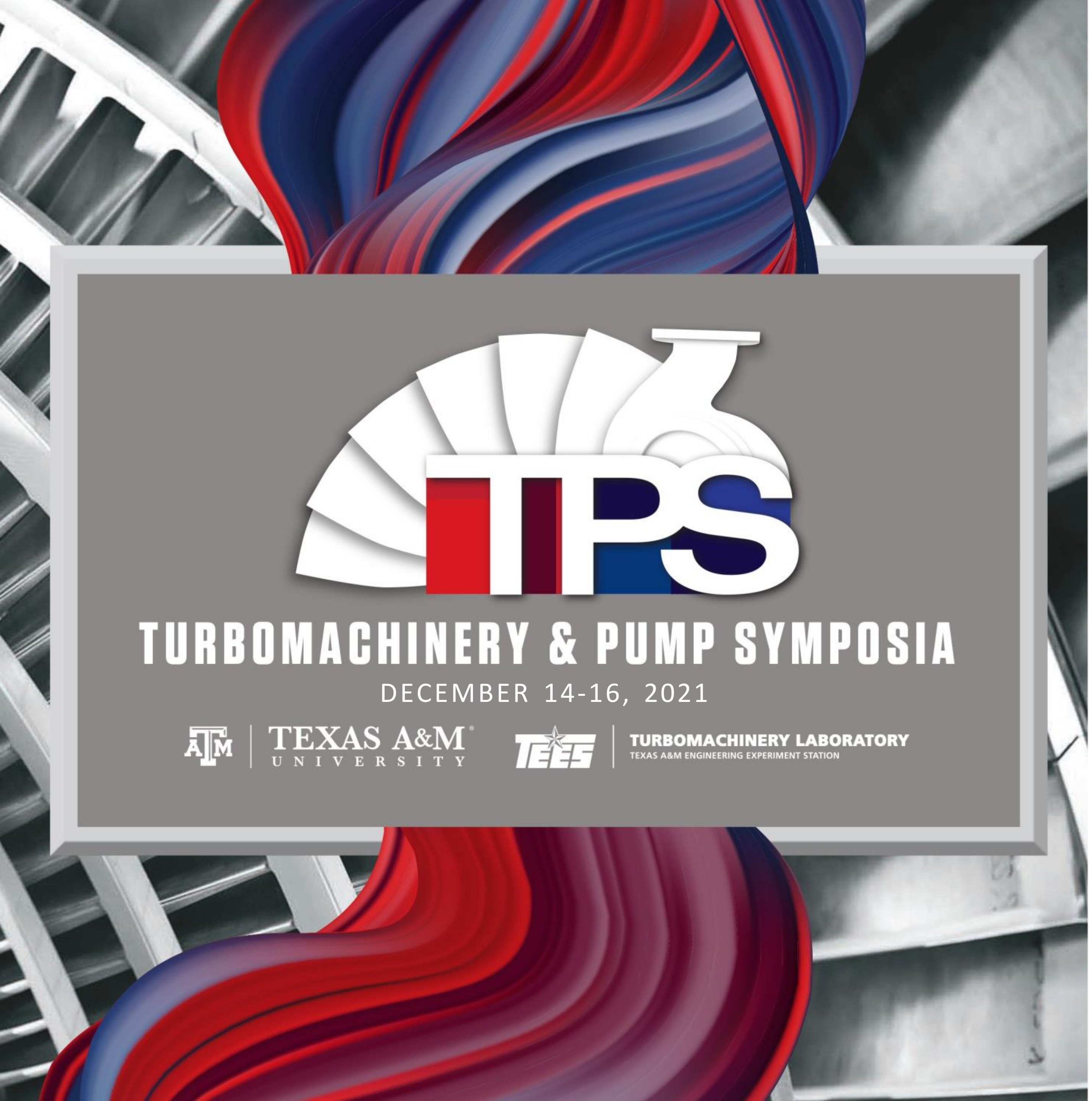

Reciprocating Compressor Crankshaft Fatigue Failure

Scott Symons,
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AIR PRODUCTS

Biography

- **Scott Symons** is a Lead Machinery Engineer in the Operations team at Air Products. He is based in Allentown, PA and has over 10 years of rotating machinery experience.

