U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: Manufacturing Process of Premium Quality Titanium Alloy Rotating Engine Components

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This advisory circular (AC) provides guidance and information for compliance with the provisions under title 14, Code of Federal Regulations (14 CFR), part 33 on the materials suitability and durability requirements of § 33.15, as applicable to the manufacture of titanium alloy high energy rotating parts of aircraft engines.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback Form at the end of this AC.

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1 **PURPOSE.**

This AC provides guidance and information for compliance with the provisions under Title 14, Code of Federal Regulations (14 CFR), part 33 on the materials suitability and durability requirements of § 33.15, as applicable to the manufacture of titanium alloy high energy rotating parts (life limited parts) of aircraft engines.

2 **APPLICABILITY.**

2.1 The guidance provided in this AC is for engine manufacturers, modifiers, foreign regulatory authorities, and Federal Aviation Administration (FAA) engine type certification engineers and their designees.

2.2 This is a guidance document. Its content is not legally binding in its own right and will not be relied upon by the Department as a separate basis for affirmative enforcement action or other administrative penalty. Conformity with the guidance document is voluntary only. Nonconformity will not affect rights and obligations under existing statutes and regulations.

2.3 This material does not change, create any additional, authorize changes in, or permit deviations from existing regulatory requirements.

3 **CANCELLATION.**

This AC cancels AC 33.15-1, *Manufacturing Process of Premium Quality Titanium Alloy Rotating Engine Components*, dated September 22, 1998.

4 **RELATED MATERIAL.**

The following materials are referenced in this document. You should use the latest approved edition which may be dated after the date of this AC as referenced materials are updated.

4.1 **Title 14, Code of Federal Regulations (CFRs).**

The following regulations are related to this AC. You can download the full text of these regulations from the Federal Register website at www.ecfr.gov.

- Section 33.15, *Materials.*
- Section 33.27, *Turbine, compressor, fan, and turbosupercharger rotor overspeed.*
- Section 33.64, *Pressurized engine static parts.*
- Section 33.70, *Engine life-limited parts*.

4.2 **FAA Advisory Circulars.**

The following ACs are related to the guidance in this AC. You should refer to the latest AC version for guidance, which is available on the DRS at https://drs.faa.gov.

- AC 21-43A, *Production Under 14 CFR Part 21, Subparts F, G, K, and O*, dated October 1, 2015.
- AC 21-9B, *Manufacturers Reporting Failures, Malfunctions, or Defects*, dated August 12, 2010.
- AC 33-2C, *General Type Certification Guidelines for Turbine Engines,* dated June 25, 2013.
- AC 33.15-2, *Manufacturing Processes for Premium Quality Nickel Alloy for Engine Rotating Parts,* dated March 22, 2017.
- AC 33.70-1, *Guidance Material for Aircraft Engine Life-Limited Parts Requirements*, dated May 31, 2017.

4.3 **Industry Documents.**

The following industry document is related to the guidance in this AC. You can obtain the document from SAE online at http://www.sae.org.

Terminology for Titanium Microstructures, SAE International Aerospace Standard, SAE AS1814, SAE International.

4.4 **Additional References.**

Appendix A contains additional references. These references provide further information and data used in the development of this AC. Specifically, the first reference of A5 was sponsored by the FAA, published in 2024, and provides a comprehensive review of the cold dwell fatigue (CDF) literature in addition to engine manufacturers field, rig and test specimen CDF experience. The critical topics covered in the appendix include:

- Uncontained engine failures related to melt anomalies,
- Improvements leading to reductions in melt anomaly rates,
- Improvements in melting controls,
- Uncontained engine failures related to CDF,
- Relationship between microtextured regions (MTRs) and CDF,
- MTR quantification,
- Titanium billet conversion processing,
- Relationship between hot working and MTR formation/minimization, and strain induced porosity,
- Alloy chemistry effects on MTRs and CDF,
- Temperature effects on CDF, and
- Relationship between MTRs and ultrasonic response.

5 DEFINITIONS.

The following definitions apply to this AC.

