Experimental Analysis of Failure of Drive Shafts

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Abstract- This paper is a detailed review on the failure analysis of shafts which are used for transmission of power or torque between two moving elements of machines which are used in different applications in our industries and day-to-day life, to give an overview on the various possible types of failures of shafts and identifying reason of their failures. For this purpose some papers on failures of shafts have been reviewed in which mechanical properties, material structure, design and various method of stress analysis have been considered as the primary parameters for their study. The whole motive behind writing this paper is to study and explain the causes of failures of shaft in a lucid way.

Keywords – Shafts, Failure analysis, Scanning electron microscope (SEM), finite element analysis (FEA).

I. Introduction

A shaft can be described as a part of a mechanical system which is used for the purpose of transmission of power or torque between two moving elements of a machine through rotational motion. Shafts form an integral part of any machinery where power transmission is required, therefore it has applications in all kinds of engineering works. For this purpose shafts are coupled with either gears, pulleys or sprocket to transmit power or torque through adjacent meshing gears, belt drives and chain drives respectively. Shafts can be broadly classified as hollow and solid shafts. Both of them are used for different kinds of design condition depending upon their static and dynamic load bearing capabilities. The most widely used applications of shafts are in vehicular crankshafts, elevator shafts, conveyer pulley shafts, hydraulic turbine shafts etc. Thus shafts are mostly highly designed and robust in nature. The failure of such highly designed shafts can lead to catastrophic events such as financial losses as well as it might risk the life of the operator along with complete failure of the mechanical system. Thus any case of shaft failure should be properly analyzed so that such events does not repeat in the near future.

Shafts are designed to bear torsional loading under dynamic conditions. The kinds of stress that can act on a shaft under varying operations may include fatigue stresses, bending stresses, thermal stresses, shearing stress, vibrations etc. The common cause of shaft failure is observed as fatigue failures. Fatigue failure means repeated action of cyclic stress acting on a material for a prolonged period leading to final failure. Generally fatigue failure takes place in multiple steps starting from crack initiation to its growth and finally leading to fracture. The other possible reasons for failure may include improper design leading to regions of high stress concentrations, misalignment between shaft and bearings, overheating, overloading and improper lubrications etc.

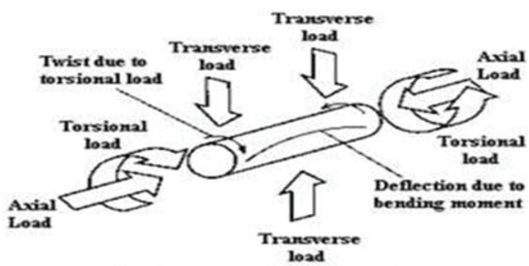

Figure 1. Different loads acting on a shaft [6]

In this paper, analysis of the shafts are done in the following pattern. For this purpose first the visual inspection of the failed shafts are done by observation and scanning electron microscope (SEM) images are compared with the help of which the fracture surface is analyzed. Then the metallurgical properties of the material are analyzed using chemical test of the specimens. Mechanical tests of the failed shaft specimen are used to find the ultimate load that can be withstands by the shaft along with other mechanical properties. For finding the causes of failure of the shafts various method of stress analysis like finite element analysis, dynamic analysis are used. By concluding the results of these analysis the cause of failure is analyzed.

II. Literature Review

A. Göksenli *, I.B. Eryürek investigated on the failure analysis of an elevator drive shaft which was in operation for a period of 30 years. The shaft was designed to transmit 6.5 HP generated by an electric motor which rotated the shaft at 1500 rpm while using a worm gear with reduction ratio of 28.6. The elevator shaft was coupled to a pulley by means of a coupling assembly using a key and was supported at three points radially forming a journal bearing like support. This elevator system had never been technically maintained during its operation years. The shaft had failed during operation which could have been a catastrophic event so the cause of its failure was investigated. The failure of this shaft had occurred at the region where the pulley was connected to the shaft [1].

