Aerospace Titanium Alloy Melt Process Quality Improvements

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Abstract

This Jet Engine Titanium Quality Committee (JETQC) paper describes industry quality improvements since 1990. Quality refers to freedom from melt-related hard-alpha and high-density inclusions (HDI). JETQC, formed under the auspices of the U.S. Federal Aviation Administration (FAA) following the Sioux City aircraft accident in 1989, is comprised of U.S., E.U. and Japanese aircraft engine manufacturers to address the quality of premium / rotor quality titanium alloy production. Titanium suppliers provide melt-related inclusion data. JETQC focuses on hard-alpha and HDI inclusion rates in premium quality (PQ) titanium alloy products for critical rotating aircraft engine applications. PQ materials typically are produced via triple vacuum arc re-melt (3XVAR) or hearth melt VAR (HMVAR) processes, but more recently, the Skull plus VAR (SVAR) process has been introduced. Hard-alpha rates have continued to decline over the last decade primarily for the HMVAR process. HDI rates declined in the early 90's, but more recently the overall rate has stayed approximately constant with inclusions confined to the 3XVAR process. Combining the trends for both hard-alpha and HDIs, the HMVAR process has demonstrated in recent years to be higher quality compared with the 3XVAR process.

Introduction

The JETQC (Jet Engine Titanium Quality Committee) was formed under the auspices of the FAA (Federal Aviation Administration) in 1990 following the United Airlines DC10 crash at Sioux City that resulted in the loss of more than 100 lives [1]. The origin of the accident was traced back to the presence of a melt-related inclusion in the fan disk of the tail-mounted engine that cracked, ultimately leading to the separation of the disk and the subsequent crash landing. The primary purpose of

JETQC is to track and monitor the PQ (Premium Quality) titanium alloy mill product and components used in jet engines powering commercial aircraft. The PQ titanium billet and bar materials are used to manufacture critical rotating parts such as disks, blisks or integrally bladed rotors, shafts, airfoils, etc. A secondary purpose of JETQC is to undertake proactive measures designed ultimately to lead to lower overall inclusion rates in PQ titanium alloy products.

JETQC Membership

JETQC membership has historically included (i) the PQ titanium suppliers, currently including ATI, Arconic-RTI, PCC-TIMET, and VSMPO, (ii) the jet engine manufacturers, currently including GE Aviation, Honeywell International, MTU, Pratt and Whitney (US and Canada), Rolls-Royce (UK and US), Safran (aircraft engines and helicopter engines) and Williams International, and (iii) the FAA. Several years ago, JETQC recognized the impending global expansion of both PQ Ti suppliers and engine manufacturers and instituted a qualification process for the incorporation of new PQ Ti suppliers and engine manufacturers into JETQC. At the end of 2018, IHI Corporation was added to JETQC membership and there are currently PQ Ti melters that are in active qualification.

JETQC Reporting

Every quarter the PQ Ti suppliers provide production volumes by melt method, by alloy to JETQC together with any inclusion finds in mill products. In the event an inclusion is found during inspection, a detailed characterization is performed including both size and composition. The size information, together with the inspection information has been provided since 1990 to the Rotor Integrity Steering Committee (RISC) that has used the information to develop probabilistic lifing methods that have been adopted by the engine manufacturers [2]. The composition information has been used by the PQ Ti suppliers to understand the likely root cause(s) for the inclusion and implement corrective actions within their raw material supply chain and their melt shop designed to eliminate any re-occurrence. Over the years, inclusion evaluations by the suppliers have substantially improved, allowing root cause(s) confidence to be significantly improved. In addition to inclusions reported by the suppliers, the engine manufacturers also report inclusion finds in components, with similar characterization in terms of size and composition.