- Anomaly. Unusual material conditions or microstructural features that include voids, cracks, inclusions, segregation, abusive machining, etc.
- Bar. Converted material having a cross section less than or equal to 16 square inches (103 cm^2), and a width less than five times the thickness.
- Beta Fleck. A region denuded in primary alpha in alpha plus beta processed titanium alloys.
- Beta Transus. The temperature at which, under equilibrium conditions, close-packed hexagonal alpha phase starts to form on cooling a titanium alloy from the high temperature body-centered cubic phase. Beta transus temperature depends on the titanium alloy composition with some elements increasing it (for example, aluminum and oxygen), and others decreasing it (for example, molybdenum and iron). In an ingot, there may be chemical segregation on a local scale and on a macroscale leading to differences in beta transus temperature within the ingot. In addition, there may be differences in chemistry associated with different types of input materials for a given alloy, resulting in a variation in the precise beta transus temperature and the rate of alpha formation as a function of temperature. As a result, it is important to have a practical beta transus temperature definition (determination) that also accounts for the rate of alpha formation as a function of temperature since processing temperatures for billet conversion, component forging, and post-forge heat treatments can often be tied to a temperature relative to the beta transus.
- Billet. Converted material having a constant round cross section greater than 16 square inches (103 cm^2).
- Bottom Charge. The material placed in the vacuum arc remelting (VAR) crucible to protect the crucible during arc initiation.
- Cold Dwell Fatigue (CDF). The imposition of a hold-time at high stress, which may reduce component fatigue life at low temperatures, below approximately 400°F/200°C. The presence of (i) MTRs formed during alpha/beta billet conversion and modified during component alpha/beta forging and heat treatment or (ii) colonies formed during cooling after final component beta forging or beta heat treatment both of which may adversely impact component and test specimen fatigue lives associated with dwell cycles at maximum stress. Component and test specimen lives may be reduced by more than an order of magnitude depending on alloy class, applied stress, stress-state, stressed volume, remaining bulk residual tensile stress, temperature, hold-time and MTR or colony characteristics.
- Cold Hearth Melting (CHM). A process (i.e., electron beam melting (EBM) or plasma arc melting (PAM)) where the metal is melted and then maintained molten as it traverses a specified hearth distance, allowing inclusion elimination either by dissolution in the molten pool, or by density separation into the skull.
- Colony. An alpha colony (or simply colony) is a microstructural assemblage consisting of alternating lamellae of alpha and beta phase formed during cooling

from above the beta transus. The alpha phase lamellae within each colony are morphologically aligned and share a common crystallographic orientation. The formation of the lamellar alpha is a result of precipitation with a specific orientation relationship to the parent beta phase and preferred growth along certain crystallographic directions. This means there is an inherited crystallographic orientation from the prior beta grain. Because dislocations can easily traverse alpha/beta interfaces in colony microstructures alpha colonies can act as a single unit with respect to CDF. As such, the size of these features should be controlled if a direct beta-transformed structure is utilized in a final product. Colony structures are also the precursor to MTRs in alpha/beta processed billet and forgings. The alpha lamellae are globularized into equiaxed alpha grains through hot-working and heat treatment. However, the crystallographic orientation of the grains may not change significantly. This could result in a cluster of similarly oriented alpha grains replacing what was previously an alpha colony. The impact of a colony on CDF in a final component may be greater than an identically sized MTR due to the common crystallographic orientation within the colony compared to the spread of crystallographic orientations within an MTR (MTR Intensity).

- Electrode. The consumable feedstock form for vacuum arc remelting (VAR) or the product of the primary EBM, PAM, or Skull that becomes the consumable electrode for the final VAR.
- Electrode Holder. The material that is joined to the top of the electrode, or the electrode stub, to hold the electrode and to provide the connection between the electrode and the VAR furnace electrical equipment.
- Electrode Marker. A titanium rod or other shape affixed to the consumable electrode, electrode stub, or electrode holder for VAR. The purpose of this marker is to provide visual reference for the electrode height position.
- Electrode Stub. The material that may be joined to the top of the electrode to provide the connection between the electrode and the electrode holder.
- Electron Beam Melting (EBM). The melting process using electron beams performed in a cold hearth that may be used in conjunction with VAR to meet the primary melting recommendations of this document.
- Established Procedure. A procedure that is subject to purchaser approval and is contained in a controlled document. It is also called a fixed process. It includes limits, controls, and applicable standards.
- Grain Flow. The general metal flow pattern within a billet, bar or forging as revealed by macroetching. This pattern is a result of the cumulative strain imparted on the material and the path over which that strain is imposed. The strain and strain path impact the size, shape, and internal structure of MTRs. The strain also impacts the specific macrotexture components that form during thermomechanical processing.
- Heat. The ingot and ingot product produced from the final VAR of a single consumable electrode (in the case of the multiple VAR process), or the ingot and

