

Comparisons and Lessons Learned from UA232 Sioux City and AA383 Chicago Uncontained Events

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Nomenclature:

The notation "UA232" refers to United Airlines Flight 232 which crash landed at the Sioux Gateway, Sioux City, Iowa airport on July 19, 1989. "AA383" refers to American Airlines Flight 383 which conducted an aborted takeoff at Chicago O'Hare airport on October 28, 2016. Reference to the "UA232 disk" refers to the fractured Stage 1 Fan disk and reference to the "AA383 disk" refers to the fractured High-Pressure Turbine Second Stage disk. The UA232 disk was made of a Titanium alloy (Ti-6-4) and the AA383 disk was made of a nickel-based alloy (Inconel 718), both workhorse alloys for the gas turbine engine business.

Background:

On July 19, 1989, a DC-10-10 powered by three CF6-6 engines suffered an uncontained separation of the number 2 (tail) engine Stage 1 Fan disk during cruise which compromised all three aircraft hydraulic systems. The only control that the flight crew had over the aircraft was by modulating the throttles for the number 1 and number 3 wing mounted engines. The DC-10-10 attempted to land at the Sioux Gateway Airport but the right wing dropped at the last moment causing the aircraft to tumble down the runway resulting in the fuselage breaking apart. Of the 296 people on-board, there were 111 fatalities yet 185 survived. The investigation later found that a hard-alpha inclusion in the fan disk forging served as a crack initiation site on the bore surface leading to fatigue propagation ultimately resulting in the disk failure. In addition, it was determined that a liberated disk fragment severed the two back-up hydraulic systems which combined with the #2 engine failure resulted in no available hydraulics to fly the aircraft.

On October 28, 2016, a B767-323 powered by two CF6-80C2B6 engines suffered an uncontained separation of the number 2 (right hand) engine High-Pressure Turbine Second Stage disk during takeoff. A segment of the disk penetrated the right wing severing a fuel line and breaching the wing fuel tank. The flight crew rejected the takeoff and quickly stopped the aircraft on the runway. There was a ground fire on the right-hand side of the aircraft. The passengers and crew exited the left-hand side of the aircraft. The Chicago O'Hare Airport Fire Department responded rapidly and extinguished the fire. All 170 people survived – most with no injuries.

Figure 1 shows two snapshots of the respective events. These events reflect two very different scenarios. UA232 was at altitude (37000 ft) when the initial disk burst occurred. The remainder of this flight was a struggle to maintain control of the aircraft. The AA383 event flight was over in a matter of seconds with an aborted takeoff and

subsequent evacuation. AA383 was fortunate to have the wind blowing in the right direction or it could have been reminiscent of the Manchester UK 1985 accident. A similarity for both UA232 and AA383 is that both events occurred in direct proximity of emergency personnel and equipment which was critical to the post event survival aspects for those on board.

Purpose:

There are many aspects of these two events that could be compared: crew resource management, emergency checklists, evacuation procedures, and disaster preparedness to name a few. This paper will strictly focus on the UA232 and AA383 disks themselves from their original fabrication to actions taken after their respective failures. It is important to note that with these events occurring roughly 27 years apart there are some key differences in the industrial, media, and regulatory environments in which they occurred. In addition, we will discuss the importance of cross-enterprise safety initiatives which are critical to assure lessons learned are applied across the entire business enterprise and industry.

NTSB Investigations:

References 1 and 2 are the respective NTSB accident investigation reports for these events. The scope here is to compare information related to the engines and the relevant disks. Table 1 summarizes the key parameters related to the two event engines. There are several things worth noting:

- 1) The UA232 engine was in for maintenance inspection less than a year before the event. The investigation would conclude that the crack in the disk was of sufficient size that it should have been detected using the fluorescent penetrant inspection (FPI) process.
- 2) Both disks did not reach their respective life limits before failing. The UA232 disk was short by 1101 cycles and the AA383 disk was short by 4016 cycles.
- 3) While rotating component lives are measured in cycles (every takeoff is a cycle) it is interesting to note that in terms of calendar time, the UA232 and AA383 engines had initial installations that went back 17 and 18 years, respectively.

Disk Anomalies:

In both events, nearly all of the fractured pieces of the disks were recovered (Figure 2) and most importantly these pieces included the primary fracture surfaces. Figure 3 shows the fracture surface of each disk and Figure 4 shows the close-up of the fracture areas highlighting their respective “anomalies”.

