpin. Becerra et al. [13] evaluated the failure of reciprocating compressor crankshafts used in bus climate control systems. Higher stresses are in the keyway zone, where the effect of the geometric stress concentration factor is the most vital. Pandey [14] considered the failure analysis of tractor diesel engine crankshafts. Studies proved that fatigue crack initiation originated from the crankpin-web fillet of crankshaft. Operations of machining, grinding, and precision induction hardening to eliminate discontinuities or crack-like defects in the fillet zone is required to prevent such fracture. Font et al. [15] considered the crankshaft failure analysis of boxer diesel engine after 95000km in service. It was concluded that the consequence of poor design of steel support shells and bedplate bridges cause crankshaft failure.

In this study, the failure analysis was conducted on the light- duty truck diesel engine crankshaft. The failure was created in the second crankpin of the zone of the crankpin-web fillet. To evaluate the mechanical properties, hardness and tensile tests were conducted and the spectrophotometer was used to determine the chemical composition of material. Moreover, for considering the microstructure, defects, fracture surface, and the cause of the failure, OM and SEM, equipped with EDS, were used.

2. Methods of Experimental Studies

The investigation and studies of crankshaft failure of the light-duty truck diesel engine were carried out as follows:

1. Selecting a broken down crankshaft
2. The analysis of the chemical composition of the crankshaft material
3. Determining the mechanical properties (hardness and tensile test)
4. Considering the microstructure by using OM and SEM
5. Investigating the crankshaft failure reasons

Items listed in the following sections will be discussed.

3. Results and Discussions

A case study was done in this research on the crankshaft failure of four-cylinder light-duty truck diesel engine. The characteristics of such engine are shown in Table 1.

Table 1
Engine specifications and conditions.

1	Engine configuration	4 stroke-cycle, turbocharger and intercooler
2	Displacement (cc)	3298
3	Bore × Stroke (mm)	100 × 105
4	Max. Power (hp/rpm)	115 / 3400
5	Max. Torque (kg.m/rpm)	29 / 2000
6	No. of cylinder	4 in-line

Fig. 2 shows the fracture location on the second crankpin from the crankpin-web fillet of crankshaft. The crankshaft failure happened after about 95000 km and its measured characteristics are listed in Table 2.

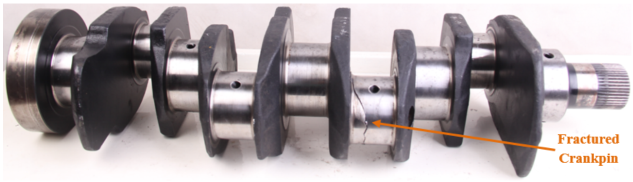

Fig. 2. Photograph of the broken down crankshaft at the second crankpin.

Table 2
Crankshaft specifications and conditions.

1	Crankshaft mass	33kg
2	Crankshaft length	612mm
3	Main journal diameters	75.79mm
4	Crankpin diameters	63.21mm
5	Operation	95000km

3.1. Properties of Crankshaft Material

Chemical composition test of the crankshaft materials was performed by spectrophotometer model, SPECTROMAXx, based on ASTM E415-14 and ASTME1086 standard. Experiments were repeated three times at 24°C and 23% relative humidity. The results of average values are listed based on weight percent in Table 1. The values of the determined elements in the Table 1 are equal to AISI4140 steel in the American AISI standard and equal to 42CrMo4 / DIN 1.7225.

42CrMo4 steel is a common chromium-molybdenum alloy steel according to DIN standard, and 1.7225 steel is under W-Nr Germany standard. DIN 1.7225 is recommended for gasoline and diesel engines crankshafts with medium to heavy duties. Forging, quenching, tempering, and nitration processes were employed to streng then this alloy. Alloy was quenched in oil at temperature of 1123 K and then was tempered at 953 K. Such operation creates surface hardness of about 280 HB. Furthermore, to increase the hardness in the main journal and crankpin of crankshaft, experiment can be carried out using flame or induction to attain a hardness up to of 480 HB. For heavy-duty applications, a nitration process is capable of reaching the surface to the diamond pyramid number (DNP) of 700 HB. These surfaces of the journal are suitable for all tin-aluminum and bronze bearings. [16].

