FAA's Rotor Integrity Research

Requirements:

A11B.PS.1 Advanced Damage Tolerance (DT) and Risk Assessment Methods for Engine Life-Limited Parts

A11B.PS.4 Improved Nondestructive Evaluation (NDE) to Prevent Uncontained Engine Failures

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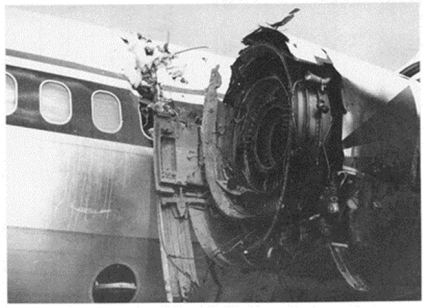
Outline

- Introduction Rotor Integrity Research
- Research Approach
- Collaboration with Industry
- RISC Roadmap
- A11B.PS.1
- A11B.PS.4
- Summary

Rotor Integrity Research

- The FAA's Rotor Integrity Program consists of two requirements that focus on Damage Tolerance (DT) and Nondestructive Evaluation (NDE) research, which complement each other.
- Both requirements sprung from 1989 Sioux City (Titanium melt defect) but over time addressed new challenges, eg, Pensacola (hole machining).
- Recent rotor failures include AA Flt 383 (Nickel Anomaly) in 2016 and Air France Flt 66 (Cold Dwell Fatigue) in 2017.
- Currently funded R&D efforts are focused on damage tolerance design methods and improving inspection methods for nickel and titanium rotor material anomalies.
- Both requirements reside in A11B Budget Line and are distinct in terms of funding, but are managed to leverage each other.

Sioux City
Titanium "Hard Alpha"



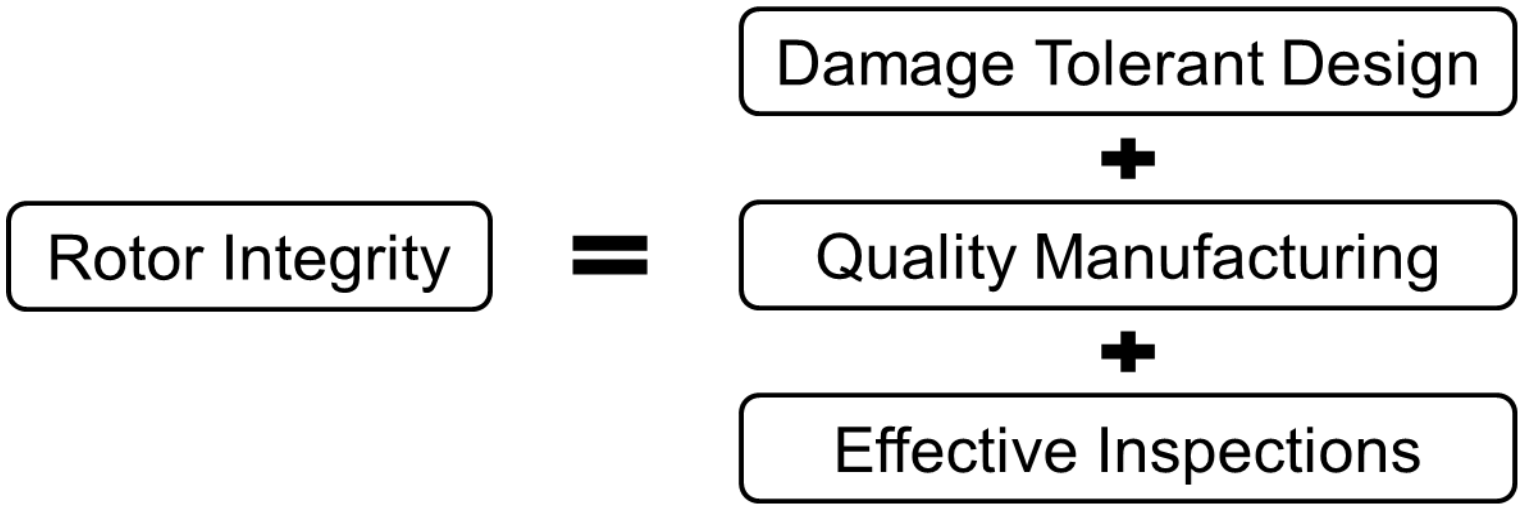
Pensacola
Hole Drilling

AA Flt 383
Nickel Anomaly

AF Flight 66
Titanium "Cold Dwell Fatigue"