The UA232 disk developed a crack due to a melt-related hard-alpha inclusion on the bore surface. This inclusion was not detected during manufacture due to its sub-surface nature and likely uncracked and non-voided condition making detection difficult. The AA383 disk developed a crack due to an anomaly called a Discrete Dirty White Spot (DDWS). Like the UA232 disk hard alpha inclusion, this DDWS was not detected during manufacture because it was subsurface and it likely was not cracked or voided.

The UA232 disk was subjected to FPI six times during its service life. It was determined that the crack had broken the surface of the fan disk and should have been detectable at least at the last FPI. The AA383 disk underwent FPI and Eddy Current Inspection (ECI) twice after entering service, inspection techniques used primarily to detect surface cracks. Multiple cracks were observed emanating from the DDWS propagating at various rates with unknown initiation times. Therefore, it could not be determined when the crack broke the surface of the disk bore.

Producing Titanium and Nickel:

UA232 Disk: The titanium used to manufacture the CF6-6 fan disk in the Sioux City event was produced in the early 1970's using the Kroll process. In this process, titanium dioxide, called rutile, is reacted with chlorine to produce titanium chloride. This is reacted with sodium to form titanium and salt. The mixture is mechanically broken down into small pieces and the salt is leached out leaving pure titanium which is often called titanium sponge due to its appearance. The titanium sponge is mixed with alloying elements and compacted into bricks. The bricks are welded together into sticks in an argon atmosphere to prevent the titanium from reacting with oxygen. The sticks are then melted into an ingot in a vacuum oven in a process called Vacuum Arc Remelt (VAR). At the time that the UA232 disk was made, the VAR procedure was then repeated in what is commonly referred to as a Double VAR process.

If the argon atmosphere present during the welding process described above is not pure and there is any oxygen present, then the oxygen may react with the titanium forming hard-alpha. A hard-alpha inclusion in titanium can be a source for the initiation of a fatigue crack in a highly stressed part such as a fan disk. Hard-alpha can be formed during other parts of the manufacturing process, but in this instance, it was believed to have been formed during the welding of the bricks.

The ingot formed after the Double VAR process is then extruded into a billet. The extrusion process works the material and may cause any hard-alpha inclusions to crack or void. Subsurface cracks and voids are detectable during Ultrasonic Inspection (UTI). The billet was subjected to contact UTI where a UTI probe was moved along the surface of the billet. The billet passed this inspection.

The billet was then cut into mults which is short for multiples. The mult for the UA232 disk was then forged and rough machined into a sonic shape which was ready for UTI. The part was then subjected to immersion UTI. In this process the part is immersed in water and the UTI probe is moved around the part but does not contact the surface of the part. Immersion UTI is more sensitive than contact UTI. The UA232 disk passed the immersion UTI.

A macroetch inspection was also performed on the UA232 disk in the sonic shape as opposed to the final machined shape. This inspection highlights microstructural changes or anomalies on the surface. The UA232 disk passed the macroetch inspection. The hard alpha inclusion located on the bore surface would have had a greater chance of being detected if the part was macroetched in the final machined shape.

The part then went through final machining and was inspected using a process called Florescent Penetrant Inspection (FPI). In this inspection, the part is immersed in or wetted with FPI fluid. The fluid is then gently rinsed from the surface of the part. The part is then inspected with ultraviolet light. If there are any surface cracks, the fluid should remain in the cracks and glow under the ultraviolet light. No crack indications were found on the UA232 disk.

Definition: Rutile (rooteel) – The lustrous red, reddish-brown, or black natural mineral form of titanium dioxide, TiO₂, used as a source of titanium.

AA383 Disk: The Inconel 718 alloy used to produce the CF6-80C2 HPT stage 2 disk in the Chicago event was produced in 1997. The Inconel material was made using a triple-melt process consisting of Vacuum Induction Melt (VIM), Electroslag Remelt (ESM), and VAR. In the VIM step of the process, the raw material, consisting of the elemental nickel material, master alloy, revert (scrap or chips from previous melts and processes), and reactive material, is melted in a vacuum furnace and is poured into ingots. The purpose of this step is to produce the desired chemistry and remove impurities. Next these VIM ingots are remelted in the ESR process. In this step of the process, the VIM ingot is lowered into a layer of active/reactive slag. As the VIM ingot melts, the molten droplets sink through the slag removing impurities. The droplets collect into another ingot, the ESR ingot. The purpose of this step is cleanliness of the material. The ESR ingot is remelted again. The process takes place in a vacuum and results in

another ingot – the VAR ingot. The purpose of this step is to establish the desired microstructure and serves to further refine the cleanliness.

