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INVESTIGATION INTO TORSIONAL FAILURE OF AUTOMOBILE CRANKSHAFT

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Abstract. The failure of crankshaft is a severe problem faced in the automobile industry. Most of the fracture is attributed to fatigue failure. Fatigue phenomenon is very difficult to understand and analyse and can be treated as an extremely important challenge to be addressed. In avoidance of the complex physical dimension of crankshaft, this study provided a simplified method of predicting fatigue life using tensile strength induced by torsional loads on the crankshaft. Investigation showed that dynamic load on rotating system had caused twisting and bending that had affected not only the mechanical properties but also the microstructure of the crankshaft material. The effect had translated to increased brittleness of the material and invariably led to sudden failure of the crankshaft below the yield strength. Proactive preventive maintenance measures were proposed for sustaining the service life of the crankshaft.

Keywords: *crankshaft, fatigue life, torsional load, mechanical failure, preventive maintenance*

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1. Introduction

Engine and its components are the origin of most of the failures taking place in automotive (Heyes, 1998). Among them, failure of crankshaft is frequently reported and therefore, a fundamental understanding of its operation and failure mechanisms can be of a great value. Crankshaft is a critical component of an automobile engine. Its function is to convert reciprocating displacement of the piston into a rotary motion. A crankshaft consists of main journals, connecting rod journals (crank-pins), counter weight, oil hole and a trust bearing journal (Kareem, 2015).

The manufacturing of crankshaft is done by roll forging from steel bar or by casting in ductile steel (Shweta, 2015). Forging has certain advantages which include lighter weight, more compact dimensions and better inherent dampening (Montazersadgh & Fatemi, 2007). There are various forces acting on the shaft but failure takes place in two positions, bending and torsion (Shweta, 2015; Kane, 2017). Firstly, failure may occur at the position of maximum bending; this may be at the centre of the crank or at either end. In such a condition the failure is due to bending and the pressure in the cylinder is maximal. Second, the crank may fail due to twisting. The transient load of cylinder gas pressure is transmitted to the crank through connecting rod, which is dynamic in nature with respect to magnitude and direction. The dynamic load on rotating system exerts repeated bending and shear stress due to torsion, which are common stresses acting on crankshaft and mostly responsible for crankshaft fatigue failure (Rathod & Mudassar, 2013). Hence, fatigue strength and life assessment plays an important role in crankshaft development and its parts considering its safety and reliable operation.Bending results in tensile, compressive and shear stresses in the material of the crank web. Twisting results in shear stresses. All the above alternating stress patterns produce fatigue and so the material must have a built in resistance to it (this is Ultimate Tensile Stress, UTS). Crankshafts fail usually because of cracks propagating from a stress concentration point (Shweta, 2015; Singh *et al.* 2015).

Only four basic failure mechanisms were identified: corrosion, wear, overload and fatigue, (Pratick & Manish, 2015; Pandey, 2003). Out of which only fatigue failure is the most common. Vibration is also one of the causes of failure of crankshaft (Shweta, 2015). If the engine is running with heavy vibration especially torsional vibration, it may lead to crack in the crankpin and journal. Insufficient lubricant can also contribute to failed crankshaft. Irregular lubrication of bearing can lead to wear, which eventually can cause crankshaft failure.

Failure analysis of automobile crankshaft is an important consideration in the efficiency and cost effectiveness of automobile engine manufacturing. A compact and durable crankshaft can bring about better fuel efficiency and higher power output. The specific objectives addressed in this paper are to: examine the causes and mode of failure in the crankshaft; analyze the failure propagation; and proffer strategy of managing the failure. The study will be limited to the analysis of failed crankshaft commonly reported in the identified crankshaft maintenance workshops within Akure metropolis, Nigeria.

Most of the methods adopted by many researchers in analysing crankshaft fatigue failures include Finite Element Method (FEM), Linear Elastic Fracture Mechanism (LEFM), and Strength and Dynamic Analysis (S&DA). Pandey (2003) investigated the failure of crankshaft of diesel engine used in tractors made from 0.45% carbon steel. The analysis showed that to avoid failure along the discontinuity in the web regions, machining and grinding need to be done carefully and it was suggested that fillet radius must be increased. Also on diesel engine, Yu and Xu (2005) conducted a failure investigation into a crankshaft used in a truck, which is made from 42CrMo forging steel. The mechanical properties of the crankshaft including tensile properties, marohardness (HB) and surface hardness (HV1) were evaluated. Fractographic studies indicated that fatigue was the dominant mechanism of failure of the crankshaft. It was concluded that the mechanical grinding should be done carefully and controlled to prevent fatigue initiation from the pin-web fillet region.

