RTI PAST PERFORMANCE	
RTI Tracking Number:	1306594 Date: 7/11/2013
Core Task:	Fatigue Failure Testing, Chemical Analysis, Mechanical Testing, Metallurgical Testing
Analytical Techniques	Mechanical/Hardness/Charpy/Feature /Chem/Photo

Report of Analytical Services -

RTI Lab#: 1306594-001A **Sample Receipt Date: 6/27/2013**

Metallographic observations:

The failed in service output shaft was received for analysis (See Fig 1). The target of the analysis was to investigate the nature of the failure by using a variety of the metallographic techniques. It should be noted that the supplier did not provided requested engineering drawing for outer shaft. The information provided by the client indicates that the material is 42CrMoS4+QT (DIN 1.7227+QT) with 55mm diameter and k6 tolerance. The results of the analyses are provided below.

As-received for analysis. Figure 1. Reduced size

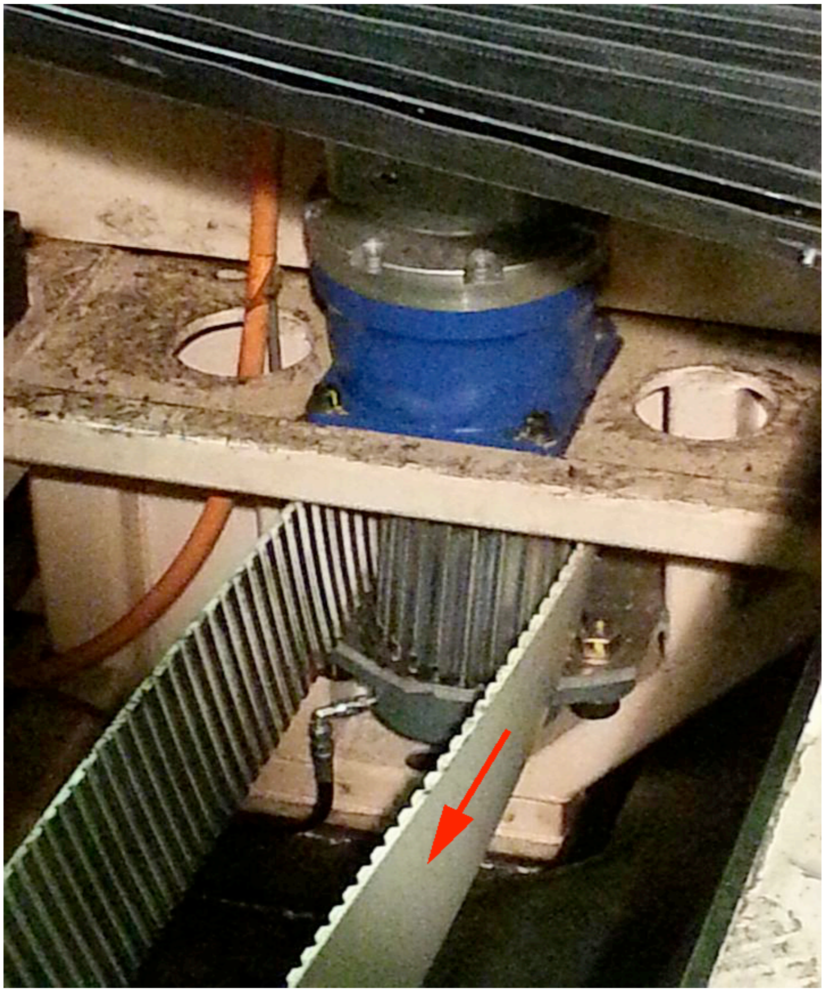


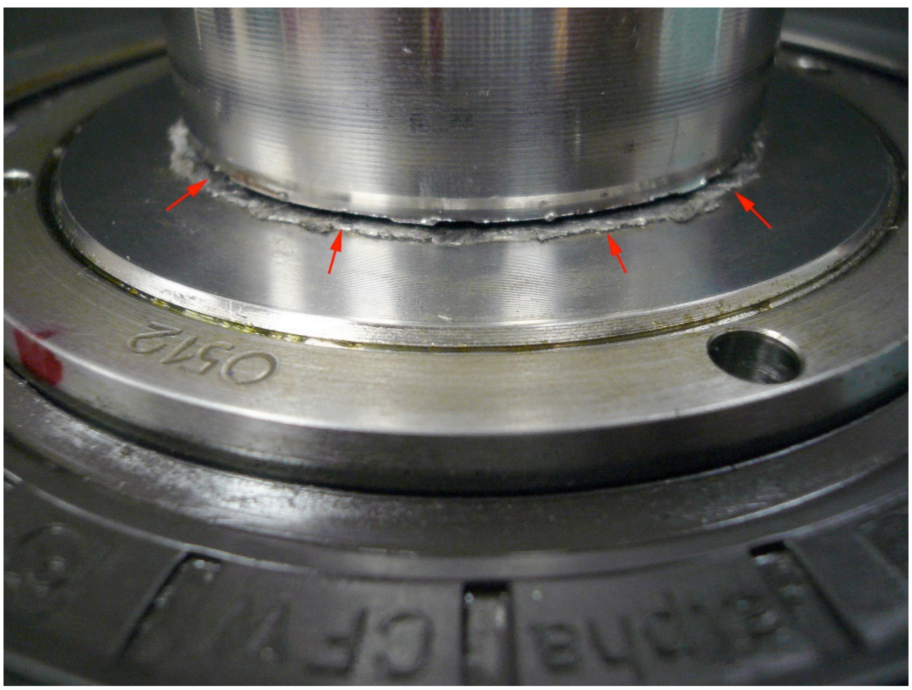
Figure 2. Image submitted by the client.
Red arrow points to direction of bending.

Macro Examination.

