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Failure Investigation for Input Shaft of Auxiliary Hoist Gear Box

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Abstract — **This review paper gives the insights of various analysis & tests carried out to find shaft failure type & its causes. Failed shaft is used in auxiliary hoist gear box for torque transmission. Shaft failed with fewer cycles of operations in very early stage of life span. The various literatures has been systematically studied, compared and reviewed to get a proper shaft failure analysis and their causes. Every analysis method has its advantages and disadvantages and used by specific industrial areas. Shaft failure causes the unnecessary shutdowns and leads to larger production losses. The objective of this paper is to study various shafts failure analysis techniques and select the best method to find out the root cause for failure of shaft used in crane hoist.**

Keywords — Shaft, Keyway, Discontinuity, Stress analysis, Finite element analysis, Shaft failure, root cause analysis

I. INTRODUCTION

A shaft is a rotating machine element which is used to transmit power from one place to another. Shaft supports components like brake drums, rollers, gears, pulleys & transmits power.

The shaft is always stepped with maximum diameter in the middle and minimum at the ends, where Bearings are mounted. The steps provide shoulders for positioning of gears, pulleys & bearings. The fillet radius is provided to prevent stress concentration due to abrupt changes in the cross section. Shaft is subjected to torque due to power transmission and bending moment due to reactions on the components that are supported by the shaft.

Discontinuity added on the shaft for essential functional requirements. There are different types of loading conditions carried (torsion, bending, axial and combination of them) by shaft during working. Here, a case study is taken on auxiliary hoist input shaft for investigation of its early failure.

FEA & KISSSOFT software analysis is also carried out and result shows the conformal agreement with physical testing during root cause analysis. At the end, the exact root cause is determined which is responsible for shaft failure.

II. LITERATURE REVIEW

A. *Failure Analysis and Redesign of Shaft of Overhead Crane : Sumit P. Raut, Laukik P. Raut*

This paper deals with the failure analysis and redesign of shaft of overhead crane having capacity 25 tonne. There is problem of failure of the shaft in gear box which is mounted on the crane. The shaft breakage occurred due to dynamic, alternating low tensile– compressive stresses and simultaneous torsion load.

B. *Failure Analysis of a Two High Gearbox Shaft : Charnont Moolwana, Samroeng Netpub*

This paper reports the results of failure analysis of a two high gearbox shaft of a gearbox in a hot steel rolling mill in Thailand which fail prematurely after about 15,000 hours of service. Standard procedures for failure analysis were employed in this investigation. The results showed that the shaft failed by fatigue fracture. Beach marks on the fracture surface were clearly visible. Fatigue cracks were initiated at the corners of the wobblers. Relatively small final fracture area of the fracture surface indicated that the shaft was under a low stress at the time of failure.

C. *Failure of two overhead crane shafts : Z. Domazet, F. Lukša , M. Bugarin*

The failure analysis of two overhead crane shafts is presented. The failure of an overhead crane drive shaft and the failure of an overhead crane gearbox shaft, due to rotating-bending fatigue. The fracture of the overhead crane drive shaft originated in small radius fillet between two different diameters of the shaft. A new shaft was made with a larger-size fillet, resulting in reduced stress concentration in this region. The failure of the overhead crane gearbox shaft originated at the intersection of two stress raisers, at the change in shaft diameter and in the keyway corner. A new shaft was made with a larger-size fillet and a larger size radius of the keyways corner to minimize stress concentration in this section. In both cases the installed couplings were replaced by gear couplings in order to allow parallel and angular misalignment as well as to avoid additional load due to misalignment. The analysis shows that the fatigue life can be significantly increased with a simple change in the structural details.

III. PROBABLE CAUSES AND INVESTIGATION STEPS OF SHAFT FAILURE

A. *Probable causes*

The major machinery shaft failure reasons can be classified into the following groups:

Mechanical: such as overhung load, bending load, torsion load and axial load.
Dynamic: vibration, cyclic, shock, etc.
Residual: manufacturing processes, repair processes, etc.
Thermal: temperature gradients, rotor bowing, etc.
Environmental: corrosion, moisture, erosion, wears, cavitations, etc.