Montazersadgh and Fatemi (2007) in their study conducted a dynamic simulation on two crankshafts, cast iron and forged steel, from similar single cylinder four stroke engines. Finite element analysis was performed to obtain the variation of stress magnitude at critical locations. The pressure-volume diagram was used to calculate the load boundary condition in dynamic simulation model, and other simulation inputs were taken from the engine specification chart. The results obtained from the analysis were used in optimization of the forged steel crankshaft geometry, material, and manufacturing processes under different constraints, manufacturing feasibility, and cost. The optimization process resulting in 18% weight reduction, increased fatigue strength and reduced cost of the crankshaft, without changing connecting rod and/or engine block.

Farrahi et al. (2011) conducted a study on Crack Analysis of a Gasoline Engine Crankshaft made of nodular graphite cast iron material. It was observed that cracks propagated axially on surface of the 4th pin journal. Microscopic observation revealed the thermal fatigue as the cause of failure on the contact of journal and bearing surface. The failure was attributed to defective lubrication system and/or high operating temperature. Patil et al. (2014) presented the case study of the crankshaft catastrophic failure of motor vehicle. The crankshaft suffered a mechanical seizure on the crankpin after 3 years in service. A transversal macrograph of the crankpin was rectified and filled with a metal alloy of the same nominal diameter. The study identified causes of failure as: inadequate added metal alloy; absence of heat treatment of the repaired crankpin surface; probable misalignment of the crankshaft on journal bearings; imbalance of the crankshaft in consequence of the deep rectification; and the crankshaft probably was not submitted to a dynamic testing.

Cervik and Gurbuz (2013) investigated the effect of fillet rolling on the fatigue behaviour of the ductile cast iron crankshaft used in diesel engines using mechanical property test. The investigation showed that stress value between fillet rolled and un-rolled conditions of the crankshaft varied between 200N/mm^2 to 810N/mm^2. Metkar *et al.* (2013) investigated the dynamic loaded stress analysis of the crankshaft to predict and compare the fatigue life of the crankshaft. The study found out critical locations on the fillet region on the crankshaft geometry which accommodated high stress concentration. Kareem (2015) evaluated the failure of mechanical crankshaft for automobile based on experts' opinion. The evaluation was based on oral interviews and questionnaire administered to experts working in the area of automobile maintenance and crankshaft reconditioning. Statistical method was used to analyse the data and the result showed that private cars had lowest rate at the initial stage while commercial buses had the highest failure rate in the long run. It is clearly shown from the literature that most of the past studies on crankshaft failure analysis were either analytical or experimental in nature. Analytical procedures based on Failure Mode and Effect Analysis (FMEA) and mechanical tests were predominantly used, torsional load effect was hardly considered in the failure analysis. This study has applied both experimental and analytical procedures under the consideration of torsion loads as major cause of fatigue stress on the crankshaft.

2. Methodology

For this investigation three failed crankshaft journal pin were assessed (Fig. 1-4). Evaluation tests were carried out using metallographic analysis, covering mechanical properties test (tension, fatigue, and toughness). Visual inspection and Scan Electron Microscope were used to examine the crankshaft to identify the mode of failure. Table 1 shows the characteristic features of the crankshafts under studied.

Table 1. Characteristics of crankshafts investigated

S/N	Specimen	Configuration	Date of production	Causes of failure
1	Specimen A	L4-cylinder , 5s Engine	1990	Poor lubrication leading to failure of 2nd pin journal
2	Specimen B (Control)	L4-cylinder, 5s Engine	1989	In service and in good condition
3	Specimen C	L4-cylinder, 5s Engine	1989	Poor lubrication leading to failure of 4th pin journal

Figure 1. Specimen A showing the failed crank pin journal

Figure 2. Specimen B showing the good crank pin journal

Figure 3. Specimen C showing the failed crank pin journal

Figure 4. Samples machined out from the crank-pins

The specimens were carefully selected to reflect commonly used brand in Nigeria. The three specimens are of the same brand and class, this allows for easy comparison and analysis. Mechanical testing is carried out to produce data that may be used for design purposes or as part of a material joining procedure or operator acceptance scheme. The most important function may be that of providing design data since it is essential that the limiting values that a structure can withstand without failure are known (Boyer, 2017). The capacity of a material to withstand a static load can be determined by tension or compression test (ITT, 2017).The tensile test was used to provide information in design calculations or to demonstrate that a material complied with the requirements of the appropriate specification (ITT, 2017). ASTM A370- Standard for Test Methods and Definitions for Mechanical Testing of Steel Products were adopted. The test is made by gripping the ends of a suitably prepared standardised test piece in a tensile test machine and then applying a continually increasing uni-axial load until such time as failure occurs. Test pieces were standardised in order that results are reproducible and comparable as shown in Fig. 5 (ITT, 2017).