Problem Statement

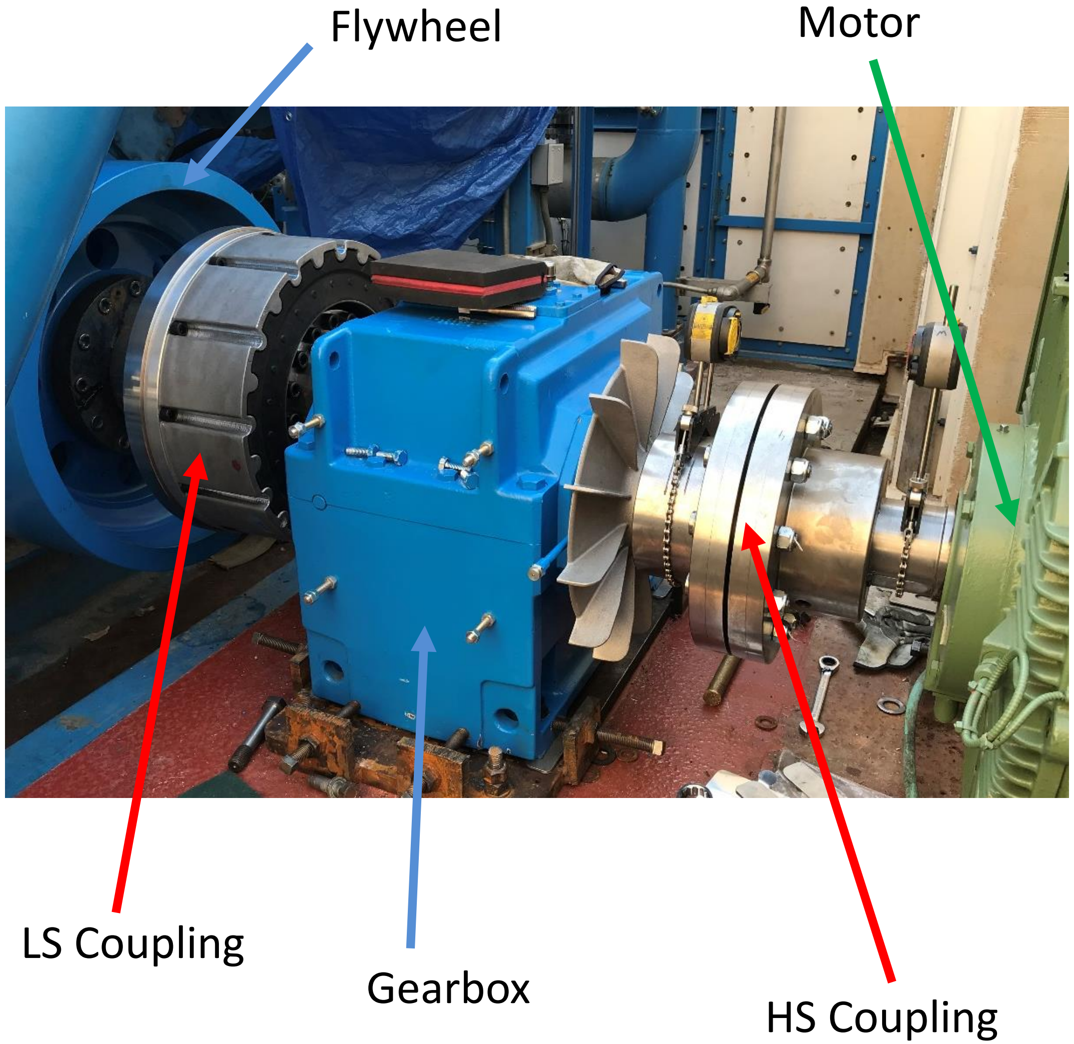
- The crankshaft of a 3-stage, W-type compressor failed after an estimated 41000 hours of operation at 568 RPM (~1.4 x 10^9 cycles).
- Compressor tripped on high vibration, detected by a mechanical vibration switch.
- Compressor restart is not permitted without inspection.
- During inspection, it was observed that the crankshaft fracture occurred between the crankcase and flywheel triggering a series of events resulting in significant collateral damage.