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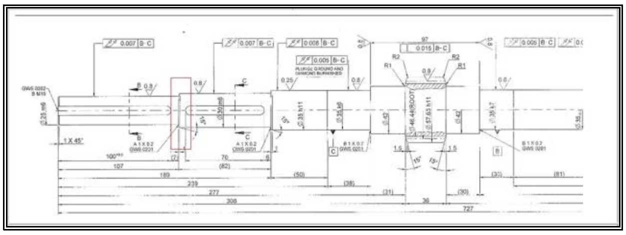
CAUSE OF TYPICAL SHAFT FAILURES	*PERCENT (%)*
Various Corrosions	34 %
Various Fatigues	33 %
Brittle Fracture	16 %
Overload	11 %
Creep, Wear, Abrasion, Erosion, etc	6 %

In this study, we have analysed input shaft of auxiliary hoist gear box which failed in the form of fracture after a year of operation. Material of shaft is as per DIN EN 10084 Grade 20MnCr5. As informed the shaft is in hardened and tempered condition. The teeth portion of the shaft is case carburized. The failure of shaft was seen during hoisting operation at the customer site and it was not going in upward direction. The crane was being operated in no load condition. So the maintenance team checked the gear box and it was found that the shaft had failed. The failure was seen at 50% production load. For this specific crane, the failure was noticed for first the time. The site photograph and drawing showing failed shaft are as given below:

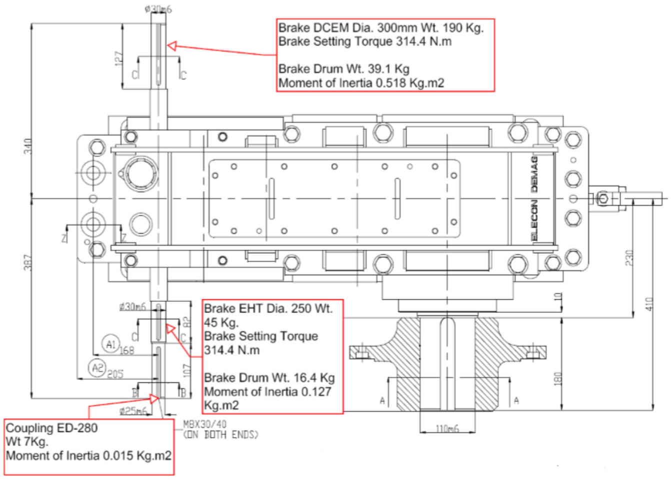
Site photograph 1

Site photograph 2

Failed area of shaft has been marked red in below drawing



The manufacturing route of shaft is as mentioned: forging – turning – hobbing – heat treatment – teeth grinding – OD grinding. The heat treatment is carried out as per shaft drawing. The gear box is driven by motor and there is thruster brake between gear box and motor. Failure took place between brake and motor. Geared coupling is used between motor and brake.



In order to investigate the root cause of failure, two samples of the failed shaft were sent to metallurgy lab. The investigation was carried out after collection of background data & history of failure with available photographic evidences, visual examination, low magnification examination, chemical analysis, SEM analysis, EDS analysis, macro structural examination, micro structural examination, tensile test, impact test, hardness tests.

Based on the investigative findings the root cause of the problem has been identified. Suitable recommendations in the form of remedial measures have been suggested to avoid its recurrence in future.

B. Investigation Steps

B.1: Visual examination

Visual examination is carried out on sample received for investigation along with photographic evidences as under:

Plate: 1 Shows broken piece of input shaft of hoist gear box in as-received condition. The fracture region is in the marking area.

Plate: 2 Shows fracture surface view. Despite some rubbing marks on fracture surface star shaped pattern is visible.

Plate: 3 Shows fracture surface view of the smaller part of shaft. Here also, star shaped pattern is visible with no deformation on the contours.

B.2: Dimensional measurement

The results of dimensional measurement are as shown in following Table:

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Locations	X-axis	Y-axis
1	30.02	30.05
2	30.04	30.05
3	34.94	34.95
4	34.70	34.98
5	41.95	42.00
6	57.21	57.42
7	41.87	41.88
8	34.93	35.02
9	30.04	30.09
10	34.05	34.06

B.3: Wet Fluorescent Magnetic Particle Inspection(WFMPI)

In order to find out any surface defects/auxiliary cracking, WFMPI test was carried out on the sample.
Equipment Used : Controls and equipment make Yoke Type Electromagnetic Crack detector.
Current Used : AC Reference Standard:As Per ASTM E 709