JETQC collates the annual PQ Ti volume and inclusion statistics from mill products (suppliers) and components (engine manufacturers) and provides an anonymous industry summary back to the suppliers. This annual summary allows the suppliers to understand how they stack-up relative to the overall industry, but crucially does not divulge supplier-specific process proprietary information. Additionally, over the last approximately 10 years, the annual summary has included proposed inclusion root cause(s) and the assessed confidence in the root cause(s). This has enabled suppliers to better understand potential inclusion risks. This reporting approach also provides an early warning system that enables both engine manufacturers and suppliers alike to understand if there are new (or old) threats that are present and require additional monitoring and/or action.

Melt Related Inclusions

Quality as defined within JETQC relates to the incidence of melt-related inclusions in the ingot used to manufacture billet and bar, and subsequently the critical rotating parts. These inclusions include (i) Hard-alpha, also known as Type I or low-density inclusions that have elevated levels of interstitial elements oxygen, nitrogen and/or carbon, (ii) high-density inclusions that are enriched in dense metals such as tungsten, tantalum, molybdenum, etc., and (iii) Type II inclusions that are enriched in Al. Figure 1 illustrates each of these three types of inclusion.

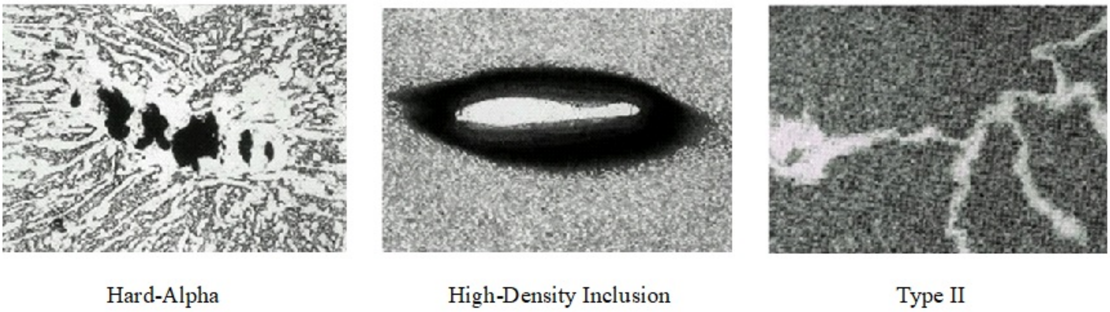

Figure 1: Optical micrographs of hard-alpha, high-density and Type II inclusions

Inclusion Formation and Impact

Hard-alpha inclusions

These inclusions typically form because of contamination of raw materials or exposure of hot titanium to the presence of air or water. The presence of nitrogen in an inclusion results in a significant increase in melting point and slow dissolution kinetics in molten Ti. The presence of nitrogen, oxygen and/or carbon in the inclusion results in a hard, brittle phase that may crack during hot working of the ingot and component and/or crack during service. [3]. Hard-alpha inclusions have historically been associated with the most serious consequences including the Sioux City accident, and there have been multiple other instances of component failures over the decades initiating from this type of inclusions.

Type II inclusions

These inclusions typically are associated with ingot shrinkage cavities near the ingot top with local aluminum evaporation into the gas-free cavities and re-deposition onto the cavity wall during high temperature exposure related to ingot casting and subsequent high temperature working operations. One component failure was attributed to the presence of a Type II inclusion in 1970 [1], but since then, the PQ titanium alloy industry has effectively dealt with this threat.

HDI inclusions

These inclusions typically are a result of contaminants in raw materials and/or process equipment and survive during melting due to (i) limited residence time in the molten pool due to their high density resulting in their falling to the mushy zone during casting, and (ii) high melting point resulting in relatively slow dissolution in the molten pool. There are no known component failures associated with this type of inclusion, however, they can cause significant production disruption.

Premium Quality Process Routes

At the time of the Sioux City accident, the typical melt route for PQ Ti material was the triple vacuum arc re-melt (3XVAR) process. This process starts with an electrode that may be formed by (i) pressing raw materials into compacts that are welded together in a chamber, (ii) welding bulk re-cycled materials together, or (iii) consolidation melted. This electrode is then consumed during vacuum arc melting in a cooled copper crucible. The melted electrode is then vacuum arc re-melted a second and a third time to produce an ingot that is free from significant chemical segregation with desirably no melt inclusions. The primary purpose of the first melt is to produce a solid ingot without any volatile residuals, such as magnesium chloride, that are associated with the Ti sponge. The second and third melts are designed to provide additional residence time for dissolution of any inclusions and to provide a final ingot with a minimum of chemical segregation from top-to-bottom and from center-to-outside diameter.