In order to compare the crankshaft material properties with the standard material, the engineering stress-strain diagram was used at ambient temperature. The crankcase oil temperature in diesel engines is in the range of 90-110°C, thus according to Refs. [17-18], in this temperature range, about 10% of the yield and tensile strength are reduced. On the other hand, according to Refs. [7,11], the maximum stresses of the torsional and bending forces are about 15% and 30% of yield strength occurring in the crankpin fillet regions. It seems that achieving mechanical properties of engineering stress-strain diagram at ambient temperature is similar to true stress-strain diagram considering the temperature ranges and the maximum stresses.

To study the mechanical properties, three tensile test samples were cut of the crankshaft by wire-cut machine and then they were machined with high accuracy according to ASTM E8M-97a standard using CNC turning machine. This standard determines the method for the tension test of metallic materials. Finally, the samples were tested by Zwick/Roell model Z100/Z250 materials testing machine with central ball-lead screw. Machine capacity was 25 tons. The method of the experimental test was similar to the method done in Ref. [19] and the results were recorded in force-displacement mode. The results with sampling rate of 2 times per second were recorded in the form of force-displacement. Samples length variation were done by extensometer with the length of 50 mm, in which the rate of speed of stroke was adjusted to 0.50 mm/min. Finally, ultimate stress (UTS), yield stress (YS), and elongation were obtained from the test results.

Table 3
The chemical composition of DIN 1.7225 and Standard.

Symbol	Fe	C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu
DIN 1.7225	96.6	0.403	0.326	0.76	0.015	0.007	1.2	0.079	0.171	0.016	0.069
Standard	Base	0.38-0.45	≤0.040	0.60-0.90	≤0.035	≤0.035	0.90-1.20	-	0.15-0.30	-	-

Table 4
Mechanical properties of the DIN 1.7225 and Standard alloy.

Symbol	Yield Stress (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
Current work	799.91	936.42	20.22
Standard alloy	Min. 650	900-1100	Min. 12

The mechanical properties of DIN 1.7225 used in the present crankshaft and standard alloy are listed in Table 4 and the engineering stress vs. engineering strain curve of crankshaft material is drawn in Fig.3.

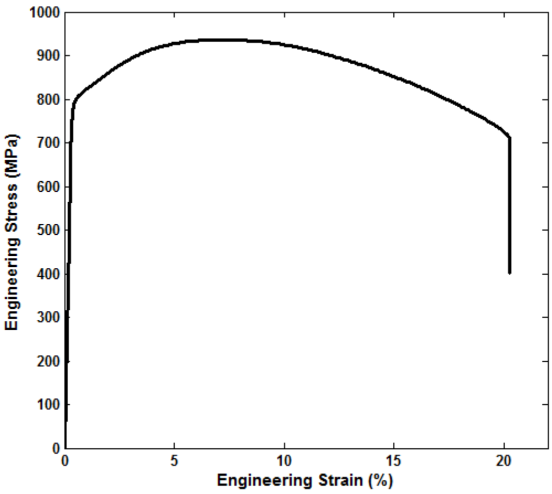

Fig. 3. Engineering stress vs. engineering strain curve of crankshaft material.

3.2. Hardness and Optical Micrographs

First a cross-section area of crankshaft crankpin with thickness of 15 mm was cut and machined on both sides. Then the surface of the sample was treated by sandpapers (from No. 60 to 1200). The polishing on the surface of the sample was done by diamond paste. Finally, to reveal microstructural feature of the sample, it was etched by 2% Nital. Fig. 4 displays micrograph of the crankpin No. 2 on the outer surface. It also shows tempered martensite steel which has the inclusion having the average size of around 10μm.