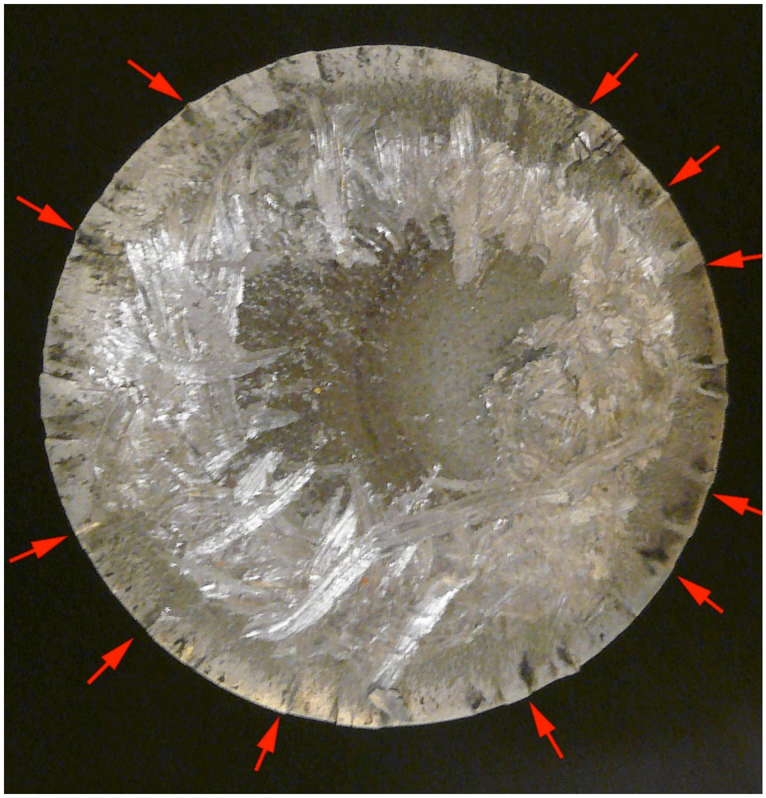
Macro examination, both visual and under a low power microscope has revealed a series of conditions as follows:

1. It is important to note that the entire fracture surface at both sides of the fractured output shaft was obliterated due to mechanical damage after the final fracture occurred. However, there are number of secondary features that relate to the failure.
2. There was an abrupt change in shaft diameter and the fracture occurred at the thinnest portion of the shaft at the small fillet (See. fig.1).
3.The fracture origin is in the small fillet from undercut (see fig. 3 red arrows). The appearance of the fracture indicated that failure was due to rotation-bending load (see fig.2); the presence of undercut provided a region of stress concentration from which fatigue cracks developed. The fatigue cracks broke out circumferentially on the shaft at the undercut and developed inward. The formation of ratchet marks at undercut region indicates that the fatigue cracks were initiated at many locations around the shaft circumference (See fig. 4 red arrows).