ingot product produced from one VAR of a single EBM, PAM, or Skull consumable electrode.

- High Aluminum Defect (HAD). An aluminum-rich alpha stabilized region containing an abnormally large amount of aluminum which may extend across a large number of beta grains (also known as Type II anomalies).
- High Density Inclusion (HDI). A region with a high concentration of refractory elements, usually tungsten, molybdenum, or columbium, having a higher density than the matrix.
- High Interstitial Defect (HID). An interstitially stabilized alpha phase region of substantially higher hardness than surrounding material, arising from very high local nitrogen, oxygen, and carbon concentrations which increase the beta transus and produce the high hardness, often brittle, alpha phase. Also commonly called a Type I inclusion, low-density inclusion (LDI), or a hard alpha these features are often associated with voids and cracks. It is worth noting that Type I TiN inclusions may actually have a density higher than that of the titanium alloy.
- Hot Topping. Adjustments of process parameters during the latter stages of a melt process to minimize pipe, shrinkage porosity, and segregation.
- Inclusions. Particles of impurities or foreign materials that are present or introduced during any stage of alloy processing. Examples include, but are not necessarily limited to HADs, HDIs, and HIDs.
- Jet Engine Titanium Quality Committee (JETQC). JETQC was formed in 1990 under the auspices of the FAA, with initial membership including all the US and European Aircraft Engine Producers before subsequently growing to include a Japanese Aircraft engine producer. The purpose of JETQC was rapid dissemination to its members of titanium alloy melt related anomaly issues and data. JETQC also includes raw material suppliers that produce premium quality titanium alloy material for the JETQC engine producers.
- Macroetch. Chemical treatment of a metal surface to accentuate structural details and anomalies for visual observation.
- Macrotexture. The presence of grains with preferred crystallographic orientations within a material traditionally represented by a pole figure showing the intensity distribution of a specific crystallographic plane normal with respect to sample axes. In contrast to microtexture, macrotexture does not imply anything about the spatial arrangement or clustering of the preferred orientations and occurs on a much larger length scale. The length scale of macrotexture may encompass the complete volume or cross-sectional area of a mill product or final component, or may vary across the cross section of a mill product or component. Because titanium alloys undergo an allotropic phase transformation during cooling, macrotexture is comprised of both deformation and transformation texture components. Deformation texture components are formed in the beta phase and alpha phase (if working at temperatures below the beta transus) during forming operations like rolling, extrusion, and forging. In this case, the change in crystal orientation may be due to

dislocation motion or rigid body rotations. Crystals rotate in response to the imposed strain-path toward orientations that flow most easily and maximize the plastic work. Upon cooling, the beta phase undergoes an allotropic phase transformation and the alpha formed by this decomposition constitutes the transformation texture. The macrotexture may be further modified by solution heat treatment, which, depending on temperature, will change the fraction and strength of the deformation and transformation texture components present. Other restoration processes like recovery, recrystallization, and grain growth may further alter the specific orientations present.