Research Approach

For High-Energy Rotors, Containment Is Not an Option



Collaboration with Industry

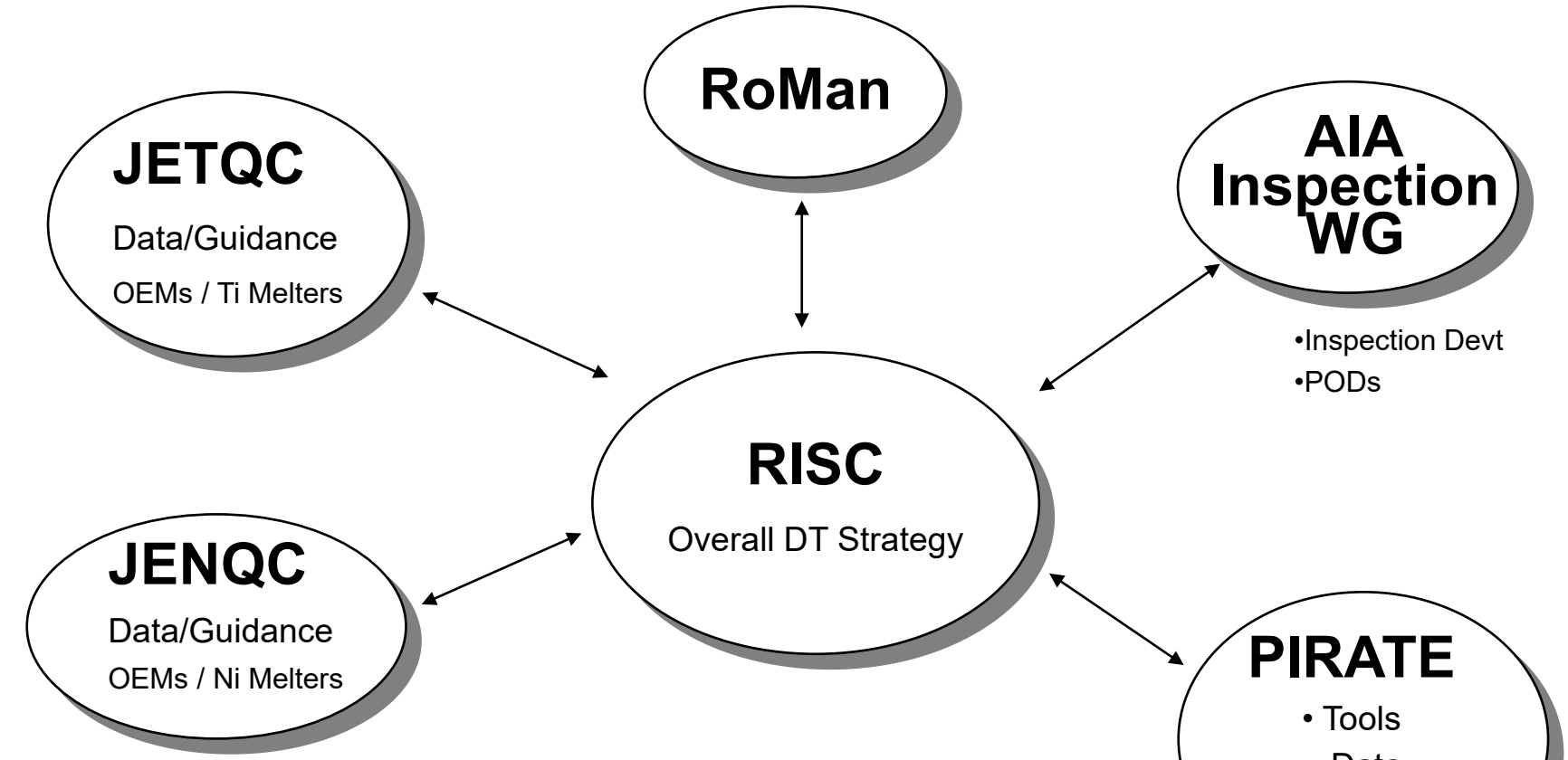
- **AIA RISC: Rotor Integrity Steering Committee**
  - Turbine Engine OEMs, FAA and Foreign Regulators
  - Charter: To address industry policy and procedures as they relate to safety issues associated with high energy rotating components.
- **RoMan: Rotor Manufacturing (RISC Sub-team)**
  - Turbine Engine OEMs, FAA and Foreign Regulators
  - Charter: Establish industry guidelines that improve manufacturing, engineering and quality practices towards eliminating manufacturing induced anomalies.
- **JETQC: Jet Engine Titanium Quality Committee**
  - Turbine Engine OEMs, Titanium Melters/Forgers, FAA and Foreign Regulators
  - Charter: To collect and share data on premium quality titanium