Figure 2. Failed shaft [1]

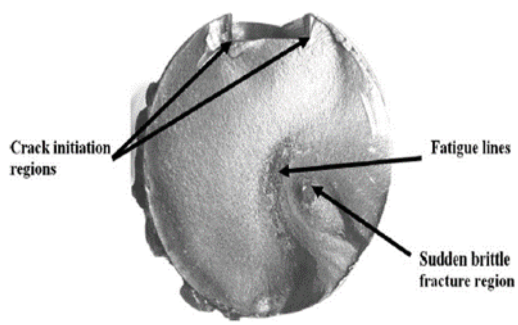

Figure 3. Fracture surface cut section [1]

Visual inspection of the fracture surface revealed the presence of fatigue cycles possibly due to torsion and bending stress acted upon the shaft. It was observed that the crack had initiated along the edges of the keyway and which propagated throughout the entire surface. Further chemical analysis was done using atomic absorption spectroscopy, microstructure of the material was also analysed along with mechanical properties and results confirmed that the material was St52.0. Stress analysis determined that due to very low radius of curvature along the keyway of the shaft there is high stress concentration in that region due to which very high notching effect is seen in that region due to shear and bending stresses. A detailed fatigue stress analysis showed that the design of the shaft had very low fatigue safety factor. Finally finite element analysis of the shaft was done using ANSYS it also revealed high stress concentrations along the sharp edges of the keyway [1].

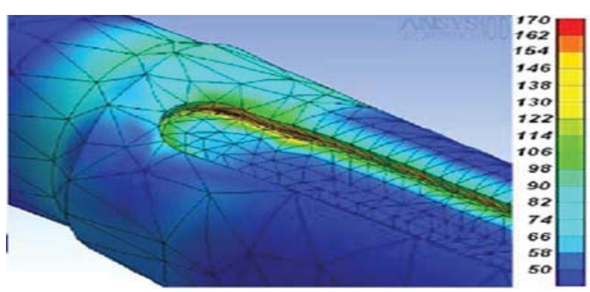

Figure 4. FEA analysis along the keyway [1]

Thus in this investigation it was concluded that failure had occurred at the sharp edges of the keyway which caused high stress concentration in that region which was caused either due to incorrect design or faulty manufacturing process and by increasing the radius of curvature the stress concentration are considerably reduced [1].

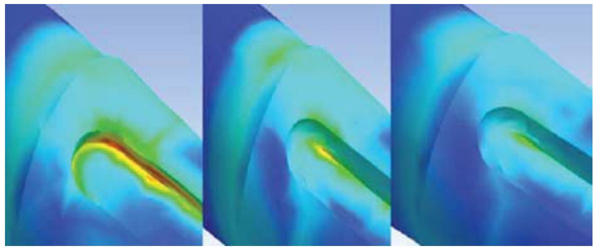

Figure 5. FEA analysis by increasing the radius of curvature of the keyway edges [1]

*B. Gys van Zyl *, Abdulmohsin Al-Sahli had done analysis on the failure of a conveyor belt drive pulley shaft which failed in seven days of service after being changed during a regular maintenance. The analysis of this shaft was necessary so that such incidents should not occur [2].*

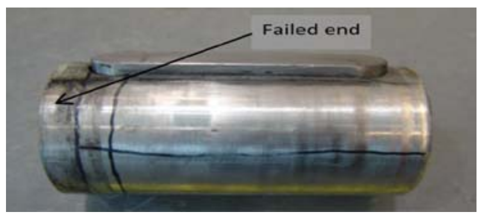

Figure 6. Failed end of the shaft inside coupling [2]

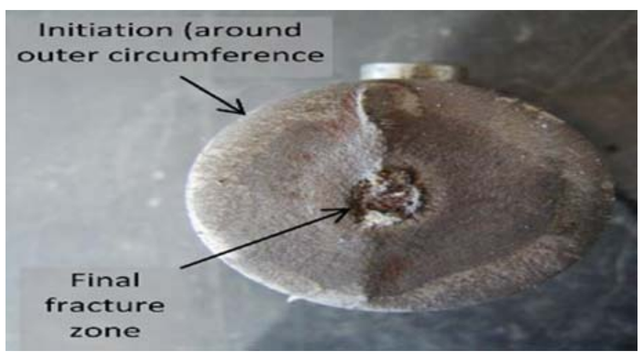

Figure 7. Fracture surface of the shaft [2]