4.This fracture also illustrates a feature often shown by fatigue failures, that is, the tendency for the fracture to be dish-shaped, and the plane of fracture turning towards the section having the larger diameter (see fig. 5). Also, it is important to note that fatigue fracture propagation proceeded with arrests and produce easily recognizable beach-marks (see. fig. 4 and fig 6).
5. The fatigue cracks propagate inward almost through the entire cross-section and then final and sudden overload fracture occurred off center (see fig. 6). The eccentric pattern of beach-marks and off center final overload fracture indicates that load on the shaft was not balanced.
6. To further the investigation the gearbox assembly was disassembled. The roller bearings, gear teeth and inner portion of the shaft revealed no evidence of wear, overheating or plastic deformation (see fig. 7 and fig. 8).



As-received for analysis. Figure 3. Reduced size
Macro-image illustrates undercut at abrupt change in shaft diameter.



As-received for analysis. Figure 4. Reduced size
Red arrows point to the ratchet marks.

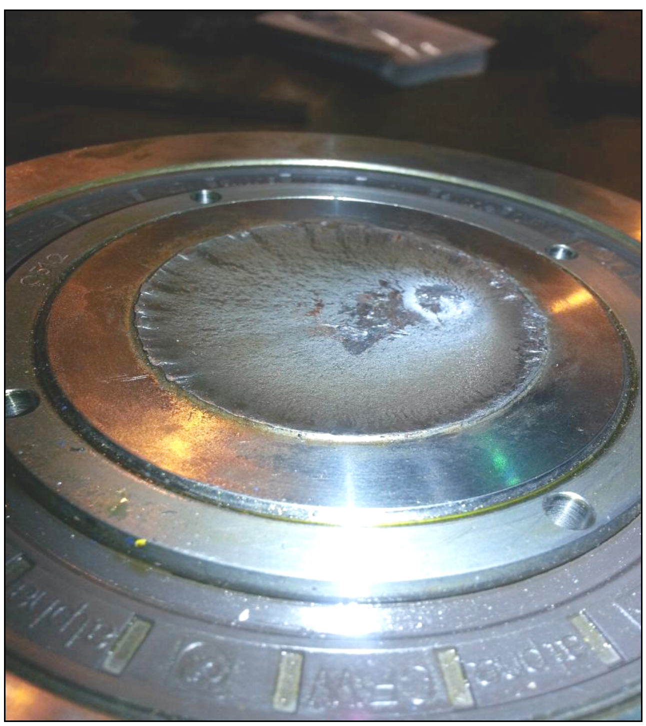
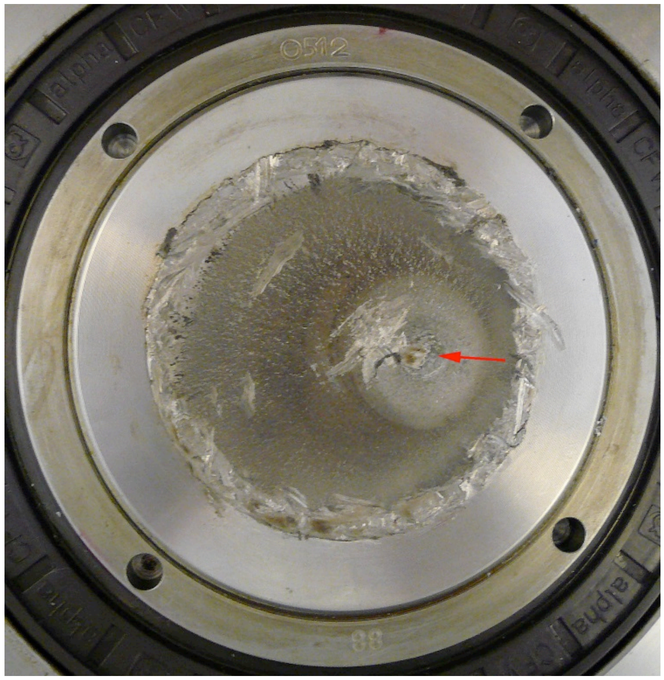


Figure 5. Image submitted by the client.