Then the hardness test was performed according to ASTM: E384-11e1 with various intervals through application of 30Kgf force per 10s and then the hardness curve along the crankpin from center to the external surface was plotted.

In Fig. 5, the hardness profile that is plotted up on the outer surface; as the graph reaches to the outer surface, the hardness increases. This behavior is related to the effect of surface hardness heating treatment done on cementation steels. To accomplish heating treatment and quenching steel in oil, carbides and martensite phases are formed on the sample surface while there are soft phases in the crankpin center. Thus, the presence of the hard phases on the outer surface of the crankpin causes increase in hardness from the center to the outer surface.

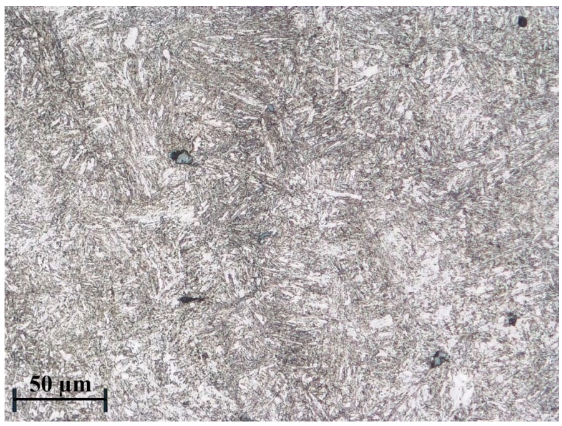

Fig. 4. Micrograph of crankpin material with 500× magnification.

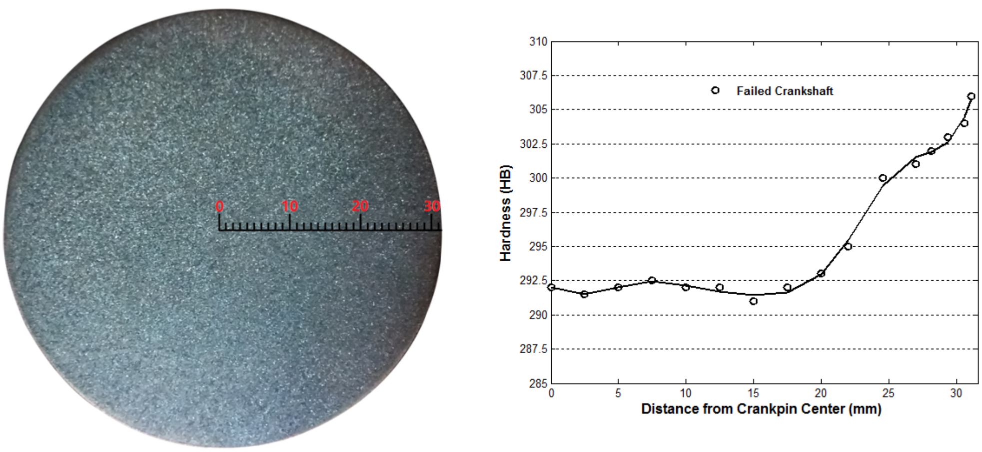

Fig. 5. Hardness distribution from center to outer diameter of the crankpin.

3.3. SEM and EDS

Fig. 6 displays the two surfaces of the fractured second crankpin, which fit together. The morphology of the fracture surface shows a smooth and flat crack initiation with the beach marks and ratchet marks and second crack propagation zone with beach marks and final fast fracture zone near the end. According to the beach marks orientation, it can be concluded that fracture starts from the crankpin-web fillet of crankshaft shown in Fig. 6 by arrow. Such cracks were initiated in the crankpin-web fillet zone which caused the premature fracture of crankshafts. This event has been referred to in the Refs. [7,9]. In addition, some scratch marks on the fracture surface shown in Fig. 6 is because of friction and striking between the two fracture surfaces after crankshaft break.