Visual inspection showed that the shaft had failed at the keyway region along corner of the shaft coupling assembly which connects the gearbox and the shaft where sudden steep change of the diameter is seen without much stress relief curve. The gearbox and the motor shaft assembly is hinged instead of being fixed on a solid foundation because of which high stress acts on the region on which failure is observed. Visual inspection of the fracture surface showed fatigue stress lines indicating high stress concentrations caused due to rotational bending While images from scanning electron microscope showed that surface appearance where the crank initiated differed from the surface where the final fracture occurred that showed evidence of a possible metallurgical changes. Metallurgical test revealed that the external surface of the shaft had been welded during a scheduled maintenance and that the fractured surface was affected due to heat generated by the welding process and which caused the material near the welded region to be less endured to fatigue stresses. Chemical analysis showed the shaft material was BS 970 150M19. Mechanical tests such as tensile, toughness, fatigue and hardness test showed that the weld metal has hardness more than the base metal. So it can be concluded that weld metal in brittle in nature whereas the base metal is ductile in nature [2].

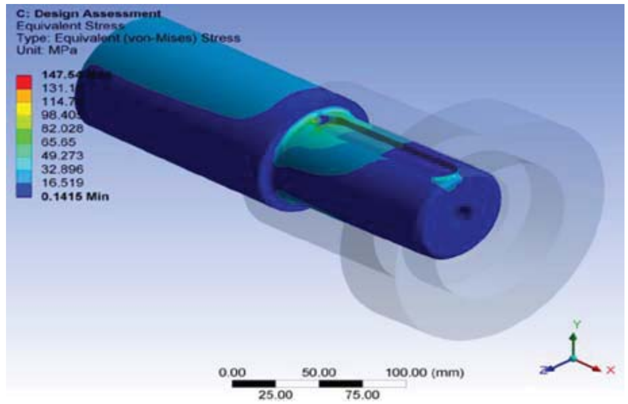

Figure 8. FEA of shaft along shaft keyway [2]

Finite elemental analysis (FEA) of the shaft had been done for stress analysis and the most vulnerable region was analysed as the corner of the keyway where the failure actually happened [2].

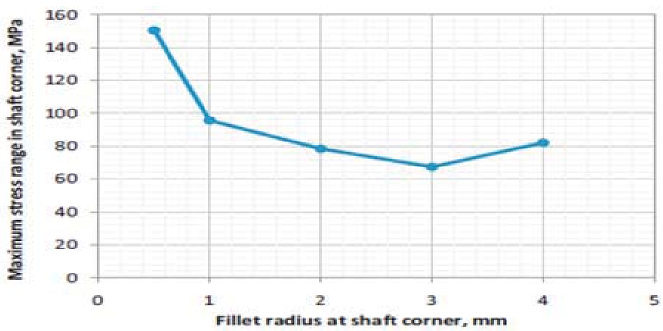

Figure 9. Reduction in stress by increase in fillet radius [2]

The conclusion of this analysis was that the failure was due to the constant load acting to the shaft due to the gearbox and the motor which was aggregated by improper welding process during restoration along the keyway region and that by increasing the fillet radius at the corner of the shaft there considerable reduction in stress acting at the keyway end where the fracture took place [2].

C. G.H. Farrahi, S.M. H-Gangaraj, S. Abolhassani , F. Hemmati , M. Sakhaei all had investigated on a premature failure of four cylinder diesel engine crankshaft. The material use for the design and manufacturing of the crankshaft was found to be GGG 70 ductile cast iron using spectrographic method and the material has yield strength of 402 MPa [3].

Figure 10. Failed section of crankshaft [3]

Visual inspection of the fracture surface was showed evidence of a brittle fracture which had occurred in the region near the first crankpin [3].

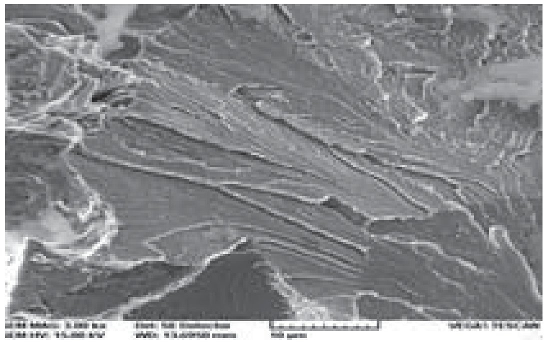

Figure 11. SEM image of fractured surface [3]