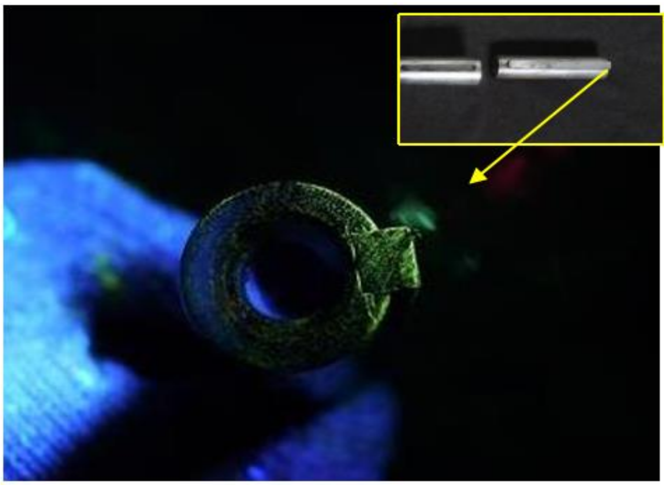

Plate: 4 The small surface plan view in WFMPI tested condition showing end opposite to the fracture surface. A linear indication seen at key way area

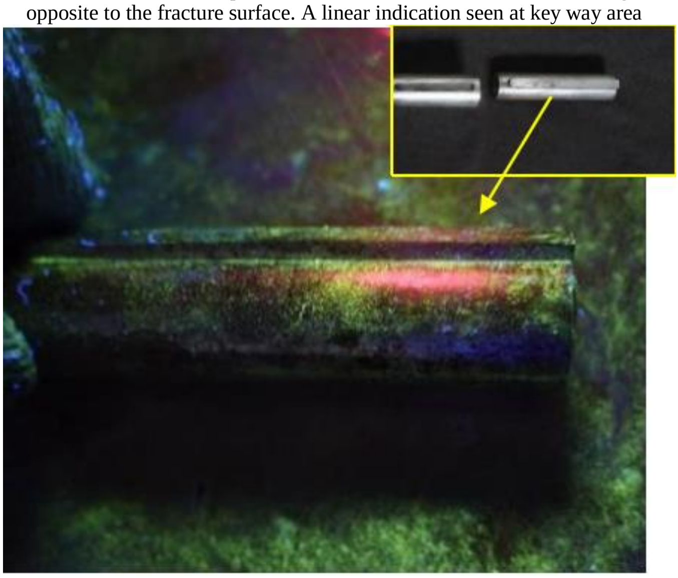

Plate: 5 Small shaft outer surface view surrounding the key way location. A tiny hairline crack like indication is seen on the surface.

B.4: Low magnification examination

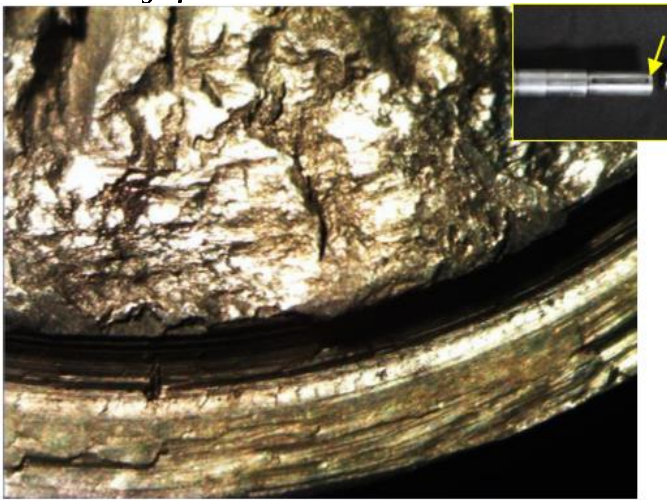

Plate: 7 Shows fracture surface low magnification view at the edges. The multiple ratchet marks are seen. Auxiliary cracking is also noticed. The rubbing is observed that seems to be post failure (10X)