To examine the fracture surface of crankpin, the broken surface shown in Fig. 6a was cut by wire-cut machine and then was put on the ultrasonic bath for one hour and finally, it was photographed using SEM model LEO 145 OVP having EDS model 7335 made by Oxford, England. EDS is able to measure the chemical composition that is used for measuring chemical composition of microcrack and around it.

SEM secondary electron image (Fig. 7) and SEM backscattered electron image (Fig. 8) were taken so as to carefully examine the origins of the cranks of fracture surfaces with 100x magnification. The images show some defects and microcracks at crack initiation. Within the crack, large microcrack clusters, typically 0.1-0.3 mm in size, and many smaller microcracks are observed (Figs. 7-10). EDS was provided for two microcracks and their surrounding areas to examine the origins of the microcracks. Microcracks having these composed elements showed the non-metallic inclusions which is rich in sulfur (S), phosphor (P), and oxygen (O) while the background doesnt include such elements (Fig. 9 and Fig. 10). Like-type inclusions were observed in the forged steel used in gas turbine part [20] and in the steel (42CrMo4) bar used in automotive applications [21].

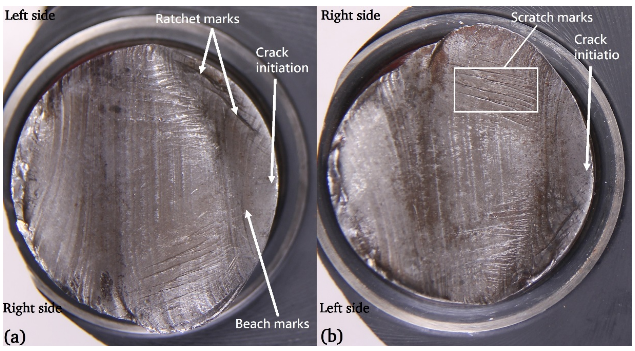

Fig. 6. The fractured surfaces of the crankshaft at the second crankpin.

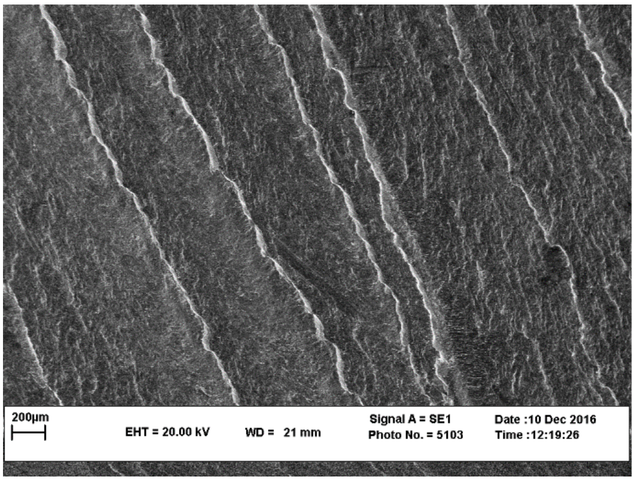

Fig. 7. SEM secondary electron image.

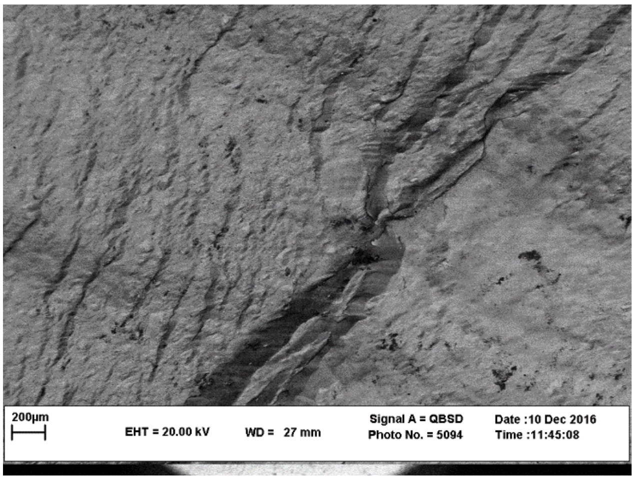

Fig. 8. SEM backscattered electron image.