The ingot then undergoes a billet conversion process including homogenization and forging. The billet produced from these processes is subjected to immersion UTI. The Chicago event billet passed this inspection.

The billet was then cut into mults. The mult for the Chicago HPT disk was then forged, heat treated, and machined into a sonic shape. The part then underwent immersion UTI which it passed. After that the HPT disk went through final machining and processing. It was then inspected using an FPI process which it passed.

Manufacturing Processes:

Both the Titanium and Inconel processes were considered state-of-the-art at the time that the parts were manufactured. The Titanium alloy was manufactured using a double VAR process. The industry had since determined that the triple VAR process produced parts that were much less likely to have inclusions such as hard-alpha than the those produced using the double VAR process. As shown in Figure 5, the rates of hard alpha inclusions and high-density inclusions improved dramatically from the early 1990s to the early 2000s "... driven by incorporating prior lessons learned and continuing to pay great attention to detail in the manufacture of Premium Quality (PQ) Ti used in critical rotating aircraft engine applications." (5) Since then, the industry has moved to a cold hearth melt + VAR process which has proven to be much better than even triple VAR as shown in Figure 6. It should be noted that double VAR is still in use by some manufacturers in relatively low stress applications.

Prior to the 1980s, Inconel was produced using the double-melt VIM + VAR process. The industry developed the ESR process which greatly improved cleanliness of the material. Around the time of the Sioux City event, GE Aviation converted to the triple-melt VIM + ESR + VAR process for all Inconel critical rotating parts. This process produced high quality parts. In fact, the AA383 event was the first time that a critical rotating nickel part had failed across the industry. The triple-melt nickel process was refined, and lessons learned were incorporated so that the inclusion rate improved even though the basic triple-melt process did not change. It should be noted that the inclusion rate for Inconel is much higher than for Titanium, however, Inconel is also more inspectable and more tolerant to anomalies than Titanium. This is in part due to differences in crack initiation and growth rates.

Inspection Processes:

Both the UA232 disk and the AA383 disk were subjected to UTI and FPI during the manufacturing process. Both were also subjected to FPI and/or Eddy Current Inspections (ECI) after entering service. The UTI process can detect cracks and voids that are subsurface. FPI can detect cracks on the surface and ECI can detect surface and near-surface cracks and voids. The Probability of Detection (PoD) for each process is less than of 100%. UTI depends on the orientation of the crack or void relative to the ultrasonic wave. Contact UTI is affected by part geometry, cleanliness, and the couplant used. Following the UA232 event, Multi-zone UTI was introduced which allowed inspections of much higher sensitivity. Phased array and circ-shear UTI are later methods which also improve the PoD.

For FPI there are many factors that can affect the PoD including the length and tightness of the crack at the surface which affects the amount of FPI fluid retained, the aggressiveness of the rinsing process, surface cleanliness, and the ability of the inspector to get a clear view of the surface due to factors such as part geometry, lighting, and inspector fatigue (human factors). Also, macroetch (ME) is often used following some manufacturing processes. ME is a chemical treatment of a metal surface to accentuate structural details and anomalies for visual observation. For Titanium, GE Aviation uses a process called Blue Etch Anodize (BEA) which, like ME, accentuates differences on the surface of the part for visual detection of anomalies. FPI, ECI, ME, and BEA inspections are effective at detecting surface or near-surface cracks and voids. UTI inspections are effective in detecting subsurface cracks and voids.

Table 2 summarizes the key parameters related to the event disks in terms of the forging and inspection processes used. Figure 7 is a schematic showing the various Titanium and Inconel melt processes and high-level manufacturing and inspection steps and their rough timing of implementation.

NTSB Recommendations:

Table 3 shows a side by side of recommendations from the two NTSB accident investigation reports (1)(2). Both events had many more recommendations than shown but the ones shown provide some interesting talking points:

- 1) Both events generate a recommendation that effectively request an evaluation of the state-of-the-art inspection techniques and whether they can be enhanced.
- 2) Both events spawn a recommendation to revise Advisory Circular 20-128(A) "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure".
- 3) The UA232 report recommends creating a historical database of rotary part failures that can be used in design assessments and safety analysis. This could be considered a precursor to the initiative to create AC39-8 "Continued Airworthiness Assessment Methodology" released in 2003. This guidance provides the historically based hazard potential for powerplant components and systems.