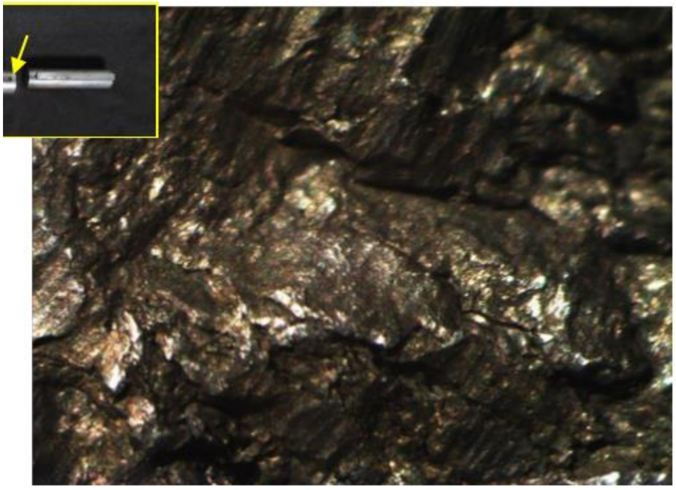

Plate: 8 Shows fracture surface low magnification view in the central portion. Petals of star pattern indicating torsional fatigue mode of failure are seen (20X)

B.5: Chemical analysis

Table2 Results obtained through optical emission spectroscopy.

Elements	Composition Measured (weight per cent) – of shaft	Required as per EN 10084 Grade 20MnCr5
Carbon	0.176	0.17-0.22
Sulfur	0.021	0.035 Max
Phosphorous	0.024	0.025 Max
Manganese	1.27	1.10-1.40
Silicon	0.263	0.40 Max
Chromium	1.06	1.00-1.30

Remark: Results show that the material meets with the requirements as per the specification of EN 10084 Grade 20MnCr5

B.6: Scanning Electron Microscopy (SEM)

SEM was conducted at fracture surface to reveal more details about failure mechanism

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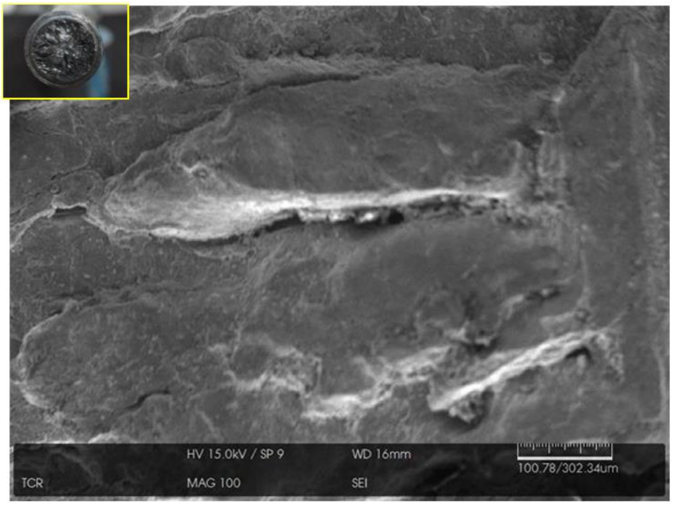

Plate: 9 Shows fracture surface view where petal like grooves indicative of starry fracture characteristic of torsional fatigue are seen. (100X)

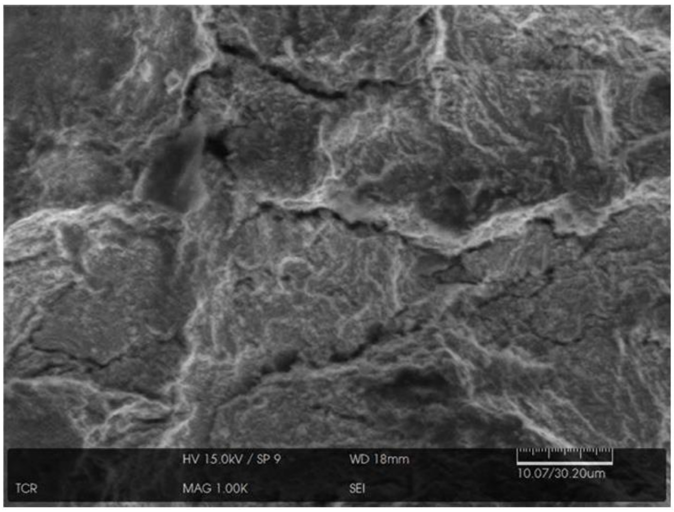

Plate: 10 Shows core portion of fracture surface view with secondary cracks. (1000X)

B.7: Macrostructural examination

In order to ascertain the material homogeneity, forging flow lines, the sample was cut in longitudinal followed by etching with 10% Ammonium Persulphate.