3.4. The Investigation of the Crankshaft Failure Cause

Finding the fracture origin is the primary goal of fractography and a correct analysis is essential. Fracture marks that occur during the event, are similar to a road map that will be used in evaluation. Initiation and propagation of fracture create certain marks on the fracture surface like: river marks, radial lines, chevrons, and beach marks that show the direction of crack growth. These marks were considered and examined for the appearance of the origin of crack. The appearance of these marks on the fracture surface is dependent on the type of tensile, shear, bending, fatigue or torsional loads, stress system nature, existence of stress concentration, environmental and material factors. Another macroscopic feature view of fatigue failure, especially for shafts, is called ratchet marks. These marks are seen where there are multiple cracks that grow and link up. Ratchet marks are like to the junctions of connection between adjacent fatigue cracks [22-23].

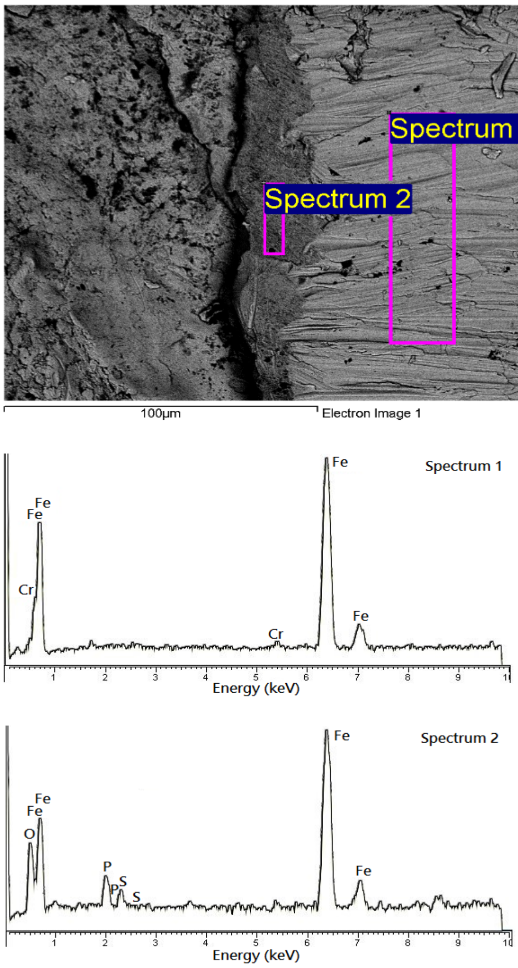

Fig. 9. Micrographs of the 2nd crankpin obtained from the right crack propagation for 1000x magnifications.