Compressor Overview

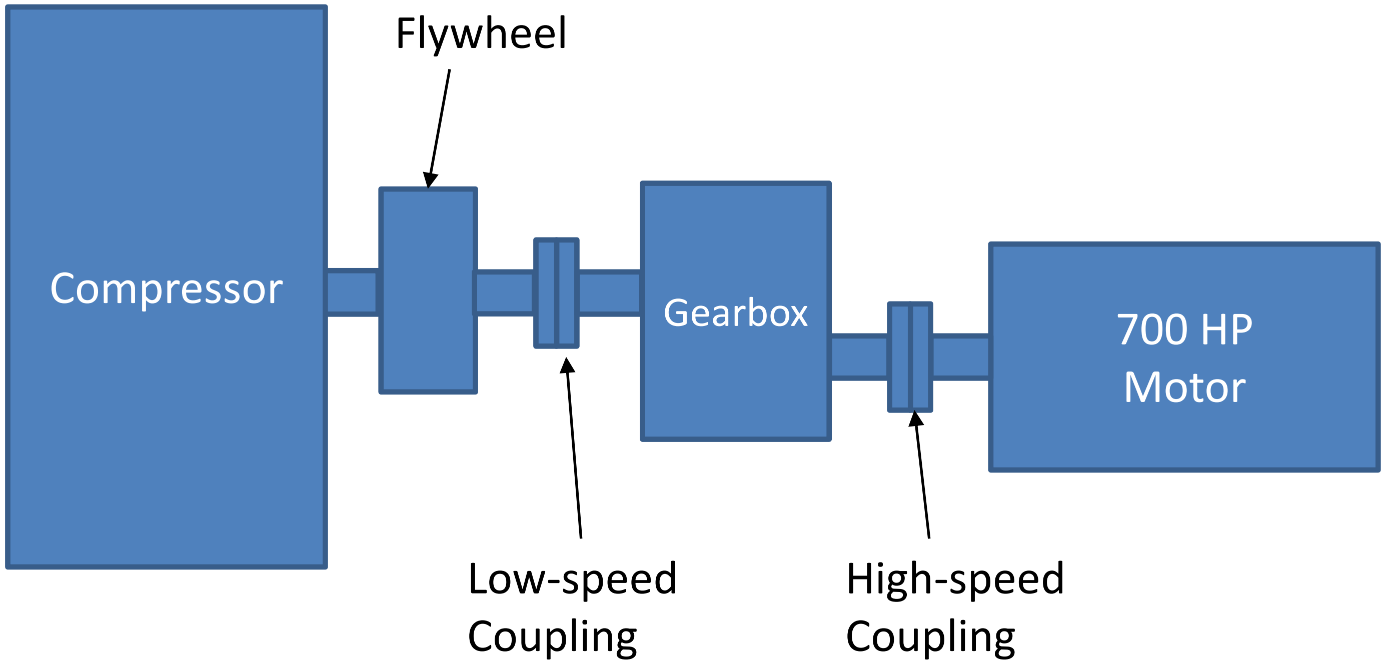
- 3-stage, W-type, oxygen reciprocating compressor
- Driven by 700 HP, 4 pole induction motor and gearbox
- Compressor speed – 568 RPM, 9.3 ft/s average piston speed
- Three double-acting (DA) Cylinders
  - 24.803”, 16.142”, 9.449”

Compressor Overview

- Commissioned: Spring 2014
- High-speed coupling: Elastomer buffers and steel pins
- Low-speed coupling: Two large rubber disk elements
- Instrumentation:
  - Stage suction & discharge fast-acting RTDs
  - Interstage PTs
  - Vibration – Compressor Only
  - Rod Drop- 2 out of 3 throws
  - Stage moisture detection