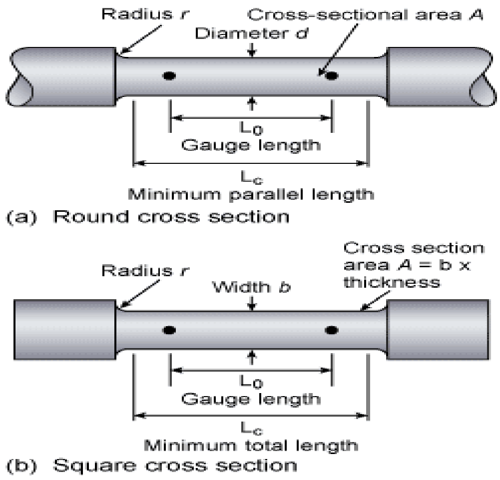

Figure 5. Tensile test specimen of the crankshafts

Specimens are said to be proportional when the gauge length, L_0, is related to the original cross sectional area, A_0 expressed as $L_0 = k\sqrt{A0}$. The constant k is 5.65 in EN specifications and 5 in the ASME codes. These gave gauge lengths of approximately 5x specimen and 4x specimen diameters respectively. While this difference may not be

technically significant, it is important when claiming compliance with specifications (ITT, 2017). Both the load (stress) and the test piece extension (strain) were measured and from these data an engineering stress/strain curve was constructed, and the following were determined: the tensile strength, also known as the ultimate tensile strength; the load at failure divided by the original cross sectional area.
The ultimate tensile strength (U.T.S.),

$$Su = \frac{P_{max}}{A_0} \quad (1)$$

where, P_{max} is maximum load, A_0 is the original cross sectional area.

The yield point (YP), the stress at which deformation changes from elastic to plastic behaviour that is, below the yield point unloading the specimen means that it returns to its original length, above the yield point permanent plastic deformation has occurred,

$$YP \ or \ \sigma y = \frac{P_{yp}}{A_0} \quad (2)$$

where, P_{yp} = load at the yield point;

By reassembling the broken specimen we can also measure the percentage elongation, El% how much the test piece had stretched at failure,

$$\%EL = \frac{L_f - L_0}{L_0} \times 100 \quad (3)$$

where, L_f is gauge length at fracture and L_0 is the original gauge length.
The percentage reduction of area, how much the specimen has necked or reduced in diameter at the point of failure,

$$\%A = \frac{A_0 - A_f}{A_0} \times 100 \quad (4)$$

where, A_f is the cross sectional area at site of the fracture.

The stated measurements accounted for the strength of the material and indicated the ductility or ability of the material to deform without fracture.

Brinnel hardness is determined by forcing a hard steel or carbide sphere of a specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation left after the test. The Brinell hardness number, or simply the Brinell number, is obtained by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimetres. The result is a pressure measurement, but the units are rarely stated.

The failed pin journal was machined out and shaped to Brinell test size specification, according to ASTM E-10 (a standard test for determining the Brinell hardness of metallic materials). The load applied in this test is usually 3,000, 1,500, or 500 kgf, so that the diameter of the indentation is in the range 2.5 to 6.0 mm. The full test load was applied for 15 seconds. Two diameters of impression at right angles were measured, and the mean diameter was used as a basis for calculating the Brinell Hardness Number (BHN).

Crankshaft are either cast or roll forged, but the indication of cold working of the material may be as a result of large fatigue stress during service. Cold deformation causes strain hardening which leads to increased tensile strength but very low ductility. A large ductility together with a high tensile strength means good toughness which is needed for the crankshaft. It is evident that fatigue stress on a material affects not only the mechanical properties of the crankshaft but also the microstructure (CDCPD, 2016).