Scanning electron microscope (SEM) also showed a crystalline type structure further without any traces of fatigue cycles which further supported that the failure was due to brittle fracture. Since the presence of brittle fracture is observed it is confirmed that the fracture was not due fatigue stress cycles. To find the stress acting on the shaft during operation, dynamic analysis of the journal bearing was done to consider the combined effect of combustion pressure exerted on the piston head which is transmitted through the connecting rod to the bearing attached to the crankshaft and the inertia forces generated due to the rotating movement of the shaft and the reciprocating movement of piston for the analysis of the stress developed along the crankshaft region where failure took place during individual combustion of the cylinders during different cycles [3].

Further finite element analysis of the shaft was done using ANSYS where the entire shaft is divided into twenty nodes and even finer mesh where severe stress concentrations are expected. The equivalent stress acting on each of the five journal bearings along the shaft is analysed and the results of the analysis was compared with the results of the dynamic analysis of the shaft. From the FEA results it was clear that the region along the first crankpin where the failure took place is most vulnerable when the third cylinder undergoes combustion [3].

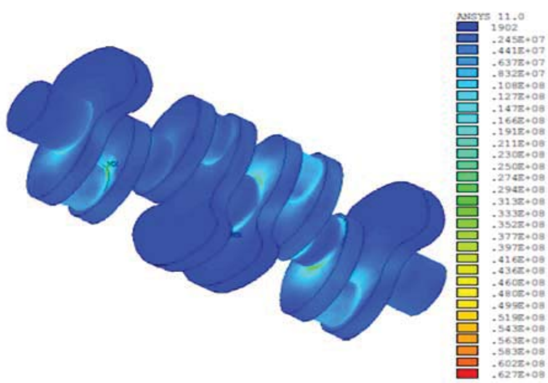

Figure 12. Equivalent von Mises stress distribution using FEA [3]

The von Mises stress distribution of the entire crankshaft showed that the maximum stress which was generated during the combustion of the third cylinder was just 15% of the yield strength of the material which was an evidence that even due the maximum stress developed during the operation of the crankshaft fatigue failure is not possible [3].

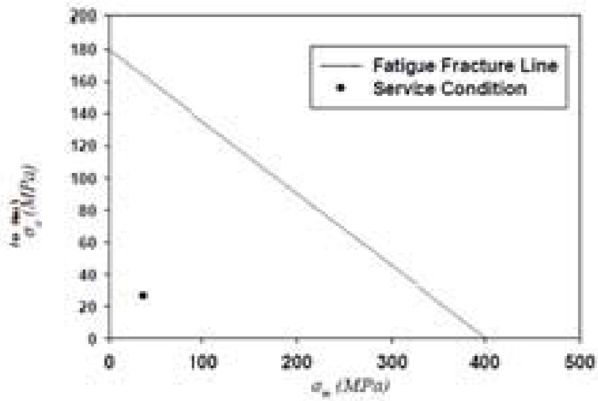

Figure 13. Soderburg diagram of the shaft [3]

This conclusion was even more supported by the soderburg diagram result which had revealed that the operational life of the crankshaft lied in the well within the safe region and that fatigue failure was not the cause of the fracture. The investigation can be concluded that the failure of the shaft was not due to improper design and material selection such as in the above cases but due some manufacturing processes like fillet rolling of the crankshaft [3].

D. H.L. Pan *, S.H. Tang, J.W. Hao had studied the failure of a rotating cantilever shaft used in a petroleum industry which had only operated for six months after being replaced due to the failure of the original shaft. The shaft was used in an expansion drier which was used to remove the moisture content from rubber in this stage before going to next production station. This shaft had to experience varying pressure and temperature cycles in a corrosive environment. Chemical test showed that this shaft was made of 35CrMo while the original shaft was of 316L [4].

Figure 14. Fracture surface of shaft [4]

Visual inspection showed that as it was observed in the first two cases that was discussed in this paper, this shaft also seem to have been improperly designed which caused regions of high stress concentrations along some regions of the shaft. Laboratory examination of the fractured surface showed corrosion effect sites on the fracture surface along with this conclusion it also revealed the crack had initiated at the shaft surface at three points and which meshed into a common region causing the final failure [4].