Equipment Arrangement



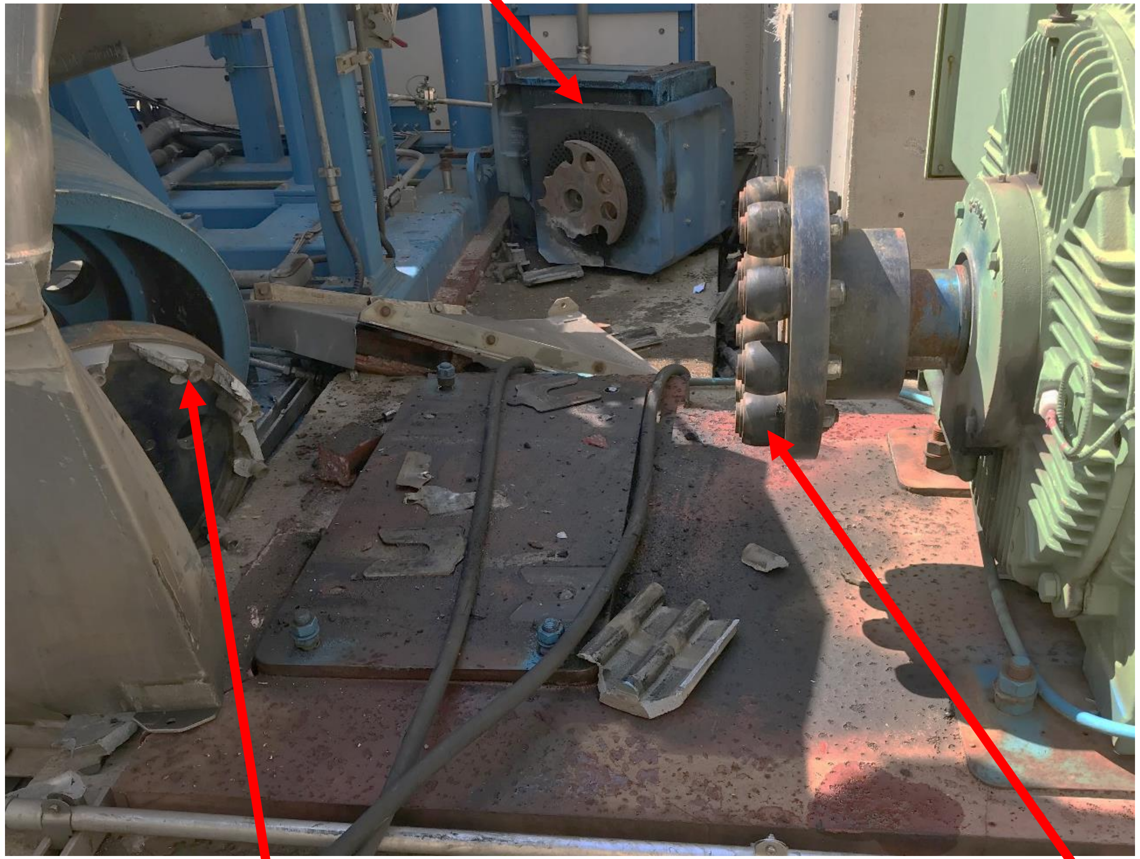
Initial Findings

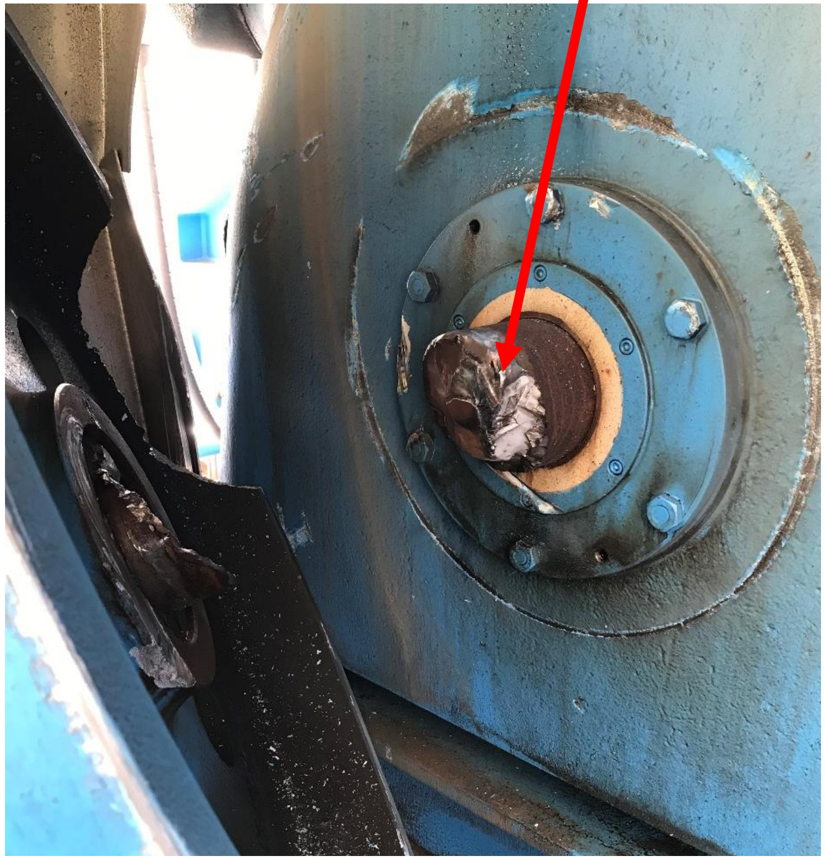
- Complete crankshaft fracture occurred between the crankcase and flywheel, significant collateral damage followed.
- The low-speed coupling broke and the gearbox hold-down bolts sheared off.
- The gearbox was thrown roughly 10 feet.
- The high-speed coupling hub slipped off the coupling elements.

Initial Findings

Gearbox thrown 10 feet

Crankshaft failed between crankcase and flywheel





Broken low-speed coupling and flywheel

High-speed coupling elements

Initial Analysis

- Initial review of the compressor crankshaft showed corrosion on a significant portion of the surface area, indicating the crack propagated well before the final failure.