As-received for analysis. Figure 6. Reduced size
Red arrow point to the location of final overload fracture.

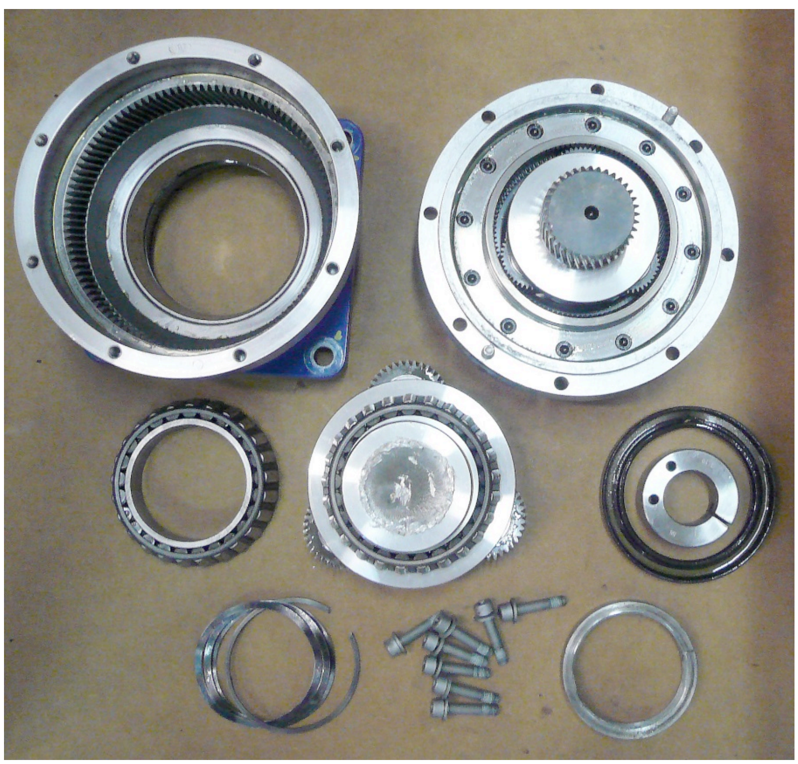


Figure 7. Reduced size
Macro-image illustrates components of gearbox assembly.

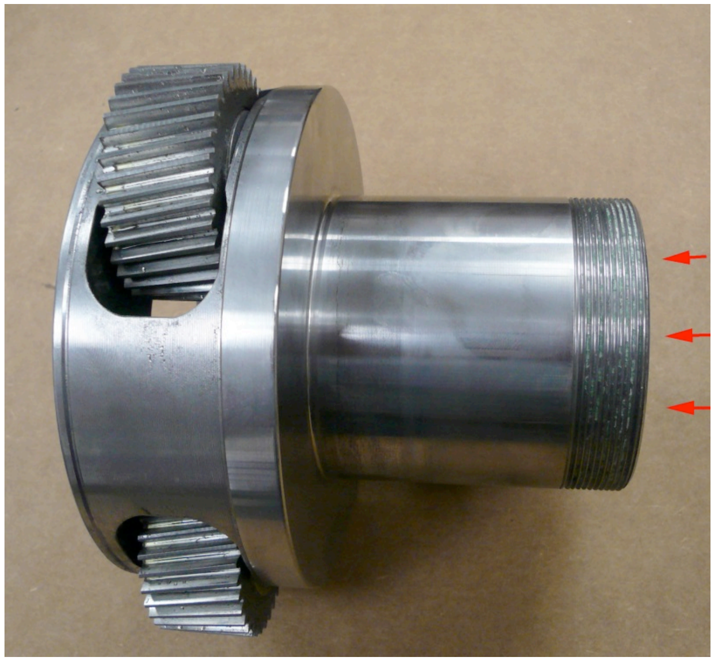


Figure 8. Reduced size
Macro-image illustrates inner portion of the shaft.
Red arrows point to the fractured region.