Discussion:

At the time of UA232, to capture a video of a commercial aviation accident was unprecedented. By the time of AA383, the airport tower has complete footage of the event and passengers disembarking were taking videos of the aftermath. Newspapers told the story of UA232, the internet captured the images of AA383.

In an evolving aviation system, technological advances and product enhancements are always being made. The 17 year span of the UA232 engine has as its backdrop the worst US aviation accident (AA FL191, crash of a DC-10 after takeoff out of Chicago O'Hare, May 25, 1979) as well as a string of other major events in the US throughout the 70's and 80's. Key improvements during this timeframe include Ground Proximity Warning Systems, the advent of Crew Resource Management (a key success factor in the UA232 event), and wind shear systems and detection training. Contrast this to the AA383 engine which throughout its 18 years in service there were only two major US domestic airliner events: AA FL587, an Airbus A300, in Queens NY, the second worst US aviation disaster in 2001 and the 2009 Colgan Air FL3407, a Bombardier Dash 8 that crashed on approach to Buffalo NY. Aviation safety within the US National Airspace System (NAS) has improved to a level that there has only been a single fatality on a US domestic airliner since the Colgan Air event just over 10 years ago.

The manufacturing processes for both Inconel and Titanium have seen improvements but the focus by industry on Titanium after UA232 has resulted in a process that minimizes hard alpha inclusions to a level unimagined in 1971 when the UA232 disk was first forged. This success was driven by a collaborative approach of industry and regulatory agencies. In the wake of UA232, nine FAA / Industry teams focused on the recommendations the NTSB made as part of the investigation. Of note are the Jet Engine Titanium Quality Committee (JETQC) and the Aerospace Industries of America (AIA) Rotor Integrity Subcommittee (RISC). Inconel has also improved but its higher tolerance to inclusions, crack initiation and growth rate made it a lower risk priority than the Titanium activities. As of November 7, 2018, the FAA has sent a request to the AIA to consider addressing the NTSB recommendations by chartering the longstanding and ongoing JETQC and RISC teams to apply their lessons learned from titanium to nickel alloys. These teams have indicated that they will support the effort.

Safety Management System (SMS):

In 2010, the International Civil Aviation Organization (ICAO) released Annex 19 which defines the Safety Management System (SMS) framework. As of March 2018, all US domestic airlines are required to have a SMS (14 CFR Part 5). In December of 2018, GE Aviation was the first OEM in the US to receive FAA acceptance of their SMS, an SMS that was in place since January 2013. Within GE's SMS, one of the key learnings as it evolves is to assure that lessons learned on one program are communicated to other programs. A formal process driving this cross-program review was implemented in mid-2017. As more operators and OEM's move towards SMS implementation and have internal lessons learned the question should be asked, what forum assures sharing of these respective findings on an industry, regulatory, global stage?

Summary / Conclusions:

This paper has reviewed the UA232 and AA383 accidents from an engine perspective. Key similarities include:

- 1) Initiation of both events was the crack propagation of a disk defect to the point of disk fracture.
- 2) The disk failures subsequently impacted aircraft systems. For UA232, the hydraulics system and for AA383 a puncture of the right-wing fuel tank.
- 3) Both disks fractured before their designated life limit.
- 4) Production and operational inspections did not find the defects / cracks.
- 5) The introduction of the anomalies in the disks was during the forging process.
- 6) Recommendations from both accidents are similar regarding engine rotating part processing and inspection – they need to be improved / enhanced.

Several differences are worth noting:

- 1) UA232 was a fatal accident with 111 fatalities, AA383 had 21 injuries (1 serious, 20 minor).
- 2) The AA383 event was the first time that a critical rotating nickel part had failed across the industry. Hard alpha issues with Titanium disks had occurred multiple times prior to UA232.

Post UA232, the industry / regulatory collaboration in activities related to understanding, improving, and enhancing Titanium forging and inspection processes is the model for addressing complex issues. However, the comparison here does show that it is critical that lessons learned in one part of our industry need a forum to communicate learnings in support of SMS activities.