Plate: 11 Shows sample in macro etched condition. Normal grain flow is visible and it is free from any internal defects.

B.8: Microstructural examination

Micro structural examination was carried out at various locations as listed below. Initially, the examination was done in as-polished condition and then after in etched condition.

- Longitudinal cross-section at fracture

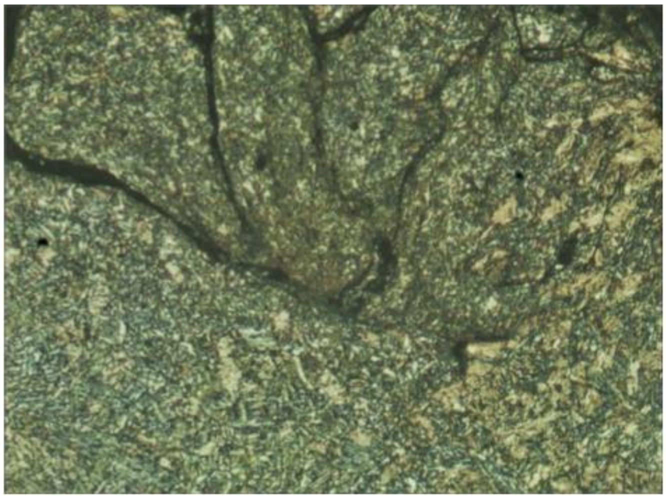

Plate: 12 Shows fracture edge microstructure of tempered martensite. Grains are slightly deformed at the edges. Crack network with uneven contours caused due to deformation is seen (200X)

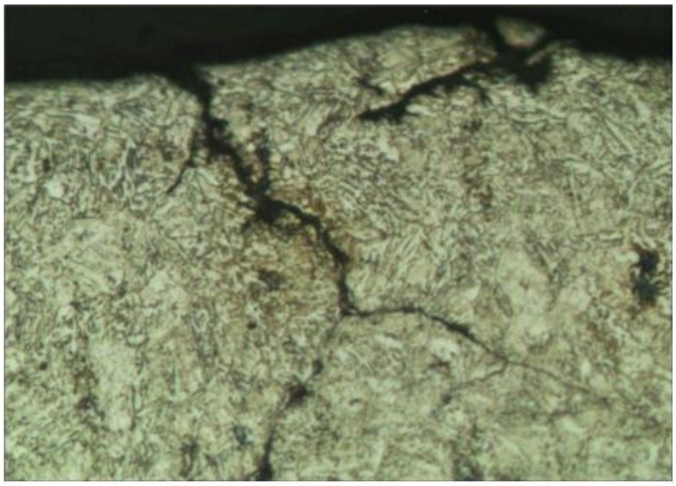

Plate: 13 Shows fracture edge microstructure of tempered martensite with ferrite traces. Transgranular cracking with fine tips and non-uniform contours are seen. (400X)

- Longitudinal cross-section away from fracture

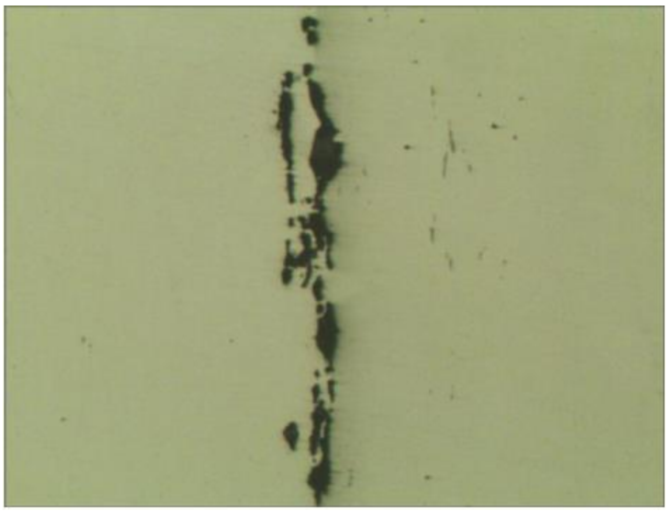

Plate: 14 As-polished view showing internal discontinuity which appears to be scale entrapment. (100X)