In a critical situation fatigue strength can be investigated via established mathematical relationship to draw inference on the fatigue behaviour of the materials. Typical fatigue strength of steel is about 0.5 of its tensile strength, to a maximum of 290MPa. In 1870s, W. Ohler, one of the pioneers in the fatigue field, found that the ratio of fatigue strength, Se to tensile strength, Su for ferrous metals followed a simple proportional relations (Forrest, 1962),

$$Se = (0.4\text{-}0.5) \times Su \tag{5}$$

Based on the numerous data of fatigue strength hand tensile strength available for steels, copper and aluminium alloys in the past century, a more general form can be summarized as follows,

$$Se = mSu \tag{6}$$

It was found that the fatigue strength either maintained constant or decrease with further increase in the tensile strength. In other words, the linear relation in Eq. (6) is no longer held at high-strength level. The critical ensile strength Suc, above which fatigue strength does not increase correspondingly, the maximum fatigue strengths $Se(\text{max})$ and the coefficient m in Eq. (6) for steels, Cuand Alalloys are summarized as (Forrest, 1962),

$$Se = (0.59 - 9.24 \times 10E - 5 \times Su)Su \tag{7}$$

From Eq. (7), the fatigue parameters in table 4 were calculated.

In failure management, choosing a suitable crankshaft for Automobile is the sole responsibility of the designer/manufacturer, but failure management is the duty of the auto user. While the auto user can do little to control the load on the crankshaft, there is much to be done by the manufacturer to offset the negative effects of the premature failure of the crankshaft. There are maintenance strategies that can be adopted to prevent sudden failure of crankshaft and one of them is the preventive maintenance strategy. Preventive maintenance is a daily maintenance (cleaning, inspection, oiling and re-tightening) design to retain the healthy condition of equipment and prevent failure through; the prevention of deterioration, periodic inspection or equipment condition diagnosis. In order to prevent sudden failure of crankshafts automobile users should adhere strictly to the standard preventive maintenance procedures.

3. Results and discussion

Geometry measurement of the failed crank-pin, using a micrometre screw gauge shows a reduction in diameter of the pin. Diameters Ø47.8 and Ø47.2 were recorded for specimen A and specimen C respectively as against specimen B (Ø48) as standard control specimen. This indicates that wearing occurred most in specimen C. This may be attributed to poor lubrication of the engine. Poor lubrication cause excessive load as the system run under heavy friction. Table 2 shows the summary of tensile test result carried out using a 20kN capacity HSM58 Universal material tester. Result shows that specimen C had the highest strength as also supported by the higher Brinnel number (Tables 2 and 3) which is quite the reverse for the metallography result as depicted on the micrograph (Fig. 8). The micrograph in Fig. 8 indicates a porous and homogeneous view of the microstructure matrix of the material. This may be attributed to cold deformation of the crankshaft. The micrograph of specimen A (Fig. 6) shows deformation lines and a deformed structure where one can no longer view the grain structure which is apparent in specimen B (Fig. 7). The micrograph in Figure 7 shows the presence of inter-metallic nucleating at the grain boundaries and within the grains.

Table 2. Summary of tensile test result

Sample	UTS-A (MPa)	UTS-B (MPa)	UTS-C (MPa)	Ductility (%) -A	Ductility (%) –B	Ductility (%) -C	Strain (mm/mm) – A	Strain (mm/mm) - B	Strain (mm/mm) - C	Elastic Modulus – A	Elastic Modulus - B	Elastic Modulus - C
Sample 1	93.88	102.04	102.04	0.229	0.143	0.257	0.00229	0.00143	0.00257	40.995633	71.356643	39.704280
Sample 2	89.79	97.96	97.96	0.229	0.143	2.86	0.00229	0.00143	0.00286	39.20960699	68.503497	34.251748
Sample 3	93.88	93.88	102.04	0.2	0.1	0.26	0.002	0.000857	0.0026	46.94	109.544924	39.246153
Average	92.516667	97.96	100.68	0.219333	0.128667	1.125667	0.002193	0.001239	0.002677	42.381747	83.135021	37.734061
standard deviation	1.928045	3.331306	1.923330	0.013671	0.020270	1.226359	0.000137	0.000270	0.000130	3.304616	18.710912	2.469459

Table 3. Summary of Brinell hardness test result

	BHN-A	BHN-B	BHN-C
Sample 1	268	252	257
Sample 2	288	168	308
Average	278	210	283

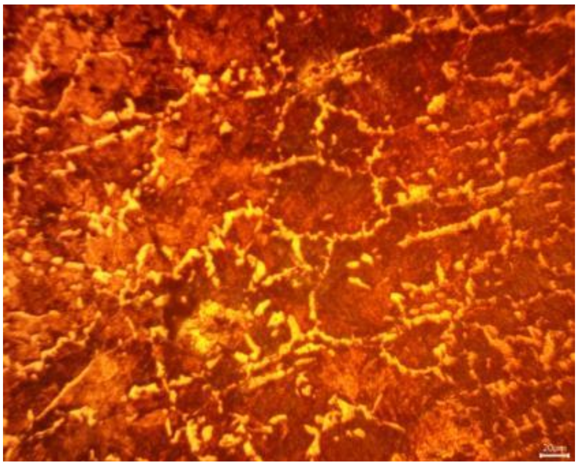

Figure 6. Micrograph of specimen A showing deformation lines and a deformed structure