Collaboration with Industry

- **JENQC: Jet Engine Nickel Quality Committee**
  - Turbine Engine OEMs, Nickel Melters/Forgers, FAA and Foreign Regulators
  - Charter: To collect and share data on premium quality nickel alloys
- **AIA Inspection Working Group**
  - Turbine Engine OEMs, FAA and Foreign Regulators
  - Chartered to address production and in-service rotor inspections
- **DARWIN Steering Committee**
  - Turbine Engine OEMs, FAA
  - Assists FAA and Southwest Research Institute (SwRI) on the development and validation of the DARWIN engine design code.

Strong industry ties to all aspects of rotor life management including design, manufacture, and operation.

Linkages – Industry Initiatives



RoMan = Rotor Manufacturing

JETQC = Jet Engine Titanium Quality Committee

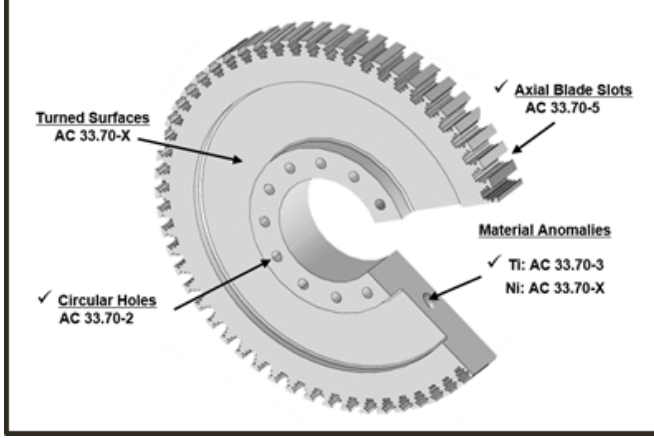
JENQC = Jet Engine Nickel Quality Committee

RISC = Rotor Integrity Steering Committee

NDI = Non Destructive Inspection Working Group

PIRATE = Probabilistic Integrity and Risk Assessment of Turbine Rotors

RISC Roadmap



As of 2021

Damage Tolerance Advisory Circular

- **Inherent Flaws** (Melt related, etc)
  - **Titanium**
    - ✓ **Hard Alpha Microtexture Regions**
  - **Ni/Powder Metals**
    - ✓ **Powder Inclusions C&W Anomalies**
  - ✓ **Analytical Method: Probabilistic FM** Risk Calc <DTR
    - •Analysis Tool calibrated by Test Case
    - •Criteria Calibrated by Experience
- **Induced Flaws**
  - **Manufacturing**
    - ✓ **Circular Holes**
    - ✓ **Attachment Slots**
    - **Turned Surfaces – On Hold**
  - **Maintenance/ Service**
    - **Non-Hazardous Regions**
  - **Analytical Method: Probabilistic FM** Risk Calc <DTR
    - •Deterministic FM?
    - •Probabilistic FM? ✓

A11B.PS.1 Advanced Damage Tolerance (DT) and Risk Assessment Methods for Engine Life-Limited Parts