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Relevant History

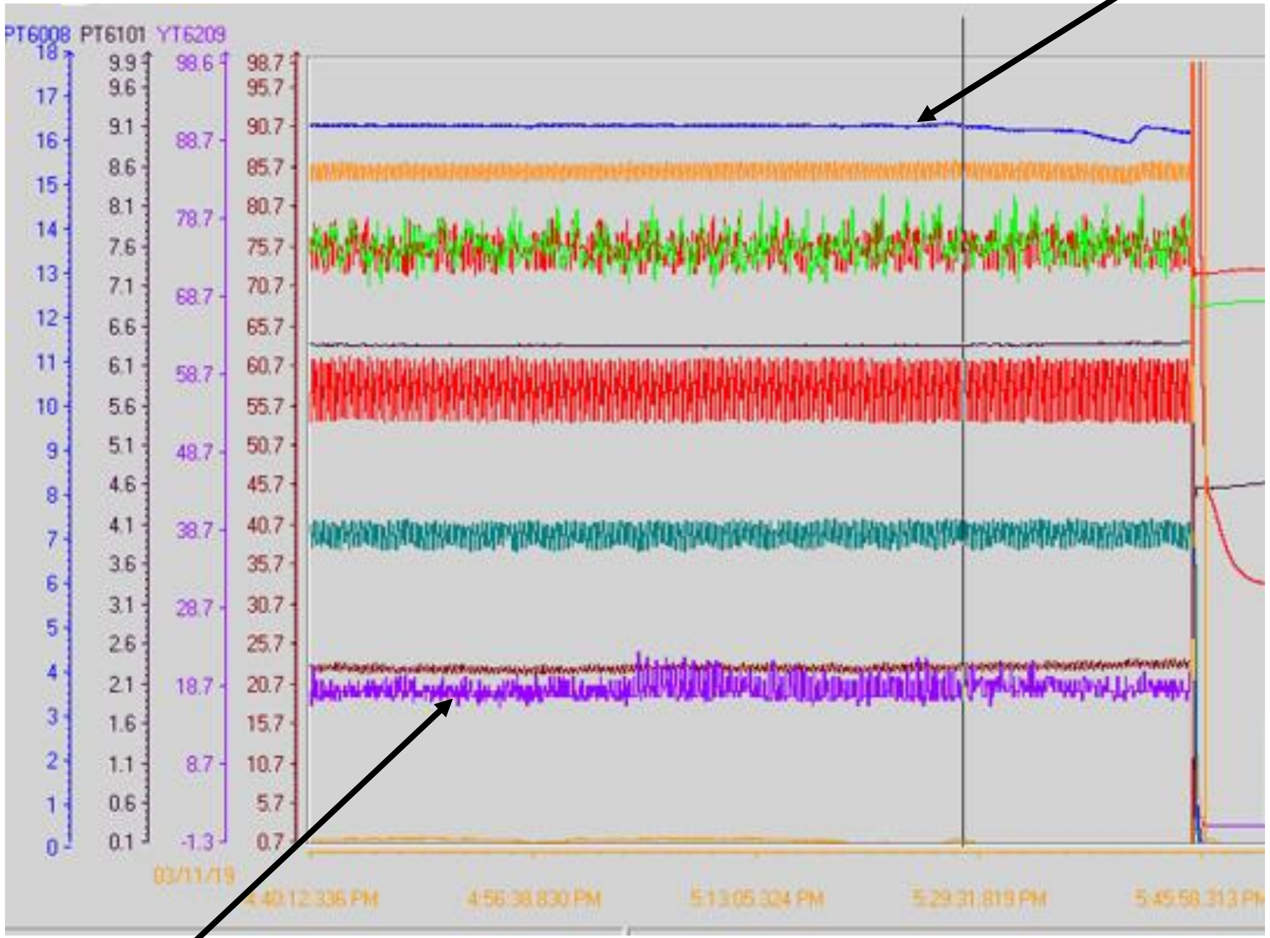
- Specified above internal maximum allowable continuous rod load (MACCRL) Limit: Rating shall not exceed 100% at relief valve setting.
  - 1^{st} stg – 114%, 3^{rd} stage – 117%
  - There was a larger compressor frame available which would have satisfied our internal standards.
- Long History of Failures: *(No proof of direct correlation to this event)*
  - Piston to Crosshead issues
  - Cast Piston failures
  - Crossheads / Crosshead Liners
- No vibration detection on the gearbox prior to this failure

Relevant History

- In the months prior to the failure, the smart vibration transmitter which detects impacts, occasionally indicated a negative value. Transmitter was found slightly loose, after the next issue it was replaced. Finally, it was bypassed until the cable could be replaced and the mechanical vibration switch was enabled.
  - Leading up to failure, it was reading below alarm and did not reach trip value prior to the shutdown.
- Motor Findings (After Failure) – no signs that motor moved
  - Motor was bolt-bound
  - Front to rear sole plates ~ 1/8" out of level
  - Side to side sole plates tilted toward shaft centerline
  - No alignment records

Trends – 1 hour

Discharge Pressure (Blue),
Scale: 0 – 18 barg



Vibration (Purple), Scale: 0 – 100 percent

Metallurgical Failure Analysis

- The crank shaft had been in service for 5 years, accumulating approximately 1.4 x 10^9 cycles.
- Fracture surface suggests a mixed mode of high-cycle and low-cycle fatigue failure, with the low-cycle fatigue occurring at the end.
- Significant torsional stress influenced crack growth.
- It is not believed that corrosion accelerated the crack or failure, although it allowed us to determine the crack propagated well before the failure.

Metallurgical Failure Analysis

Predominantly transverse to the shaft axis, upper section contains both transverse and oblique-angle fractures.

Closeup of ‘A’ surface showing the crack path around the periphery as a wavy pattern, indicative of a significant torsional stress influencing propagation.