- Microtexture Region (MTR). A localized region in an alpha/beta converted billet or an alpha/beta processed component forging where neighboring alpha grains and secondary alpha platelets have similar crystal orientations such that the feature may act as a larger structural unit during deformation or crack growth. MTR size, shape, density, intensity, frequency, orientation, orientation spread, neighboring region characteristics, volume fraction, and primary alpha volume fraction, are important parameters when characterizing MTR features. These features are known to impact CDF capabilities. MTRs are also sometimes referred to as "macrozones" or "primary alpha colonies." MTR regions were identified once electron backscatter diffraction (EBSD) methods were developed which allowed correlation of specific microstructural features with their underlying crystallographic orientation.
- MTR Density. A measure of the area fraction of the alpha grains in an MTR that have a similar basal (0001) plane orientation. This factor includes contributions from both primary alpha and secondary alpha platelets.
- MTR Frequency. The number of MTR features within a volume of titanium.
- MTR Intensity. A measure of the range of variation of crystallographic orientations of all the alpha grains within an MTR that includes weighted contributions from the fraction of well-aligned alpha grains as well as the fraction of not well-aligned grains. The weighting of contributions are a function of alignment and area (or volume) fraction. Low MTR orientation spread with high MTR density would be referred to as an intense MTR. A material having intense MTRs does not imply anything regarding the macrotexture, i.e., the macrotexture could be weak or strong in a material having intense MTRs.
- MTR Neighboring Regions. The region surrounding MTR features. These could include MTR features of different character or regions of substantially randomly oriented alpha (average orientation regions). The neighborhood surrounding MTR features are critical to the potency of MTR's impact on CDF.
- MTR Orientation. The dominant crystallographic orientation of the alpha grains within an MTR region. MTRs with the basal plane oriented nearly perpendicular to the principal stress direction are classified as "Hard MTRs." Combinations of other orientations that enable easy basal or prismatic slip relative to a stress axis are classified as "Soft MTRs." Both "hard" and "soft" MTRs influence CDF performance of titanium materials. The "soft" regions accumulate significant creep strain during the dwell portion of a cycle while the "hard" regions are potent crack

nucleation sites that then offer very limited resistance to crack propagation. EBSD or similar methods are needed to assess crystallographic orientations in an MTR.

- MTR Orientation Spread. A measure of the average crystallographic misorientations of the similarly aligned alpha phase grains within an MTR.
- MTR Quantification. Methods to quantify MTR size, shape, density, intensity, frequency, orientation, orientation spread, neighboring region characteristics, volume fraction, and primary alpha volume fraction, are important parameters when characterizing MTR features. This characterization requires a means of discerning and measuring alpha grain orientations.
- MTR Shape. The general geometric morphology of a contiguous area of similar alpha grain orientations, which may be expressed as the aspect ratio of longest and shortest dimensions, or the ratio of the axes of an ellipse fit to the MTR in 2D cross-section.
- MTR Size. The size of a contiguous area of similar alpha grain orientations plus all other grains internal to this region often expressed as an area or equivalent diameter in 2D cross-section.
- MTR Volume Fraction. The summed volume (or area) of all MTR features, including all grains internal to the MTRs, divided by the total volume (or area) of titanium investigated.
- Non-Consumable Electrode Melting. A method of consolidating and melting titanium and its alloys using arc energy from an electrode designed to carry the melting current without being consumed. It may be a continuous or batch process and may, or may not, fully melt the input materials. It should not be considered a primary or a complete melt step, therefore the term “consolidation melt” is used.
- Non-contiguous MTR Size. The size of a region of similar alpha phase orientations that are not necessarily in direct contact with one another plus all other grains internal to this region.
- Plasma Arc Melting (PAM). A melting process using plasma torches performed in a cold hearth that may be used in conjunction with VAR to meet the primary melting recommendations of this document.
- Plate. Material converted by hot working and delivered as straight lengths of constant rectangular cross section, having a width greater than five times the thickness.
- Premium Quality (PQ). Material produced under special process and quality control requirements and used primarily for engine life-limited (critical) rotating parts. It should be noted that both within the engine industry and airframe industry, premium quality material is also produced for critical non-rotating parts. The requirements related to static premium quality material for these critical non-rotating parts may be different and are not specifically addressed in this document.
- Primary Alpha. Alpha grains that are a result of primary and secondary sub-beta transus working, and which are not transformed during final solution heat treatment.

These grains can be spherical or elongated and can have a crystallographic orientation similar to neighboring alpha grains. The volume fraction of these grains influences mechanical properties, including CDF.