Research Project Description

- Characterizing crack nucleation/growth behavior of Ni anomalies & Ti cold dwell fatigue (CDF) on service life;
- Spurred by the AA Flt 383 HPT failure and the AF Flt 66 fan failure due to anomalies of Ni and Ti, respectively.
- Developing DT analysis methods, tools, and data that take into account those failure mechanisms.
- 3 Projects:
  - PIRATE 3 – addressing Ni anomalies
  - Model Cold Dwell Fatigue in DARWIN
  - CDF Literature Review

Sponsor Anticipated Outcome

- New AC 33.70-6 will address DT of Ni Material Anomalies in High Energy Rotors to assist with compliance of rule 33.70. Draft AC expected by FY25.
- Incorporate DT methodology for Ni material anomalies into DARWIN design code. (FY25)
- Results of CDF Literature Review will be used to update AC 33.15-1 on Manufacturing Quality Ti Alloys used for Rotors (FY23)

Critical Milestones

- PIRATE 3
  - Awarded grant with SwRI (07/20)
  - Conducted preliminary test on Ni material (06/21)
  - Develop Ni anomaly test matrix (12/22)
  - Complete phase 1 testing (10/24)
- Model Cold Dwell Fatigue in DARWIN
  - Awarded IAA with USAF-AFRL (02/22)
  - Report (08/23)
- Cold Dwell Fatigue Literature Review (10/22)

Research Accomplishments in FY22

- PIRATE
  - DARWIN 10.0 release 09/22 contains enhanced features to enable FAA certification assessments for Axial Blade Slot Analysis, Updated Titanium Anomaly Distributions, and 3-D Visualization and Speed Enhancements

A11B.PS.1 Advanced Damage Tolerance (DT) and Risk Assessment Methods for Engine Life-Limited Parts

PIRATE 3 (Probabilistic Integrity and Risk Assessment of Turbine Engines)

- 4-year Grant to Southwest Research Institute awarded July 2020
- Driven by Chicago AA 383 event, this grant will examine DT issues associated with Ni anomalies
- Several types of Ni anomalies exist but this will focus mostly on DWS (Dirty White Spot)
- Research Questions: what type/size anomalies do we need to worry about; how fast do they nucleate into cracks; how to best calculate their fracture risk, etc.
- Currently working with RISC to plan a Ni mechanical testing program. Planning team includes a Ni melter who will assist in making or identifying Ni materials (billet or forgings) with anomalies.
- After testing, specimens will be cut up to characterize morphology of each anomaly.
- Incorporate Ni anomaly crack growth models and anomaly size and frequency distributions from JENQC efforts into Advisory Circular 33.70-6 and DARWIN.

A11B.PS.1 Advanced Damage Tolerance (DT) and Risk Assessment Methods for Engine Life-Limited Parts

Model Cold Dwell Fatigue in DARWIN

- Inter Agency Agreement with Air Force Research Lab (AFRL) June 2022
- Driven by Air France Flt 66 and cold dwell fatigue of titanium fan
- Based on a general probabilistic crack growth model developed by AFRL to calculate the Minimum Low Cycle Fatigue Life or “Min-Life”
- Objective is to investigate the use of Min-Life model in DARWIN as a tool for prediction and management of cold dwell fatigue in titanium rotors.
- Funded 50-50 between FAA and AFRL.
- Report with assessment and recommendations due August 2023.

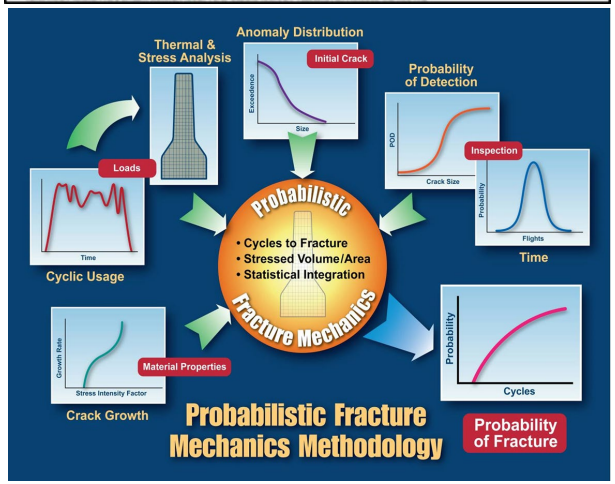
Cold Dwell Fatigue (CDF) Literature Review

- Comprehensive report summarizing all aspects regarding CDF
- Report will be used as a reference document to update AC 33.15-1 “Manufacturing Process of Premium Quality Titanium Alloy Rotating Engine Components”.