Physical tests:

Analytical method: ASTM E10-10.

Hardness (HBW)* readings were taken at the mid-radius of the transverse cross-section of the shaft (see fig. 9). The surface was carefully polished prior to the hardness testing.

Designation	Reading
1	255
2	248
3	248
4	248
5	248

* Brinell hardness was performed with a 3000kg load and a Ø 10mm tungsten ball.

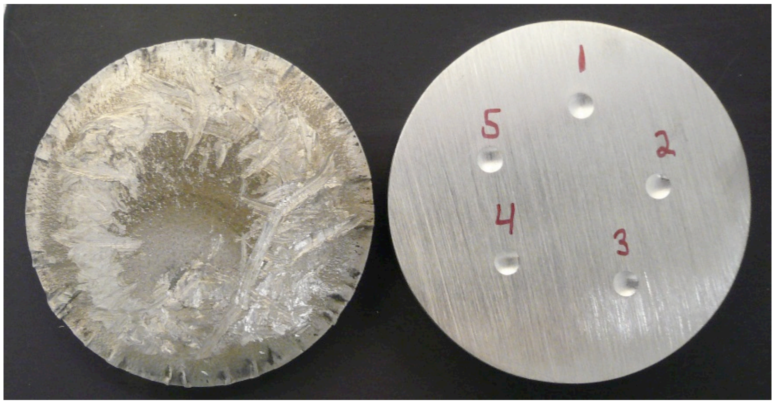


Figure 9. Reduced size.
Marco-image illustrates locations of hardness indentations.

Chemical Analysis:

Analytical method:
Bulk chemical analysis by Glow Discharge- Optical Emission Spectrometry (GD-OES) in accordance with LECO GDS-850A Glow Discharge Spectrometer.

Designation	Elements (All units are % by wt.)												
	C	S	P	Si	Mn	Cr	Ni	Mo	V	Al	Cu	Ti	Nb
Shaft	0.38	0.024	0.016	0.25	0.76	1.03	0.02	0.19	<0.008	0.024	0.08	<0.008	<0.008

Mechanical properties:

Sample tested in accordance with the current revision of ASTM A370-11, E8/E8M-09 and DIN 1.7227+QT with shaft diameter 55mm with k6 tolerance. Direction: Longitudinal

Test	Result	Units	Low Limit*	High Limit*
Tensile Strength	**792**	N/mm^2	900	1100
Yield Strength (0.2% Offset)	**598**	N/mm^2	650	
Elongation (in 1.0 in)	24.0	%	12	
Reduction of Area	61.8	%	50	

*Note: The limits given for material 42CrMoS4+QT (DIN 1.7227+QT) with diameter 41mm –100 mm in Quenched and Tempered condition.

Impact Energy:

Sample tested in accordance with the current revision of ASTM A370-11, E23-07 and DIN 1.7227+QT with shaft diameter 55mm with k6 tolerance. Direction: Longitudinal

Test	Result	Units	Low Limit*	High Limit
Size Scale	Full			
Temperature	Ambient	Deg. F		
Impact Energy for Specimen 1	53	Joules	35	
Impact Energy for Specimen 2	41	Joules	35	
Impact Energy for Specimen 3	60	Joules	35	
Impact Energy Average	51	Joules		
Lateral Expansion Specimen 1	33	x .001 in		
Lateral Expansion Specimen 2	26	x .001 in		
Lateral Expansion Specimen 3	38	x .001 in		
Percent Shear Specimen 1	40	%		
Percent Shear Specimen 2	30	%		
Percent Shear Specimen 3	40	%		

*Note: The limits given for material 42CrMoS+QT (DIN 1.7227+QT) with diameter 41mm –100 mm in Quenched and Tempered condition.

Metallography:

To further the investigation the fractured outer portion of the shaft was sectioned longitudinally (with respect to the axis of the part), metallographically prepared in accordance with ASTM E3-11, and microscopically examined in the as-polished and etched conditions.