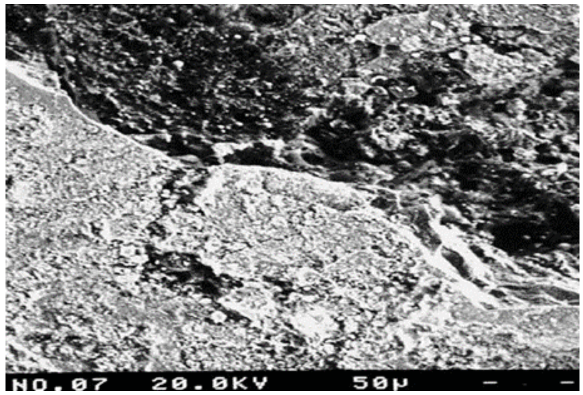

Figure 15. SEM image of the fracture surface [4]

Scanning electron microscope images showed that the crack had initiated from the surface of the shafts where effects of corrosion such as corrosive spots were observed along with evidence of fatigue stress cycles which had acted upon that region [4].

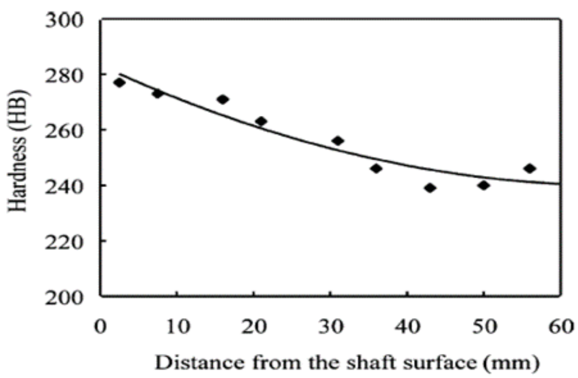

Figure 16. Hardness variation in shaft radially [4]

Metallographic examination revealed that the shaft was not quenched and tempering of the shaft was not done properly so only the outer part of the shaft was hardened but the centre of the shaft remained unhardened because of which made the central part of the shaft is more vulnerable to fatigue failure. Finite element analysis of the shaft was done using ANSYS 7.0 which revealed that the material chosen for the replacement shaft i.e. 35CrMo had less resistance to corrosion under the same loading condition than the original shaft. Thus it was finally concluded that the shaft failed due to combined effect of fatigue cycles and corrosive environment which was aggregated by faulty design and incorrect material selection [4].

E. Changli Wang a,*, Chengjie Zhao a, Deping Wang b had investigated on a sudden failure of a brand new crankshaft during test run in just 20 min. It was a catastrophic event and to know the cause of the failure and ensuring that such event does not repeat in future a very effective analysis was necessary [5].

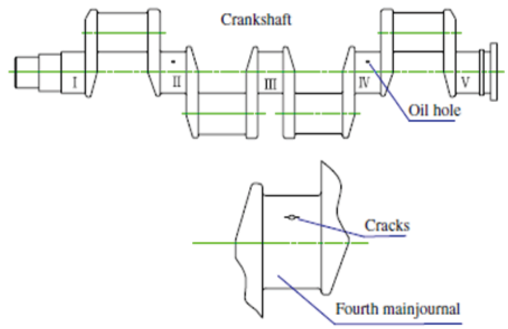

Figure 17. Schematic diagram of the failed crankshaft [5]

During inspection of the crankshaft four cracks were noticed around the forth journal bearing region along with complete failure of the main bush causing the copper cylinder inside the bush to completely wear off [5].

Figure 18. Failed main bush of the shaft [5]

Colour changes were also observed in the journal bearing with blue and black mark zones on the outer surface of the bearing which was enough evidence to conclude that it was caused due to large amount of heat generated during operation possibly due to high frictional forces existing between the shaft and the bearings. The material of the crankshaft was identified as 40CrMnMo by chemical analysis [5].