- Primary Alpha Volume Fraction. The summed volume (or area) of all primary alpha grains divided by the total volume (or area) of titanium investigated.
- Production Approval Holder (PAH). The holder of a production certificate (PC), parts manufacturer approval, or technical standard order authorization who controls the design and quality of a product or article(s). A person who has been issued a production approval by the FAA.
- Residual Stress. Stresses that are contained within the volume of a component. These internal stresses can be created through thermomechanical processing, during quenching (e.g., quenching from solution heat treatment), joining, localized mechanical deformation (e.g., hole expansion), machining, or from surface processing (e.g. shot peening). Residual stresses are important to control. Final evaluation of life limited components should consider all manufacturing methods to which the material is exposed.
- Segregation. Volumes in the alloy product containing an abnormal content of alloying elements, which may also appear as zones of abnormal quantities of either the alpha or beta phases of titanium.
- Skull. The solidified metal in the hearth of the CHM process. During CHM, the skull is the solidified layer of metal adjacent to the hearth, not including the molten pool.
- Skull Melting. The skull melting process, used as the primary melt process, where material in the form of revert solids and chips along with virgin material is melted, under vacuum, in a water-cooled hearth prior to being tilted and poured into a mold. Heat is provided for the melt by an arc initiated between the charge material in the hearth and a consumable electrode. The solidified remnant material remaining in the hearth after pouring is used as the consumable electrode for the subsequent melt.
- Sonic Shape. The sonic shape is the intermediate machined rectilinear or curvilinear forging shape at which the forging may be ultrasonically inspected. Shape and envelope relative to the finished component should be controlled.
- Sponge. The form of titanium or zirconium metal extracted or produced from the natural minerals containing $FeTiO_3$ (Ilmenite), TiO_2 (Titanium dioxide), or ZrO_2 (Zirconium dioxide), respectively.
- Sponge Batch. The metal product of a single titanium or zirconium sponge reactor process.
- Sponge Lot. The mixed or blended sponge product containing portions of one or more sponge batches.
- Stressed Volume. The volume within a component which is at or above a specified level of stress. This is an important parameter relative to probabilistic lifing and

volumetrically distributed life-limiting features, such as MTRs and melt-related anomalies.

- Supplier. Any person, including a firm, corporation, company, government entity, etc., that provides a product, article, or service, at any tier in the supply chain, that is used or consumed in the design or manufacture of, or installed on, a product or article.
- Turnings. Metal chips produced as a result of being removed by machining titanium alloy disk or billet material.
- Vacuum Arc Remelting (VAR). The VAR process used to produce ingots meeting the recommendations of this document, either as a final melt subsequent to CHM, skull melt or as multiple VAR product.
- Void (Clean). A cavity constituting a structural discontinuity related to solidification and conversion conditions of the ingot without any associated contamination.

Note: Other microstructure terms used in this document are consistent with those found in *Terminology for Titanium Microstructures - Aerospace Standards (AS) 1814*.

6 BACKGROUND.

6.1 The manufacture of titanium alloy forged rotating components can introduce component life limiting anomalies at all stages of material processing, from sponge processing, through melting, billet conversion, component forging/heat treatment, joining and machining. Appropriate, robust manufacturing process controls, in addition to inspection methods, can enable detection and elimination of these anomalies. Since optimum capability to detect these anomalies may vary according to their type and source in the manufacturing process, the manufacturing process should be established so that, at each stage, appropriate controls and inspections are in place to minimize the occurrence of and to maximize detection of such anomalies based on the best available technologies.

6.2 The traditional melting process for titanium alloys has been the VAR process. Triple VAR was previously recommended as a standard for critical rotating component use. Improvements in VAR technology have resulted in a significant reduction in the occurrence of melt related inclusions since the mid-1980s. The newer CHM technology greatly reduces the risk of having HDIs surviving through the melting cycle. Cold hearth melting technology involves a CHM cycle (either PAM or EBM) followed by a final VAR cycle and has become another standard for premium quality titanium. A well-controlled CHM Plus VAR process has demonstrated the capability of reducing HID and HDI rates compared with a well-controlled triple VAR process. The presence of the hearth melt in a well-controlled CHM Plus VAR process allows a significantly longer residence time during CHM, enabling inclusions to dissolve and HDIs to density-separate compared with a well-controlled VAR process.