A11B.PS.1 Advanced Damage Tolerance (DT) and Risk Assessment Methods for Engine Life-Limited Parts

DARWIN: Design Assessment of Reliability with Inspection

- A probabilistic DT, fracture mechanics-based design life code that determines probability of fracture of rotors and other LLPs
- Developed for FAA by SwRI in cooperation with RISC
- Only commercially available probabilistic DT software
- DARWIN output accepted by FAA to comply with 33.70
- FAA DARWIN funding now leveraged by funds from other government agencies (DOD & NASA) greater than 1:1.
- All government agencies have free use of DARWIN
- DARWIN software licensed by 20 manufacturers (with fees reinvested for general enhancements)
- Future versions will add DT of Ni Anomalies and Ti CDF
- Currently being investigated for Metal Additive Manufacturing (AM) Parts (separate from A11B funding)



A11B.PS.4 Improved Nondestructive Evaluation (NDE) to Prevent Uncontained Engine Failures

Research Project Description

- Reduce the risk of rotor failures by detecting anomalies in nickel (Dirty White Spot) and titanium MTRs (microtextured regions).
- Spurred by Safety Recommendations from the AA Flt 383 HPT failure and the AF Flt 66 fan failure due to anomalies of Ni and Ti, respectively.
- 2 Current Projects:
  - Nickel Billet Inspection (funded)
  - Forging Inspection Round Robin AIA Inspection Team (no FAA funds provided)

Sponsor Anticipated Outcome

- Industry specification for Ni Billet inspection (FY24)
- Issue Policy requiring improved Ni billet inspection referencing the industry specification (similar to Ti).
- Establish POD curves to support the development of the DT framework and advisory circular to address Ni material anomalies (AC 33.70-6).
- Issue Policy on Best Forging Inspection Practices

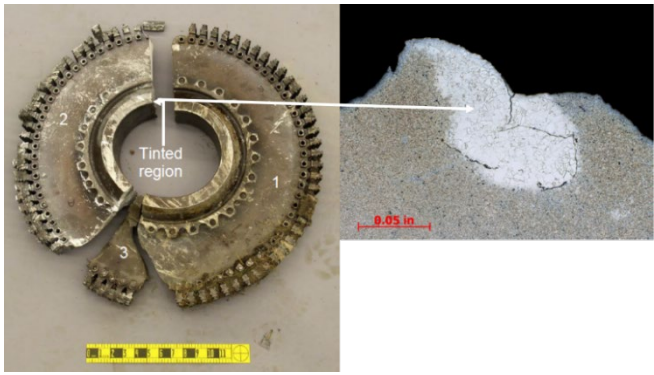
Critical Milestones

- Nickel Billet Inspection
  - Nickel Billet Calibration Standard (09/22)
  - Back-to-Back testing of 75K lbs each of double & triple melt nickel billets with conventional and multi-zone ultrasonic systems and verify results. (FY24)
  - Draft industry specification for Ni Billet inspection (FY24)
- Forging Inspection Round Robin
  - Draft Best Practices Document (12/22)

Research Accomplishments in FY22

- Nickel Billet Inspection
  - All subcontracts in place (03/22)
  - Completed calibration standard design (04/22)
  - Received Alloy 718 for calibration standard (04/22)
  - Fabricate calibration standard (09/22)
- Forging Inspection Round Robin
  - OEM Round Robin Forging Insp. Complete (04/22)

A11B.PS.4 Improved Nondestructive Evaluation (NDE) to Prevent Uncontained Engine Failures