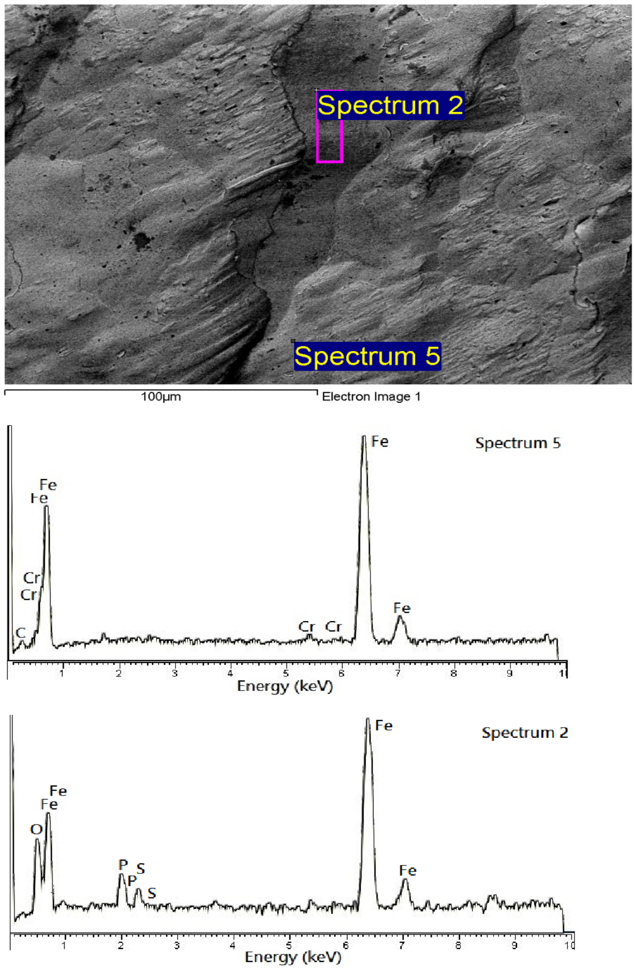

Fig. 10. Micrographs of the 2nd crankpin obtained from the left crack propagation for 1000x magnifications.

Figs. 9b and 10b clearly show the fact that the increase in P and S is considerably in the microcrack starting point. The presence of these elements on grain boundary causes the embrittlement of the material and crack propagation. Due to the high bending load caused by combustion pressure of engine, there is the possibility of crack growth in crankshaft. If the content of sulfur (S) is in range of 0.035 to 0.05 wt%, it will be useful for steel machining and if it is greater than the given range, there is a higher the possibility of crack formation. The high amount of phosphor in the range of 0.04% makes the steel brittle [24]. The results of EDS observations showed that inclusions of non-metallic arent distributed throughout on the steel and in some places leads to the formation of the microcrack clusters.

4. Conclusions

An overview of the study of considering crankshaft failure of four-cylinder light-duty truck diesel engine was conducted and the following results were drawn.

1. The morphology of the fracture surface showed that fatigue crack is the main cause of failure. Fatigue crack growth was initiated from a surface defect, in the form of non-metallic microcrack clusters. The failure happened after about 95000 km on the second crankpin at the crankpin-web fillet of crankshaft where the stress concentration was the highest.

2. A careful study by OM showed that the steel microstructure is of tempered martensitic kind in which non-metallic inclusions are frequently seen in the cross-section area of the test sample with the average size of around 10μm.

3. SEM that was equipped with EDS was used to evaluate the fracture surface and the fracture cause. The morphology of the fracture surface showed a flat and smooth crack initiation where appear the beach marks and ratchet marks and propagation zone, with beach marks, and final fast fracture zone in front of the fracture surface end.

4. The results of EDS observations showed that inclusions of non-metallic arent distributed throughout on the steel and in some places lead to the formation of the microcrack clusters having the effective length varied from 0.1 to 0.3mm. As a result, high bending load of the combustion gases and the high stress concentration at the crank-web fillet location cause early crankshaft failure.

References

[1] E. Herz, R. Thumser, J.W. Bergmann, M. Vormwald, Endurance limit of autofrettaged Diesel-engine injection tubes with defects, Eng. Fra. Mec., 73 (2006) 3-21.

[2] K.M. Kockelman, Y. Zhao, Behavioral Distinctions: The Use of Light-Duty Trucks and Passenger Cars, J. Trans. and Sta., 3(3) (2000) 47-60.

[3] B. Dondlinger, Chapter 16: Cranktrain (Crankshafts, Connecting Rods, and Flywheel), http://www.academia.edu/ 23448052/ Chapter 16 Cranktrain Crankshafts Connecting Rods and Flywheel, 2015, (accessed 08.04.15).

[4] M. Fonte, P. Duarte, V. Anes, M. Freitas, L. Reis, On the assessment of fatigue life of marine diesel engine crankshafts, Eng. Fail. Anal., 56 (2015) 51-57.

[5] R. Bosch GmbH, Automotive Handbook, 9th Edition, Wiley, (2015).