Microcleanliness rating:

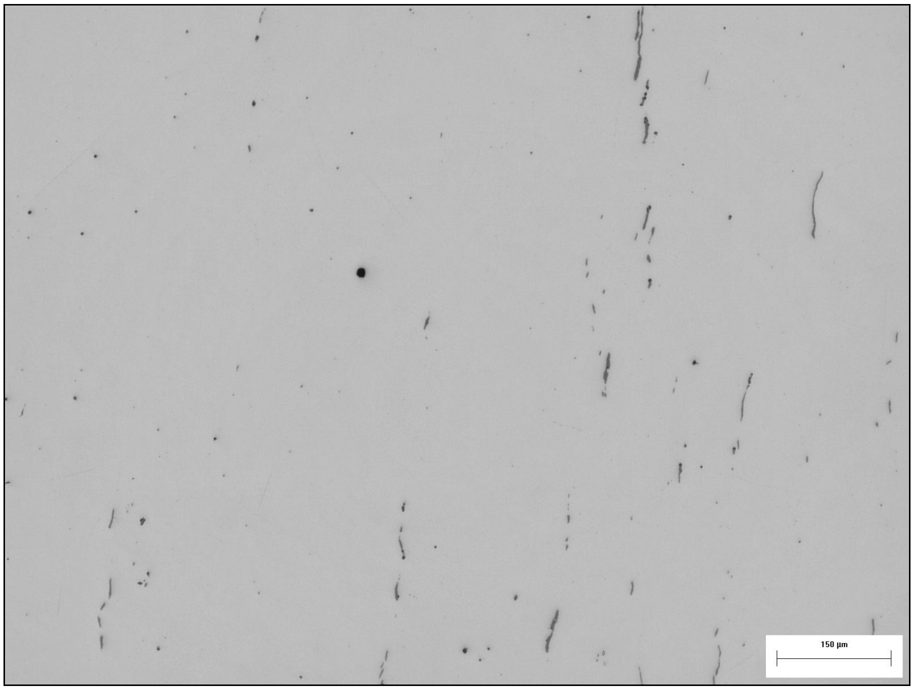
Analytical method: ASTM E45-10^{e1}, method A, Plate I.

A longitudinal specimen of this material was microscopically rated at 100x in as-polished condition for inclusion content of the steel by comparing with ASTM E45-10^{e1}, method A,
Plate I. (see fig. 11).

Worst-Field Inclusion Ratings (Method A) Severity Levels

Classification of the inclusions	**A** (Sulfide Type)		**B** (Alumina Type)		**C** (Silica Type)		**D** (Globular Type Oxide)	
	Thin Series	Heavy Series	Thin Series	Heavy Series	Thin Series	Heavy Series	Thin Series	Heavy Series
Analyzed sample	2½	½	0	0	½	½	1	1

It should be pointed out that the higher amount of internal discontinuities such as soft manganese sulfide (MnS) non-metallic inclusions (rated 2½) in shaft material would contribute to premature failure.



As-polished condition. Figure 10. 100x
Micro-image of a representative structure.

Metallographic examination of the etched cross-section revealed inhomogeneous microstructure, which consists of alternating bands of acicular ferritic with fine pearlitic colonies and dense fine lamellar pearlite colonies (see fig. 11and fig.12). It should be noted that the typical microstructure for (DIN 1.7227+QT) material in Quenched and Tempered condition is tempered martensite. Also, banded structure is very sensitive to the transverse bending loading.