The manufacturing process used to produce titanium alloy forged rotating components may result in the presence of MTRs in the final part. Depending on the alloy, operating stress, stress-state, stressed volume, remaining bulk residual tensile stress, operating temperature, hold-time, etc., the presence of MTRs might result in reduced component life. The manufacturing process should be established so that, at each stage, appropriate controls are in place to minimize the severity of the MTRs. A significant amount of research has been performed related to MTRs and CDF (refer to appendix A, paragraph 5(1)), but much has yet to be learned. Initial directional guidance related to billet conversion and component forging is provided in Section 10, but it is recognized that this guidance may change as more research is conducted.

6.3 AC 21-43A, *Production Under 14 CFR Part 21, Subparts F, G, K, and O*, provides a means to obtain and maintain production approvals. However, these documents do not fully cover the manufacturing processes used in the manufacture of premium quality titanium alloy forged rotating components for type-certificated turbine engines. This AC, therefore, provides supplemental guidance for the establishment of manufacturing processes, in-process material and component inspections, and finished component inspections, for manufacture of premium quality titanium alloy forged rotating components, such as disks, spacers, hubs, shafts, spools and impellers.

6.4 AC 21-9B, *Manufacturers Reporting Failures, Malfunctions, or Defects*, details the requirements for reporting failures, malfunctions, and defects of products and articles. These requirements apply to a holder of a type certificate (TC), amended type certificate, supplemental type certificate, parts manufacturer approval, or technical standard order authorization, or the licensee of a TC.

7 GENERAL.

7.1 Part 21 requires that PAHs must establish and maintain, as appropriate, manufacturing and process control and inspection systems which ensure that products used in type certificated engines conform to FAA-approved design data.

7.2 PAHs should also assure, through appropriate agreements with their suppliers, that effective process control documents are developed, identifying significant process control points, parameters and control limits. Measurement of these process control parameters should be made at the control points; consideration should be given to use the statistical process control.

7.3 A method of approval for changes to the process control documents, and the means of handling exceedances of any defined control limits, should be established between the PAH and the suppliers. Process operations where inclusions could be formed or entrapped, or segregation generated, or porosity induced, or MTRs formed or altered should be particularly detailed for control, monitoring, and detection.

7.4 Records of material and component inspection and disposition results, property test results, traceability of forged components to billet location, material heat, and to raw material ingredient lots making up the heat, as well as other records indicated in this

AC, should be maintained for the appropriate period of time, per §21.137(k), and be available for review as needed.

7.5 New melters, raw material suppliers, and their processes should be adequately qualified.

7.6 A system of handling deviations and non-conformances with respect to product or part limits should be established between the PAH and the suppliers.

8 RAW MATERIALS AND STORAGE.

8.1 Raw Material Requirements.

8.1.1 Raw Material Controls.

Melt suppliers should maintain effective specifications and procedures for procurement, storage, and processing of charge materials for VAR, CHM or skull melting. Raw material suppliers should maintain effective production controls and inspect material on a sampling plan sufficient to assure compliance with the melt supplier raw material requirements. Melt suppliers should additionally inspect/verify conformance to requirements and ensure that raw material suppliers (and any sub-tiers of the raw material suppliers) exercise effective diligence to ensure the absence of inclusions/extraneous material in the raw materials and associated processing equipment, that might persist into the final product based on the production route.

8.1.1.1 **Charge Composition**.

The charge materials should be composed of only approved raw materials, such as sponge, master alloys, elemental additions, titanium oxide, and recycled material (where permitted). The weight percent, chemical composition, and batch or lot number of each type of raw material used in the charge materials should be recorded and maintained for each heat of the material. Charge materials containing alloy elements should be added in a form that allows complete dissolution and homogenization following melting.

8.1.1.2 **Titanium Sponge**.