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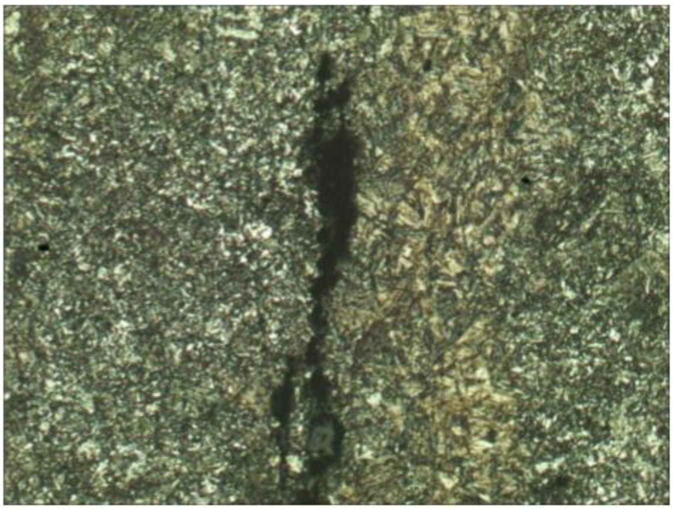

Plate: 15 Shows scale entrapment assuming the shape of crack with non uniform contours. Microstructure is tempered martensite with traces of ferrite. (200X)

- Transverse cross-section at crack

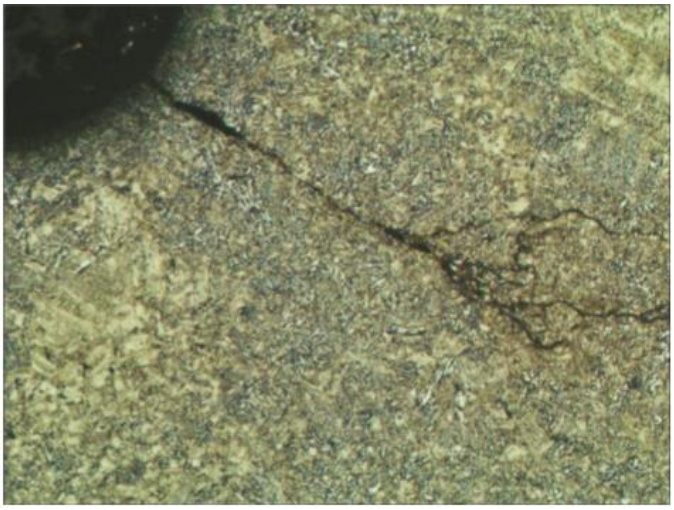

Plate: 16 Shows crack initiating from the keyway contour that has become branching in nature as it propagates. Microstructure is ferrite in traces and tempered martensite. (100X)

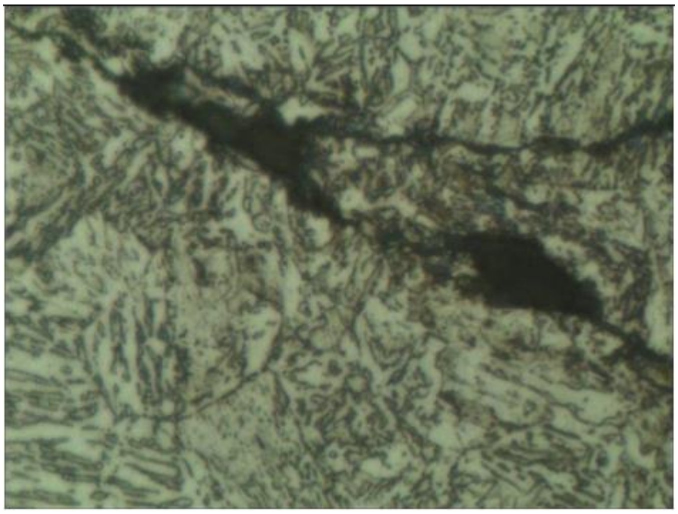

Plate: 17 Shows high magnification view at crack tip with branching tendency. Microstructure is ferrite traces and tempered martensite. (1000X)

B.9: Inclusion Rating

In order to find the quality of steel based on non-metallic inclusion contents, the rating was carried out as per ASTM E-45 after metallographic polishing of sample, in un-etched condition. The results are shown in Table 3.

Table 3 Inclusion rating result

	Type A		Type B		Type C		Type D	
	Thin	Thick/ Heavy	Thin	Thick/ Heavy	Thin	Thick/ Heavy	Thin	Thick/ Heavy
Inclusion rating	1.5	0.5	-	-	-	-	1.5	-

B.10: Tensile test

Tensile test was carried out on the test specimen drawn from sample. The results are reported in Table 4.