References:

- 1) Aircraft Accident Report "United Airlines Flight 232, McDonnell-Douglas DC-10-10, Sioux Gateway Airport, Sioux City, Iowa, July 19, 1989"; National Transportation Safety Board, PB90-910406
- 2) Aircraft Accident Report "Uncontained Engine Failure and Subsequent Fire, American Airlines Flight 383, Boeing 767-323, N345AN, Chicago, Illinois, October 28, 2016"; National Transportation Safety Board, PB2018-100344
- 3) Flight 232: A Story of Disaster and Survival, Laurence Gonzales, W.W. Norton & Co, New York, 2014
- 4) "What Did We Know? What Did We Do About It? Making Decisions in Large Organizations", Fred Herzner, Smart Business Network, 2017
- 5) "Aerospace Titanium Alloy Melt Process Quality Improvements", Andrew Woodfield and Gérard Lemaitre, 14th World Conference on Titanium, Nantes (France), 2019, in press
- 6) Powerplant Group Chairman's Factual Report (AA383); NTSB DCA17FA021



United Airlines Flight 232
Sioux Gateway Airport, Sioux City, Iowa
July 19, 1989



American Airlines Flight 383
Chicago O'Hare Field
October 28, 2016

Figure 1: Event Images

Item	UA232	AA383	Comments
Engine Type	CF6-6	CF6-80C2B6	
Engine Serial Number	451-243	690-373	
Time Since New (hrs)	42436	68785	
Cycles Since New	16899	10984	Fan Life Limit 18000 cycles, HPT S2 Life Limit 15000 cycles
Time Since Last Disk Inspection (hrs)	2170	19139	
Cycles Since Last Disk Inspection	760	3057	
Time Since Last Shop Visit (hrs)	2170	8998	Reliability Improvement Program (RIP) SV for AA383, HPT module not disassembled, HPT S2 disk not inspected
Cycles Since Last Shop Visit	760	1451	RIP SV for AA383, HPT module not disassembled, HPT S2 disk not inspected
Installation Date (initial)	6/23/1972	4/30/1998	
Installation Date (final position)	10/25/1988	12/4/2013	