It was recognized that the 3XVAR process was not fully capable of removing hard-alpha and high-density inclusions due to the limited residence time in the molten titanium, so the industry investigated alternate methods to produce PQ Ti materials. This led to the development of cold hearth melting routes using either electron beam or plasma arc melting with the hearth being water-cooled copper. The electron beam melting method is conducted under vacuum and tends to evaporate volatile alloy elements, such as aluminum. The plasma arc melting method is performed under inert gas and tends to absorb some of the inert gas. Both routes use a final VAR melt to provide uniform chemistry in the case of electron beam and remove any absorbed inert gas in the case of plasma arc. The primary quality benefits of the cold hearth process are (i) molten metal flows horizontally across the hearth and so any high-density inclusions will fall to the bottom of the hearth, whereas in the in-line 3XVAR process, any high- density inclusions will fall rapidly to the bottom and potentially survive into the final ingot, (ii) low density inclusions will float on the surface and be subject to direct impingement of the electron beam or plasma arc, resulting increased probability that inclusion dissolution will occur, and (iii) increased overall residence time of up to an order of magnitude over 3XVAR allowing for a higher probability that inclusion dissolution will occur. Additionally, the cold hearth melt processes potentially have a greater flexibility of raw material forms that can be used, enabling improved economics. The hearth melt plus vacuum arc re-melt (HMVAR) process was introduced around the time of the Sioux City accident [4], and over the ensuing 30 years has become the predominant PQ melt method as discussed below. One of the key reasons for the success of the PQ HMVAR process is that seeded heat trials are conducted during qualification and validate that the hearth melt process is extremely robust and eliminates all inclusions of all types that are intentionally seeded into the input materials. These process parameters that result in complete inclusion elimination are then used for production. There is no equivalent process demonstration for the 3XVAR process.

More recently, an alternate melt method has been introduced by one supplier that uses a water-cooled skull and arc melting to produce a large quantity of molten Ti alloy and then after a pre-determined time, the furnace is tilted and the molten Ti alloy is poured into a mold. Due to the solidification conditions, a large center-line shrinkage pipe is formed along a significant proportion of the ingot requiring a subsequent VAR melt to reduce [5].

Figure 2 shows schematically the three PQ Ti melt routes described above and includes the subsequent high-level manufacturing steps to convert an ingot into an engine component. Multiple inspections are performed at different points in the process to validate that the finished component is inclusion-free. The mill product is ultrasonically inspected, the forging is ultrasonically inspected and macroetched. A key improvement in ultrasonic inspection for both mill product and forging occurred following the Sioux City accident with the introduction of zoned ultrasonic inspections that enabled a much higher sensitivity inspection to be performed. This initially resulted in an increase in mill product inclusion finds, but the industry quickly identified the root causes of the inclusions and implemented the appropriate corrective actions. More recently, phased array ultrasonic inspections have also been introduced.

The FAA has issued AC33-15.1 that captures the high-level lessons learned regarding melting, processing and inspections related to the production of PQ Ti parts [6].