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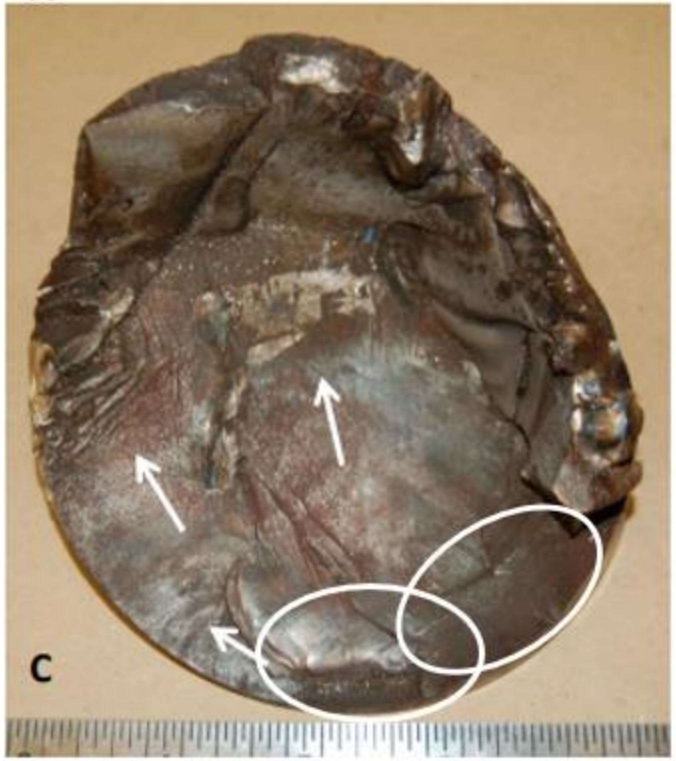
Metallurgical Failure Analysis



Crack initiation areas, post-fracture damage prevents further identification.

Arrow indicates a clear rotational component to the propagation of the end of the failure.

Torsional Analysis – Post Failure

- OEM used incorrect elastomeric elements on low-speed coupling. Torsional stiffness used in the analysis was lower than the installed coupling stiffness.
- "Time in service" – mechanical work hardening will increase torsional stiffness of the low-speed coupling
- Torsional natural frequencies of the drive train are not within 10% of operating speed, which meets the API 618 guideline.
- The predicted levels of torsional response satisfy torsional fatigue-based and vendor-specified guideline performance limits. However, they do not satisfy API 618's vibratory torque limit of 25% at maximum compressor load.

Conclusions

- Crankshaft fracture was a result of a fatigue failure.
- Incorrect low-speed elastomeric elements and mechanical work hardening significantly increased the torsional stiffness of the low-speed coupling, relocating the torsional resonance closer to the operating speed, thus resulting in higher torsional vibration.
- One of the previous failures in conjunction with the higher levels of torsional vibration may have resulted in crack initiation and propagation.
- From review of the trends and metallurgical analysis, there was no evidence to support a single overload immediately prior to failure or a gearbox failure.

Implemented Solutions

- Change to correct elastomeric elements on LS coupling, reduce torsional stiffness. No issues over last 20,000 hours.
- Clarified maintenance strategy on elastomeric elements.
- Revised our internal standard to recommend limiting the maximum-allowable, continuous, rod-load rating to 90% at relief valve setting for critical compressors.
- Increased size of motor bolt holes to allow for recommended alignment.
- Crankshaft inspections between crankcase and flywheel added to quarterly checklist.

Lessons Learned

- Although elastomeric couplings may pass visual inspections, they have a defined life, during which the torsional stiffness will increase from work hardening.
- Atmospheric conditions may reduce element life, this plant was onsite at a Pulp Mill.
- It’s important to verify the correct elastomeric elements are used.
- Stay within MACCRL limits, calculation should use minimum inlet pressure and safety valve set pressure.
- Proper installation and alignment is critical early step to achieving design life of rotating equipment.
- In critical applications, the gearbox shall have vibration protection.