Table 1: Comparison of Event Engine Parameters



Recovered fragments of the Stage 1 Fan Disk from UA232

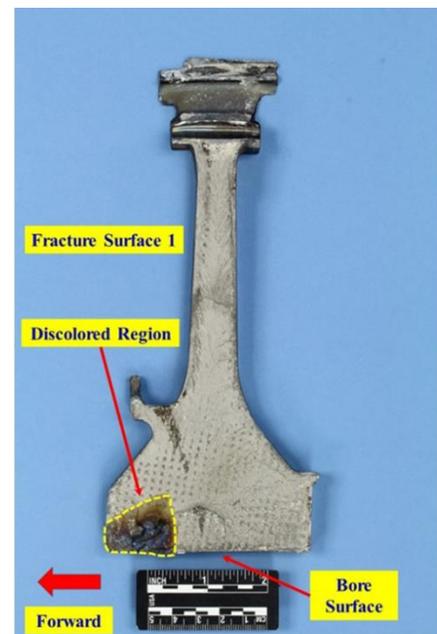


Recovered fragments of the High Pressure Turbine Stage 2 Disk from AA383

Figure 2: Disk side-by-side comparison

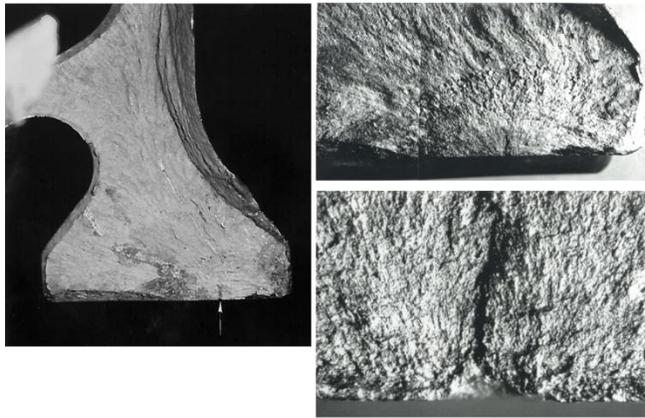


Failure Surface of the Stage 1 Fan Disk from UA232

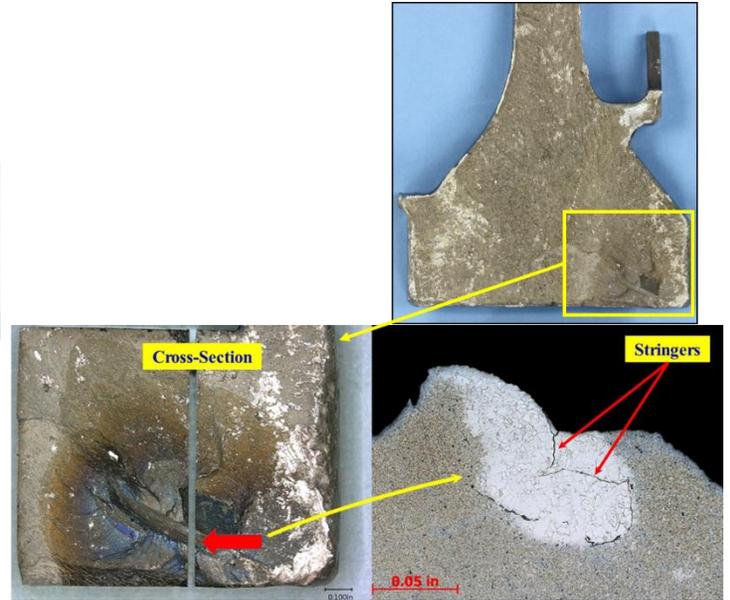


Failure Surface of the High Pressure Turbine Stage 2 Disk from AA383

Figure 3: Failure Surface Comparison



Anomaly area of the Stage 1 Fan Disk from UA232



Anomaly area of the High Pressure Turbine Stage 2 Disk from AA383

Figure 4: "Anomaly" Comparison

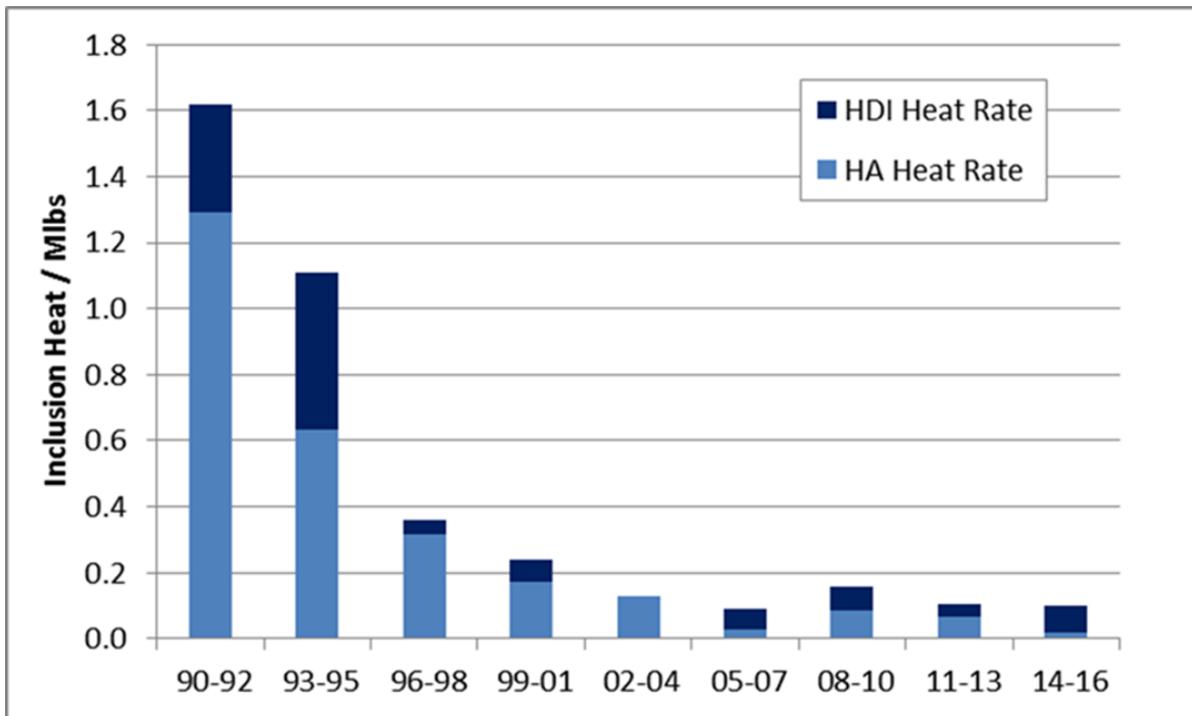


Figure 5: Hard-alpha and high-density inclusion rates from 1990 through 2016 in Premium Quality Ti (5)