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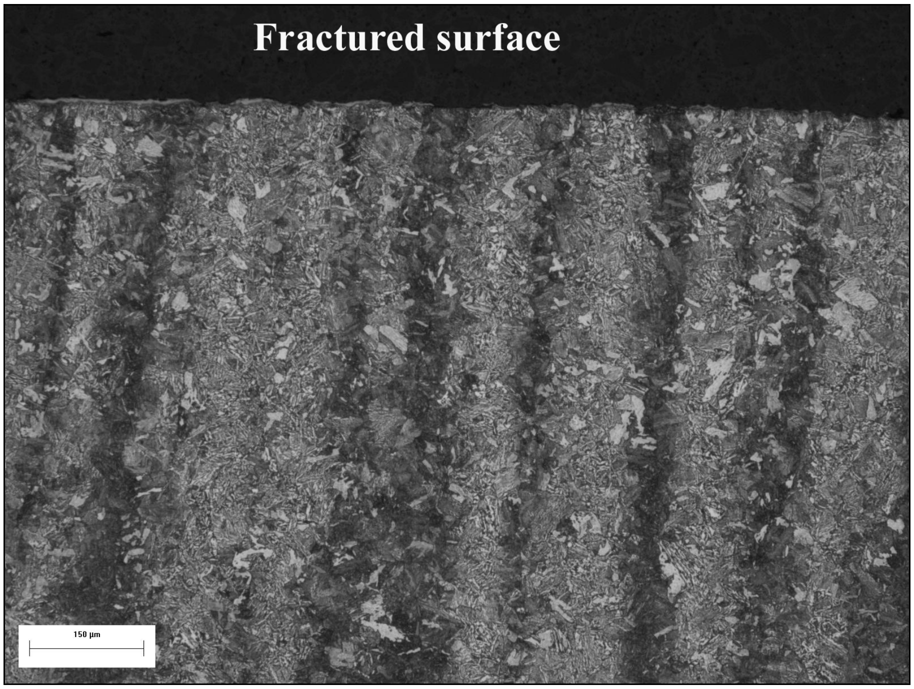
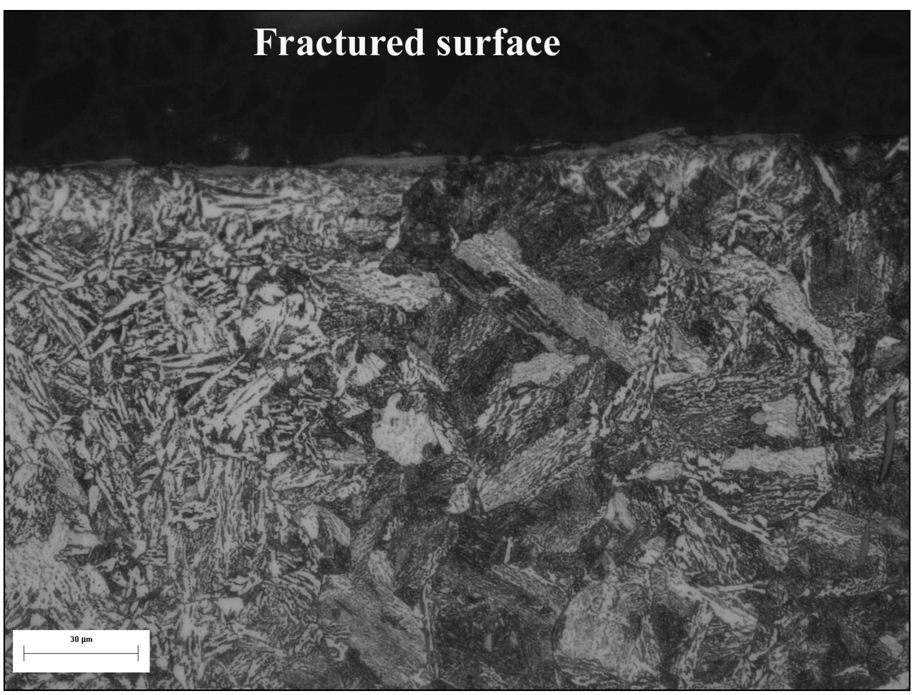


Etched condition Figure 11 100x

Micro-image of a representative structure.



Etched condition Figure 12 500x

Micro-image of a representative structure.

Conclusion:

It is our considered opinion that the cause for the fracture observed in this investigation can be attributed to several factors; namely:

1. Undesirable quality of the shaft material (the amount of non-metallic inclusions in steel is too high for shaft application).
2. Undesirable (improper) heat treatment condition of the shaft material.
3. The mechanical properties below specified by DIN 1.7227+QT limits.
4. Design error – the undercut at the small filet of the shaft.
5. Assembly and/or design error – the load on the shaft was not balanced. However, the unbalanced load on the shaft can be caused by the conditions described above.

Note: The findings/opinions in this report are based on the analysis of the failed parts received and the information provided. If additional information becomes available, we reserve the right to supplement the findings of this report based on that information.