[6] M. Fonte, M. Freitas, Semi-elliptical fatigue crack growth under rotating or reversed bending combined with steady torsion, Fatigue Fract. Eng. Mater. Struct., 20(6) (1997) 895-906.

[7] M. Fonte, P. Duarte, L. Reis, M. Freitas, V. Infante, Failure mode analysis of two crankshafts of a single cylinder diesel engine, Eng. Fail. Anal., (2015), http://doi: 10.1016/j.engfailanal.2015.02.014.

[8] M. Fonte, V. Infanteb, M. Freitas, L. Reisb, Failure mode analysis of two diesel engine crankshafts, Procedia Structural Integrity, 1 (2016) 313-318.

[9] M. Fonte, B. Li, L. Reis, M. Freitas, Crankshaft failure analysis of a motor vehicle, Eng. Fail. Anal., 35 (2013) 147-152.

[10] M.A. Alfares, A.H. Falah, A.H. Elkholy, Failure analysis of a vehicle engine crankshaft, J. Fail. Anal. Preven., 7 (2007) 12-17.

[11] G.H. Farrahi, F. Hemmati, S.M. H-Gangaraj, M. Sakhaei, S. Abolhassani, Failure analysis of a four cylinder diesel engine crankshaft made from nodular cast Iron, J. Eng. Res., (2011) 21-27.

[12] F.S. Silva, Analysis of a vehicle crankshaft failure, Eng. Fail. Anal., 10 (2003) 605-616.

[13] J.A. Becerra, F.J. Jimenez, M. Torres, D.T. Sanchez, E. Carvajal, Failure analysis of reciprocating compressor crankshafts, Eng. Fail. Anal., 18 (2011) 735-746.

[14] R.K. Pandey, Failure of diesel-engine crankshafts, Eng. Fail. Anal., 10 (2003) 165-175.

[15] M. Fonte, V. Anes, P. Duarte, L. Reis, M. Freitas, Crankshaft failure analysis of a boxer diesel motor, Eng. Fail. Anal., 56 (2015) 109-115.

[16] S. Khatri, D. Kharade, K. Varpe, Review on optimization of crankshaft, Int. J. Adva. Tech. Eng. Sci. (ijates), 4(3) (2016) 339-350.

[17] Q. Zhang, Z. Zuo, J. Liu, Failure analysis of a diesel engine cylinder head based on finite element method, Eng. Fail. Anal., 34 (2013) 51-58.

[18] C. Kilicaslan, U. Ince, Failure analysis of cold forged 37Cr4 alloy M10x28 bolts, Eng. Fail. Anal., 70 (2016) 177-187.

[19] K. Aliakbari, KH. Farhangdoost, Plastic deformation influence on material properties of autofrettaged tubes used in diesel engines injection system, J. Press. Ves. Tech., 136 (2014) 136 / 041402-1.

[20] J.H. Bulloch, A.G. Callagy, Assessment of a premature failure in a gas turbine part, Eng. Fail. Anal., 7 (2000) 411-426.

[21] A. Vazdirvanidis, G. Pantazopoulos, A. Louvaris, Failure analysis of a hardened and tempered structural steel (42CrMo4) bar for automotive applications, Eng. Fail. Anal., 16 (2009) 1033-1038.

[22] ASM Metals Hand Book Volume 12 - Fractography. Second printing, May 1992.

[23] V. Infante, J.M. Silva, M.A. Silvestre, R. Baptista, Failure of a crankshaft of an aeroengine: A contribution for an accident investigation, Eng. Fail. Anal., 35 (2013) 286-293.

[24] T.V. Shibaeva, V.K. Laurinavichyute, G.A. Tsirlina, A.M. Arsenkin, K.V. Grigorovich, The effect of microstructure and non-metallic inclusions on corrosion behavior of low carbon steel in chloride containing solutions, Corros. Sci., 80 (2014) 299-308.