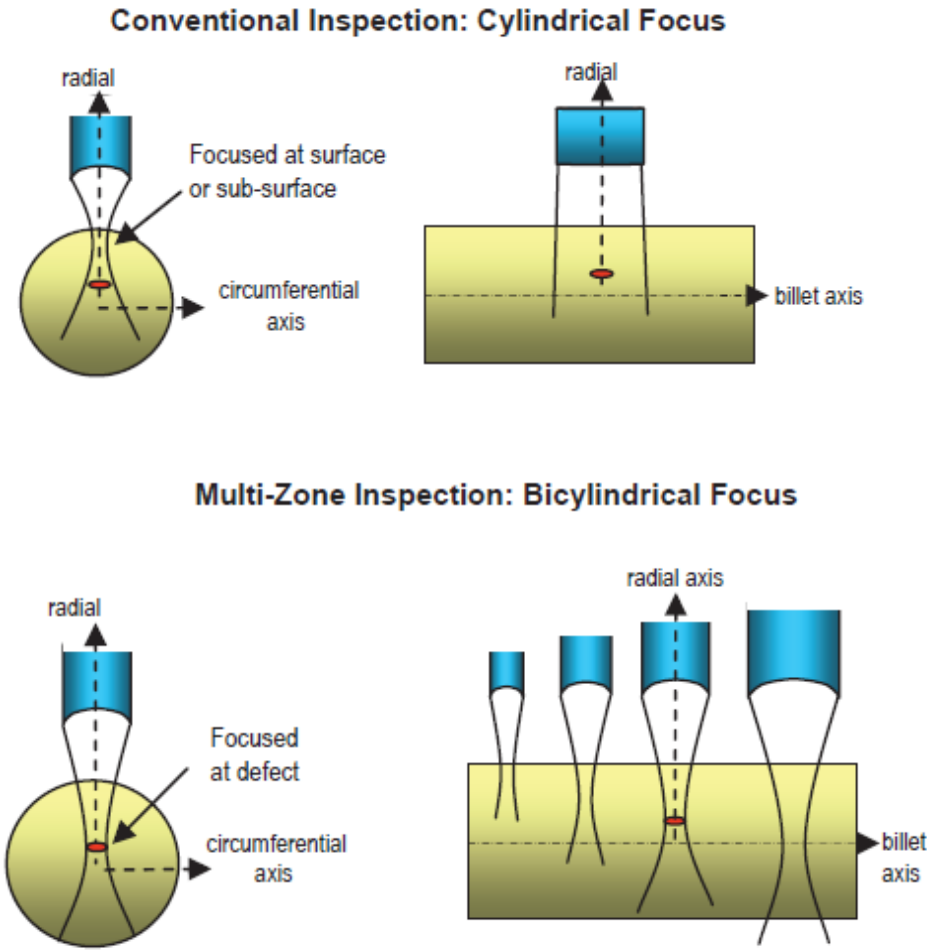


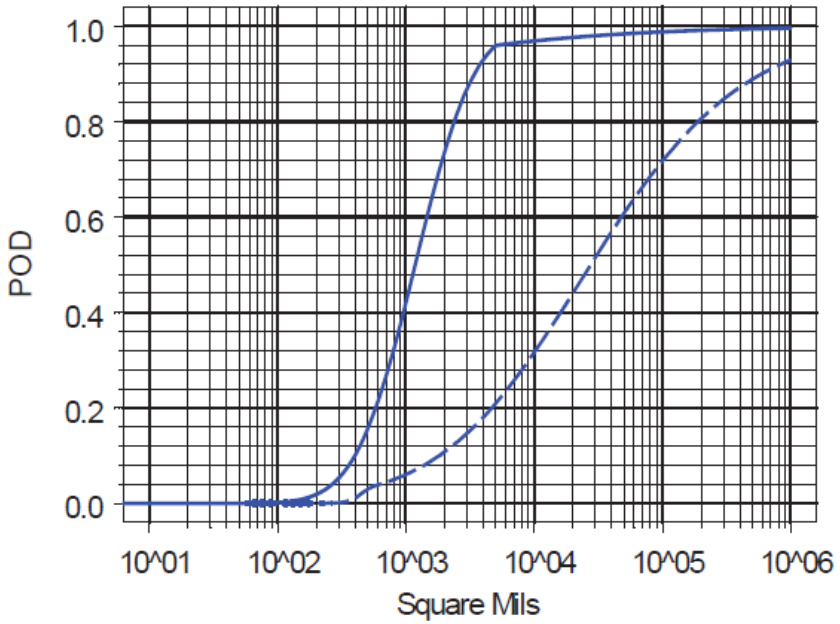
Nickel Billet Inspection

- Driven by 2 NTSB recommendations from the AA 383 event.
  - A-18-3: "…evaluate current and enhanced inspection technologies …for nickel alloys…and issue guidance…"
  - A-18-4: "…require subsurface in-service inspection…for all engines."
- Contract awarded 09/21 with a period of 30 months.
- Billet Inspection Team comprised of SwRI, P&W, GE, RR, and ATI.
- Apply a high sensitivity multizone (MZ) ultrasonic system developed during the FAA's Engine Titanium Consortium (ETC) and compare results to current NDE methods.

- Back-to-back studies will be carried out on 75K lbs each of double melt and triple melt Ni billets to detect anomalies.
- Ultrasonic indications will be sectioned to confirm findings.
- Goal is to develop an industry inspection specification similar to one for titanium billet (SAE AMS 2628B)
- Will work with Ni DT project (PIRATE 3) to share Ni anomalies for mechanical testing.