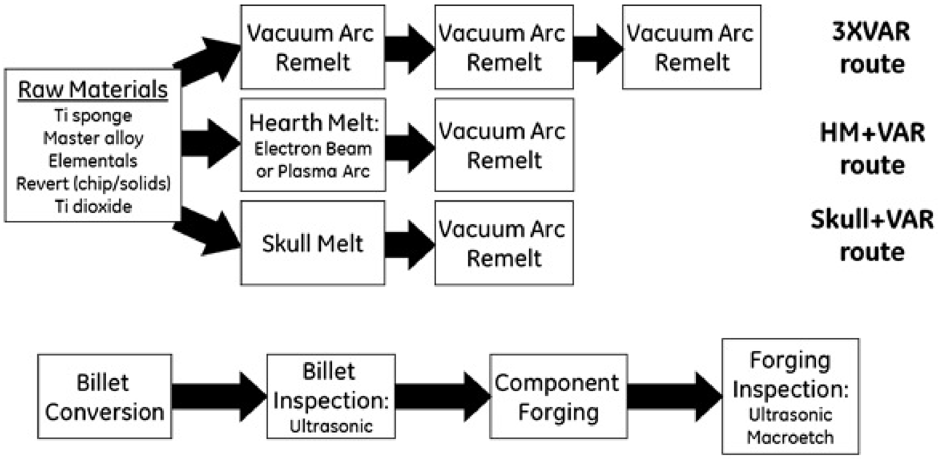

Figure 2: PQ Ti process map illustrating the three current Ti alloy melt process

Results

JETQC has published the hard-alpha inclusion statistics at two prior World Titanium Conferences [7, 8]. The initial hard-alpha inclusion heat rate was more than 1 per million pounds of PQ Ti material produced in the aftermath of the Sioux City accident when the industry data was first collected. JETQC uses inclusion heat rates to measure overall inclusion rates since it is possible that an inclusion that is present during melting may (i) remain as a single entity, or (ii) disintegrate into multiple fragments either during melting or billet conversion. The use of inclusion heat rate eliminates this issue, providing that in the case of multiple inclusions in a heat they are confirmed to be of the same type and chemistry and therefore likely originating from the same root cause. Reference [8] showed that the hard-alpha inclusion rate in the 2002-2005 timeframe had decreased by an order of magnitude to approximately 1 in 10 million pounds of PQ Ti material. This reference also described the many raw material and process improvements that were responsible for the more than an order of magnitude improvement in hard-alpha inclusion heat rate. At a very high level, these improvements included (i) use of vacuum distilled sponge, (ii) increased controls surrounding all raw materials, (iii) more robust melt processing methods related to electrode preparation, melting, etc., and (iv) attention to melt shop house-keeping to avoid contaminant pick-up onto in-process electrodes and contaminant drop-in into melt furnaces.

This paper now updates the hard-alpha inclusion statistics up to 2016 and in addition provides a summary for HDI inclusion statistics. This paper also addresses at a high level for the first time the difference between 3XVAR and HMVAR inclusion statistics since it has become clear that there is a significant difference in quality between the two processes.

Updated hard-alpha inclusion heat statistics

Figure 3 shows the updated hard-alpha inclusion heat statistics in 3-year increments and it shows that since the last report which covered through the end of 2005, there has been a further reduction to approaching 1 hard-alpha heat per 50 million pounds of PQ Ti material over the last three reported years (2014-2016). This represents a continued outstanding performance by the Ti suppliers, driven by incorporating prior lessons learned and continuing to pay great attention to detail in the manufacture of PQ Ti used in critical rotating aircraft engine applications.