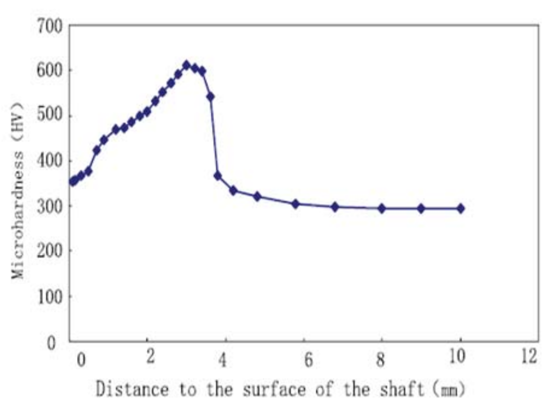

Figure 19. Variation of hardness along the surface of the shaft [5]

Hardness test of the specimen of the failed shaft showed variation between the hardness of the surface of shaft in where failure occurred and the other regions of the shaft. This was because of the thermal stresses acted upon the failed region which had caused the surface hardness to reduce and making it more vulnerable to fatigue failure. Further by investigating the images of scanning electron microscope it was observed there is variation in hardness within the material of the shaft from surface to core. Fracture analysis of the shaft revealed that the cracks causing the fracture initiated at three different regions and all had undergone different kinds of metallurgical changes finally resulting into the fracture. Detailed analysis of the grain boundaries showed that the grain boundaries along the surface are larger as compared to the one at the centre and that slip of grain boundaries in different slip angled planes are also observed [5].

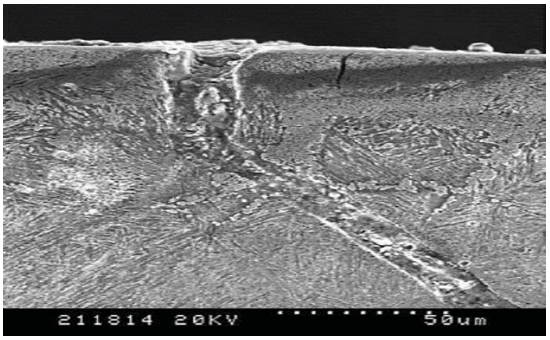

Figure 20. SEM image of first and second stage of crack [5]

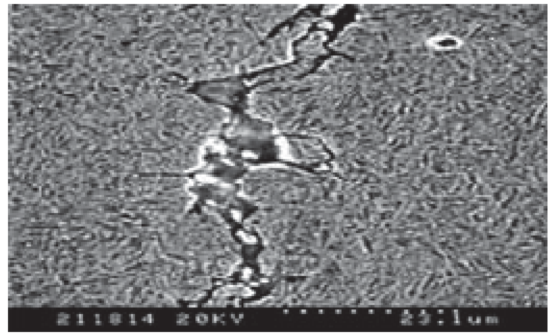

Figure 21. SEM image of final stage of crack leading to failure [5]

Thus result of fracture analysis had concluded that multiple cracks had originated perpendicular to the shaft surface along the oil hole at the journal bearing region and had propagated via different slip planes leading to final fracture. Fracture analysis concluded the phenomenon of propagation of the crack which the cause of the crack was found by failure analysis method. The conclusion of the failure of the shaft could be traced back to the combined effect of friction between the shaft and the bearing or bushing assembly and the misalignment of the shaft bearing holes. Since all the bearings had not failed so the assumption of bad lubrication was ruled out and the cause was determined was the misalignment of the shaft bearing assembly because of which an unusual type of friction caused the temperature to rise very high and this resulted into development of very high thermal stresses. This unaccounted thermal stress caused the failure of the shaft [5].

IV.CONCLUSION

As discussed in the above cases most of the shafts failed due to cracks initiated along the keyway region as a result of high stress concentrations caused due to sharp edges having no or very less stress relief radius which gives rise to high notching effect in those regions along with fatigue stress cycles finally leading to failure of the shaft. In order to avoid such failures the designer should consider such possible failure case as a reference while designing the shaft and provide with adequate stress relief radius to stress concentrations in any region of the shaft.

Another very important factor responsible for failure of shafts was revealed to be the selection of material for designing of the shaft. While choosing the material for designing of the shaft, factors such as working conditions of the shaft like corrosive or acidic environment as well as the load bearing conditions of the shaft should be considered with adequate factor of safety so that the shaft does not fail due to fatigue stress within the fatigue life expectancy of the shaft.

Other factors such as improper lubrication, incorrect or overloading of shaft, misalignments between shaft and bearings, incorrect assembly, wrong maintenance should be taken care of during working condition to avoid failure of shafts. Thus all the causes of failure of shafts and their solutions are discussed in this paper.

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