Ultrasonic Inspection ETC Results Conventional vs Multizone



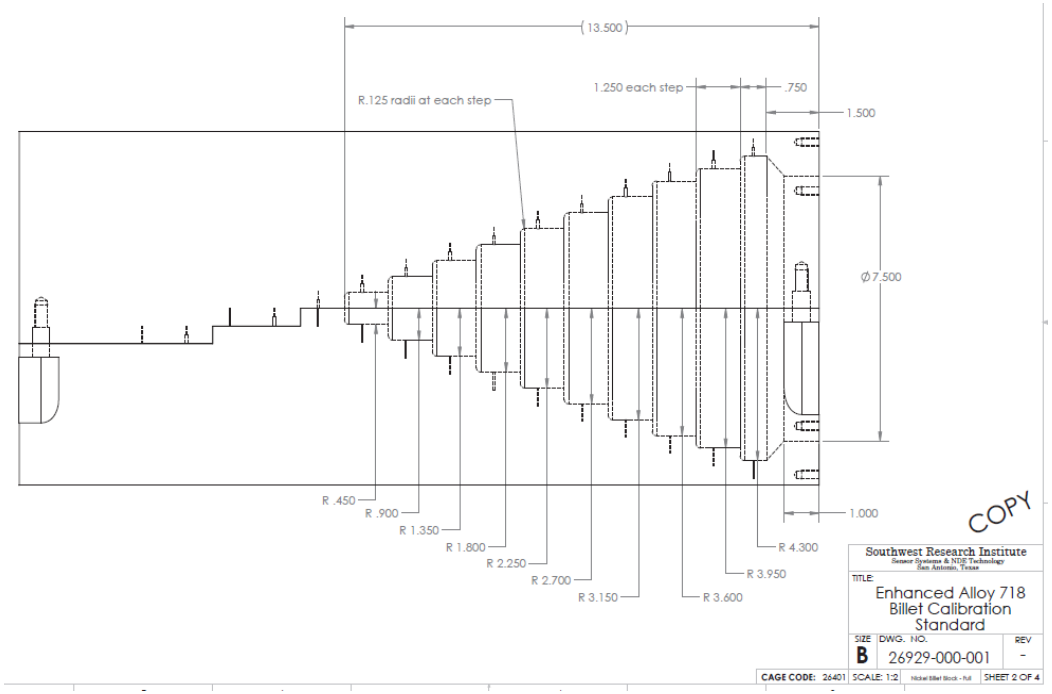


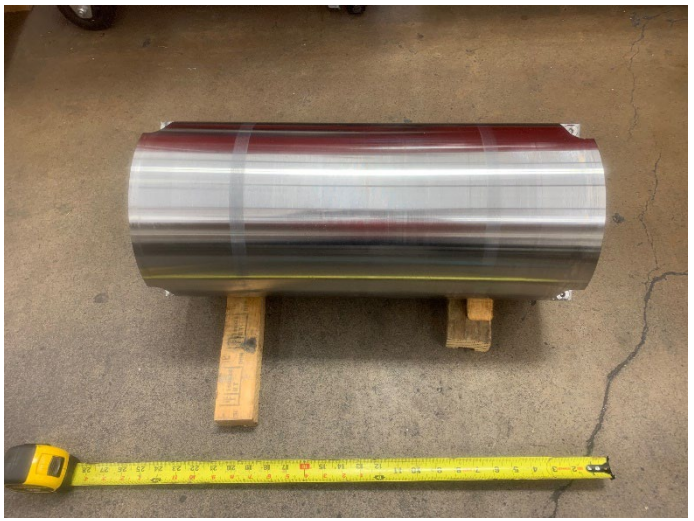
MZ: Reject indications with amplitude equal to or greater than 7/8 of signal from a 2.64 in. diameter FBH or SNR equal to or greater than 2.5

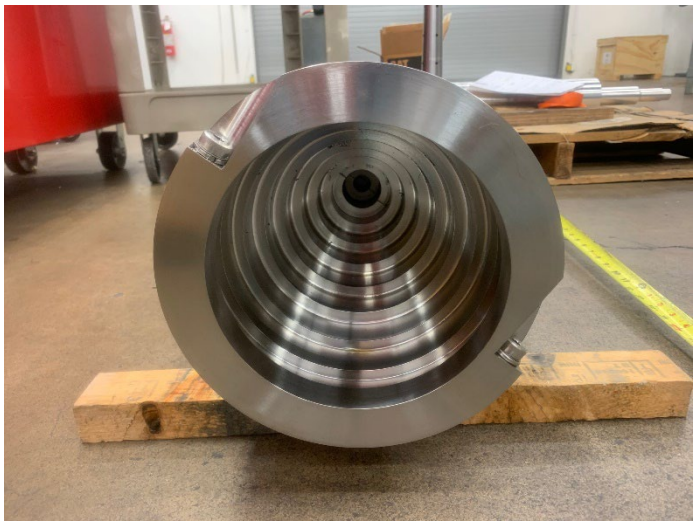
CONV: Reject indications with amplitude greater than or equal to 75% of signal from 3/64 in. diameter FBH

Figure 21. Comparison of Conventional and Multizone PoD Estimates

Nickel Calibration Standard







A11B.PS.4 Improved Nondestructive Evaluation (NDE) to Prevent Uncontained Engine Failures

Cold Dwell Fatigue (CDF)

- 2017 Air France A380 uncontained fan failure caused by CDF of Ti-6-4.
- FAA is working with BEA (French NTSB) to address recommendations on CDF.
- In certain orientations soft Ti grains will creep and shed load on to harder adjacent grains causing a stress riser and crack nucleation at the harder grain boundary.
- Once nucleated, the crack can grow quickly through grains of certain orientations
- The issue is exacerbated in Ti with large microtextured regions (MTRs) which results in larger degrees of load shedding and also larger uninterrupted paths of rapid crack extension - increasing crack growth rate and decreasing fatigue life.
- There is currently no NDE method to inspect for MTRs.
- FY23 plans to form a new IA with the USAF AFRL to leverage their Metal Affordability Initiative (MAI) to better understand CDF and to develop NDE methods to detect MTRs.

Summary

- FAA has a longstanding Rotor Integrity Research Program that has adapted over the years to address new challenges.
- Based on three prong approach to improve design, manufacturing, and inspection of critical parts.
- Unprecedented collaboration with the Turbine Engine Industry.
- Prior work has resulted in Advisory Circulars and DARWIN software to satisfy Rule 33.70 (Engine Life Limited Parts) and improved nondestructive evaluations (NDE).
- Current Focus is on Damage Tolerance and NDE Methods for Nickel Anomalies and Titanium Cold Dwell / Microtextured Regions.

Questions/Comments?

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