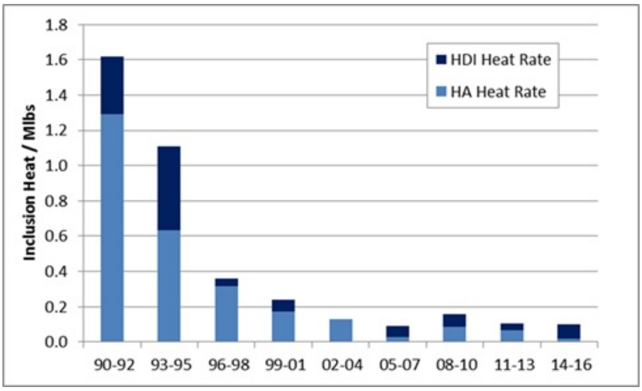

Figure 3: Hard-alpha and high-density inclusion rates since 1990

HDI heat statistics

Figure 3 also shows for the first time the high-density inclusion heat statistics in 3-year increments. The data show the initial rate was on the order of about 0.4 HDI heat per million pounds of PQ Ti through the mid-nineties and then declined to less than 0.1 HDI heat per million pounds of PQ Ti through 2016. The primary reason for this reduction is attributed to the significant increase in controls over raw materials and melt process equipment repair. Unlike the hard-alpha inclusion heat rate data shown in Figure 3, the HDI inclusion heat rate data do not show a continued decline over the last approximately 10 years. This is largely been attributed to the presence of small, molybdenum-rich inclusions that have been detected in molybdenum-bearing alloys such as Ti-6246, Ti-6242 and Ti-17 as zoned ultrasonic billet inspection was adopted across the industry.

Inclusion statistics by melt route

Figure 4 shows for the first time the split between hard-alpha and HDI inclusion heat rates in billet produced by 3XVAR and HMVAR. The absolute inclusion rates are not shown in Figure 4 to protect supplier proprietary information; however, the figure is informative as it shows an approximately similar overall inclusion rate in the early years between production of HMVAR and 3XVAR material. In the early years, the hard-alpha inclusion heat rate is clearly higher for HMVAR material, while the HDI inclusion rate is clearly higher for 3XVAR material. As described earlier, HMVAR was introduced for several reasons, including density separation that would allow HDIs to sink to the bottom of the hearth. Figure 4 in the early years clearly bears this anticipated benefit out. Based on the longer residence time in the hearth, it was also expected that the hard-alpha inclusion heat rate should have been lower in HMVAR compared to 3XVAR but Figure 4 does not bear this out. It is believed that this is due to a combination of (i) methods used to condition the HM electrode surface prior to the VAR melt step (i.e. post-hearth melt), and (ii) adoption of zoned billet inspections that were adopted predominantly in HMVAR materials in the early production years.

Figure 4 shows in recent years that there has been a dramatic shift in billet inclusion rates, particularly for HMVAR, with a total elimination of HDI heats, and close to zero hard-alpha inclusion heats representing about a 50X rate reduction. For 3XVAR, there has been a smaller, approximately 3X reduction in inclusion heats with both hard-alpha and HDI inclusion heats remaining. The total billet volumes represented in recent years in Figure 4 is approximately 100 million pounds for both HMVAR and 3XVAR.

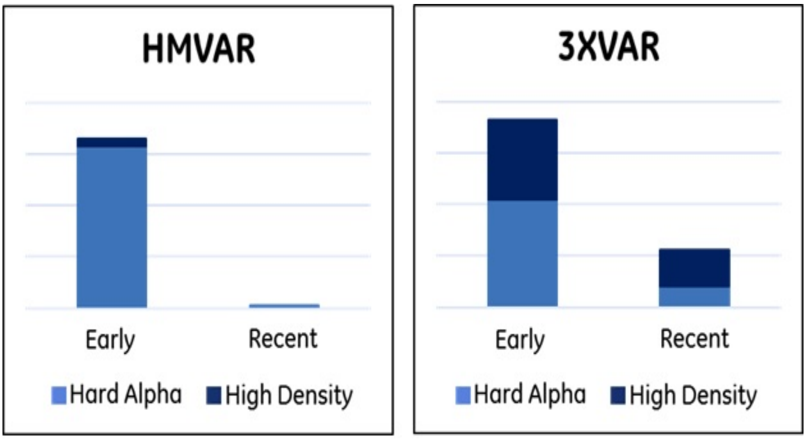

Figure 4: Hard-alpha and high-density inclusion rates for HMVAR and 3XVAR

Conclusions

Several conclusions can be drawn from this work:

1. JETQC membership has expanded and is expected to continue to expand.

2. The entire PQ Ti industry has focused on the threat of melt-related inclusions to improve air travel safety and through co-operative efforts with the FAA, the suppliers and the OEMs has resulted in a significant reduction in risk.

3. HMVAR melt process has been demonstrated to be extremely robust and has consistently delivered the highest level of PQ Ti quality to the industry. The statistics support that the final VAR melt step has been well-controlled.

Acknowledgements

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