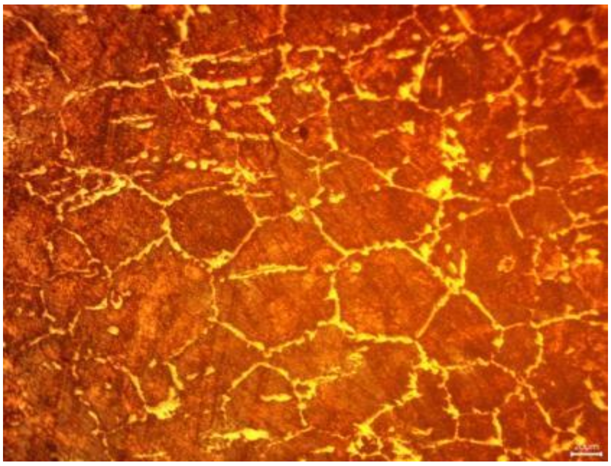

Figure 7. Micrograph of specimen B showing good lines and structure

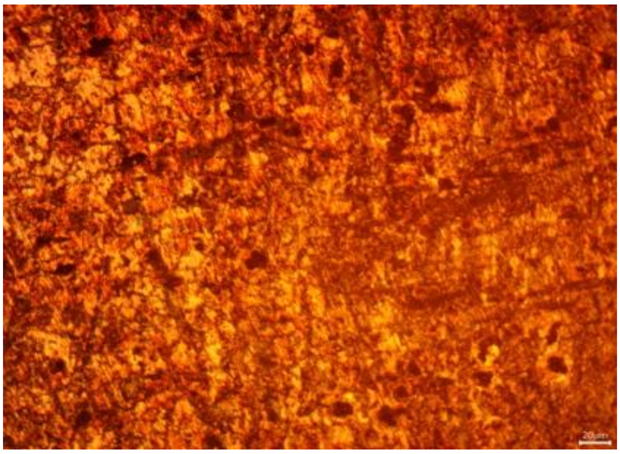

Figure 8. Micrograph of specimen C showing a porous and homogeneous view of the microstructure matrix of the material

Table 4. Tensile and fatigue strength conversion

	Tensile strength (MPa)	Fatigue strength (MPa)
Specimen A	92.516667	53.79
Specimen B	97.96	56.91
Specimen C	100.68	58.46

The higher fatigue property of specimen C can be attributed to the excessive load on the crank shaft during its service life (Table 4). It can be concluded that the excessive load on the crankshaft leads to unnecessary increase in strength at the expense of ductility. This led to un-timely failure of the material. Specimen A in Figure 6, shows the same trend as specimen C in Figure 8, but with a better microstructure arrangement when compared with specimen C (Fig. 8). This is also indicated in the mechanical properties of the material shown in Tables 2-3. The microstructure matrix of Specimen B (which was used as the control sample and did not fail in service) shows a much better arrangement that is similar to standard crankshaft material (Fig. 7). This outcome was supported by the sustainable results as indicated in elastic modulus of 83Gpa and ductility of 0.12% that were obtained from the specimen as shown in Table 2.

4. Conclusion

From the results the following conclusions can be drawn.

- Specimen testing indicates that the mechanical properties and microstructure of crankshaft were affected by the dynamic load and the rotating system.
- The deformation of the crankshaft and subsequent failure were caused by excessive load.
- The increase in the strength of the material before failure was attributed to strain hardening of the crankshaft due to dynamic load.
- The increase in strength of the material did not translate into increase in ductility as one of the important requirements for the crankshaft reliability performance.
- The micrograph shows the presence of intermetallics nucleating at the grain boundaries and within the grains. Strength improving intermetallics can prevent failure due to brittleness of the crankshaft. This can be achieved by using alloys that can improve the strength and the ductility of the crankshaft under fatigue stress.
- Proper lubrication should be done on routine bases to prevent excessive load on the bearings and the crankshaft.
- Excessive vibration in the system gave rise to crack propagation and uneven load. Vibration should be checked regularly and adjusted if required to prevent premature failure.
- The limitation of the study was inability to experimentally carry out fatigue test due to non-accommodation of the specimen size by the available fatigue testing apparatus. Experimental investigation of fatigue strength may be needed to validate the results obtained from the analytical approach.

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