Table 4 Tensile test result.

	Measured	Required (min)
Dia (mm)	9.90	-
Area (mm^2)	76.98	-
Gauge Length (mm)	50.00	-
Final Length (mm)	58.05	-
0.2% Proof (N)	48208	-
Ultimate Load (N)	67600	-
0.2% Proof (N/mm^2)	626.24	700
U. T. S. (N/mm^2)	878.15	1000
% R.A	61.03	35
% Elongation	16.10	9
Fracture	Within Gauge Length	-

Remark: Results shows that the material does not meet the requirements as per specification EN 10084 Gr 20MnCr5. (Required values obtained from TC no. M12424)

B.11: Impact Testing

Impact test was carried out on the test pieces drawn from shaft and results are reported in Table 5

Table 5 Impact test result.

Test Method	ISO 148-1 :2010
Specimen Size (mm)	10
Test Temperature (°C)	23
Specification	EN 10084 Gr 20mncr5.
Energy Absorbed in Joules (1)	60
Energy Absorbed in Joules (2)	70
Energy Absorbed in Joules (3)	64
Average in Joules	64.67

B.12: Hardness measurement

Hardness was measured at different locations. The results are reported in Table 6.

Table 6 Hardness test result

Locations	Hardness in "BHN" at 187.5 kg load.			
	1	2	3	Average
At shaft surface	266	266	267	266.33
At shaft core	262	262	263	262.33
At key core	271	271	270	270.67

IV. DISCUSSION

Based on the investigation done so far following salient points are summarized:

1. The input shaft of auxiliary hoist gear box failed in the form of fracture within a year of operation.
2. MOC of shaft is as per DIN EN 10084 Grade 20MnCr5.

3. Visual examination shows relatively flat nature of fracture surface which is square to the shaft axis.
However, fracture surface shows a starry pattern indicating torsional mode of failure. Fracture surface also shows post-fracture rubbing marks.
4. Dimensional measurement does not indicate any abnormal variation or distortion on the shaft. No deformation is seen on the key way contours.
5. WFMPI highlights randomly oriented hairline cracks on shaft surface at location even away from
the fracture.
6. Low magnification view highlights multiple ratchet marks on the fracture contours along with secondary cracks. This is followed by star shaped patterns accentuating torsion fatigue mode of failure.
7. MOC of the shaft conforms to EN 10084 grade 20MnCr5.
8. SEM highlights petals formed on the edges of the fracture surface indicative of starry fracture characteristic of torsional fatigue mode of failure.
9. Macrostructural examination indicates normal grain flow and the shaft is free from any internal defects.
10. Microstructural examination highlights following:

- Close cluster of inclusions that are a elongated in shaft matrix. Oxide scale entrapment.
- Scale entrapment at the edges assuming the shape of the crack.
- Fracture surface indicates cluster inclusions and cracks having random contours. The grains at fracture edge are deformed with cracks.
- Transgranular fatigue mode of cracking is seen initiating from the key way contours. That is away from the failure region.
- Rubbing marks are seen on the outer surface along with uneven external metal surface layer.
- Microstructure tempered martensite with traces of ferrite.

11. Tensile test results show lower 0.2% PS and UTS values.
12. Impact test results at room temperature indicate good toughness of the material.
13. Hardness values appear to be normal.

V. CONCLUSIONS AND MOST PROBABLE CAUSE OF FAILURE

1. MOC, microstructure and hardness values appear to be normal. However, the metallurgical integrity of the shaft is inferior in terms of poor tensile strength and increased level of inclusions in cluster form in localized regions. Moreover, centerline discontinuity in the form of scale entrapment is also noticed, although it has not influenced the damage scenario.

2. The fracture surface indicates star shape pattern with multiple facets in smooth petal like shape oriented in radial direction indicating failure under torsional fatigue.

The shaft failure has taken place due to some possible jamming or obstruction created that impressed upon the excessive stresses promoted failure under torsional fatigue.

VI. RECOMMENDATIONS

1. Reasons for jamming of the shaft during service required to be deliberated from the operation conditions.

2. The shaft quality needs to be improved from metallurgy point of view in terms of reduced inclusions and freedom from center line discontinuity.
Design expert may be consulted for acceptance standard.

ACKNOWLEDGMENT

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