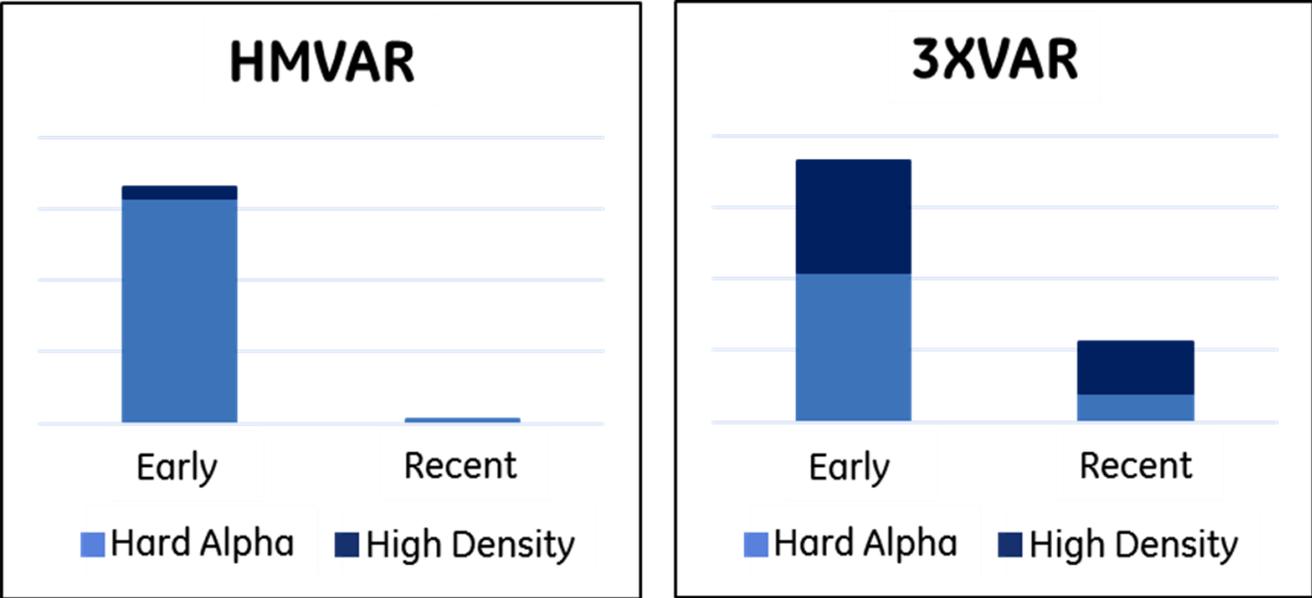


Figure 6: Premium Quality Ti hard-alpha and high-density inclusion rates for HMVAR and Triple-VAR (5)

Item	UA232 Fan Disk	AA383 HPTS2 Disk	Comments
Alloy	Ti-6Al-4V	Inconel 718 (Wrought Nickel Base)	
Final Production Inspection Technique(s)	Immersive ultrasonic, Macro-etch, FPI	Immersive ultrasonic (prior to final machining), FPI	
Forging House	ALCOA / TIMET	ATI Specialty Materials	Histories of the UA232 disk forgings are not straightforward. Details can be found in the NTSB Accident Report.
Melt Date	2/23/1971	6/17/1997	
Melting Process	Double Melt (vacuum arc remelt x 2)	Triple Melt (vacuum induction melt, electroslag remelt, and vacuum arc remelt)	UA232 event disk was part of last heat that used Double melt, subsequent GE specs required Triple Melt
Billet Inspection(s)	Contact ultrasonic	Longitudinal wave water immersion, pulse-echo ultrasonic inspection	

Table 2: Comparison of Disk Forging / Inspection Parameters

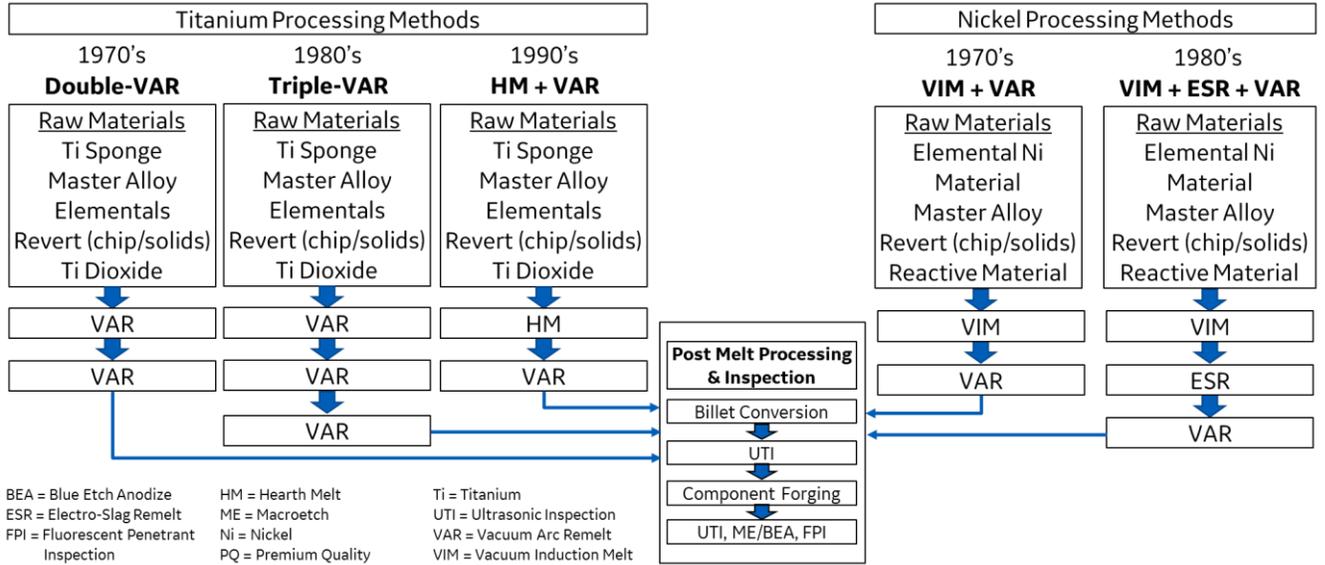


Figure 7: Side-by-side Premium Quality Ti & Ni Processing

UA232	AA383
<p>Intensify research in the nondestructive inspection field to identify emerging technologies that can serve to simplify automate, or otherwise improve the reliability of the inspection process. Such research "should encourage the development and implementation of redundant ("second set of eyes") inspection oversight for critical part inspections such as for engine rotating components. (Class II, Priority Action) (A-90-167) <i>Note that this recommendation was sent to the FAA and a similar one was sent to AIA.</i></p>	<p>Establish and lead an industry group that evaluates current and enhanced inspection technologies regarding their appropriateness and effectiveness for applications using nickel alloys, and use the results of this evaluation to issue guidance pertaining to the inspection process for nickel alloy rotating engine components. (A-18-3)</p> <p>Require subsurface in-service inspection techniques, such as ultrasonic inspections, for critical high-energy, life-limited rotating parts for all engines. (A-18-4)</p>
<p>Analyze the dispersion pattern, fragment size and energy level of released engine rotating parts from the July 19, 1989, Sioux City, Iowa, DC-10 accident and include the results of this analysis, and any other peripheral data available, in a revision of AC 20-128 for future aircraft certification. (Class II, Priority Action) (A-90-170)</p>	<p>Revise Advisory Circular (AC) 20-128A, "Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliary Power Unit Rotor Failure," based on an analysis of uncontained engine failure data since the time that the AC was issued, to minimize hazards to an airplane and its occupants if an uncontained engine failure were to occur. The revised AC should include modifications to the accepted design precautions for fuel tanks given the fires that have occurred after uncontained engine failures. (A-18-5)</p>
<p>Create the mechanism to support a historical data base of worldwide engine rotary part failures to facilitate design assessments and comparative safety analysis during certification reviews and other FAA research. (Class II, Priority Action) (A-90-172)</p> <p><i>Note that this recommendation can be considered a catalyst for AC39-8 Continued Airworthiness Assessment Methodology released in 2003</i></p>	

Table 3: Comparison of NTSB Recommendations (Abbreviated and Emphasis Added)