Titanium sponge suppliers should have established procedures and limits for the production of high purity premium quality titanium sponge. A representative sample of each sponge lot should be visually inspected to established standards to ensure its freedom from burned particles capable of causing HIDs, and from other contaminants. Sponge particles removed during this inspection should be evaluated to determine if the entire sponge lot should be subject to disqualification. The titanium sponge supplier should establish specific acceptance standards, including chemical analysis of suspect sponge particles. Sponge batches or lots that have been involved in a fire at any stage of their processing should not be considered for premium quality rotor application.

8.1.1.3 **Zirconium Sponge**.

Zirconium sponge suppliers should have established procedures and limits for the production of high purity zirconium sponges. Each zirconium sponge lot should have a representative sample visually inspected to compare to established standards to identify and remove particles suspected of containing either burned sponge or other contaminants considered to cause HIDs. Suspect particles from this inspection should be removed and evaluated to determine if the entire sponge lot should be subject to disqualification. The zirconium sponge supplier should establish specific acceptance standards, including chemical analysis of suspect sponge particles. Any zirconium sponge batch and lot which has been involved in a fire after inspection should not be considered for premium quality rotor application.

8.1.1.4 **Master Alloys**.

Master alloy suppliers should have established procedures and limits for the production of high purity master alloys. Master alloys should be inspected to established standards to identify and remove detrimental foreign material, oxides, nitrides, and other contaminants considered to cause HIDs or other deleterious inclusions.

8.1.1.5 **Elemental Additions**.

Elemental additions should be processed to preclude contaminants considered to cause HIDs or other deleterious inclusions.

8.1.1.6 **Titanium Oxide**.

Oxides of titanium used as raw material charge should be in powder form and be processed to preclude the presence of detrimental foreign material.

8.1.1.7 **Recycled Material**.

All recycled materials should be cleaned and be free from contamination. The following limitations should be considered when recycling previously melted alloy:

- **Multiple VAR Processed Material**.

  In general, only turnings should be permitted to be directly recycled in multiple VAR processed premium quality titanium alloy. When used as recycled material, turnings should be segregated as to alloy, crushed, and cleaned, and should be 100 percent radiographically inspected for particles considered to cause HDIs and the particles removed. Bulk weldables should be prohibited for use in multiple VAR processed material, except when previously melted (consolidated) by an approved CHM process. The restrictions on use of bulk weldables in such a CHM or skull consolidation melt should follow the limitations set forth in the following paragraph which applies to material that has been PAM or EBM melted as the primary melting operation.

- **CHM or Skull Plus VAR**.

  Previously melted materials may be recycled through the primary CHM or skull melting process, provided the material is clean, free of scale and slag. Recycled material should be of the same alloy, or compatible alloy composition. Preparation and cleaning procedures should be established for each form of recycled material. Each form of recycled material should be cleaned and inspected to established standards. A radiographic inspection may be considered unnecessary for turnings. Material forms with surface connected internal cavities, exfoliations and other features that prevent complete visual inspection, should not be recycled. Recycling of grinding products, dust, and sludge should be prohibited. Recycling of material that has been involved in fire at any stage of charge material preparation should be prohibited. Flame-cut materials may be used in CHM or Skull Plus VAR processed material provided that the affected areas are cleaned and inspected.

8.2 **Bottom Charge Materials**.

If a bottom charge is used for VAR, the composition, form, preparation, and inspection procedures should be established. Sponge should not be used as the bottom charge.

8.3 **Raw Material Storage**.

Procedures to prevent damage and deterioration of each product and article during handling, storage, preservation, and packaging should ensure all virgin raw material, turnings and bottom charges are stored in covered containers, in a secure area, immediately after inspection to preclude the extraneous addition of foreign or uninspected material.

9 CONSOLIDATION AND MELTING.

This section details some of the more significant process parameters, controls and procedures recommended in the areas of input material consolidation and ingot melting for the production of premium quality titanium. These items should be viewed as guidelines which, when incorporated into the suppliers' specific method of manufacture, should result in a well-controlled process that minimizes HDI and HID occurrence, and produce sound ingots with acceptable homogeneity.

9.1 **Consolidation**.

Fixed blending and consolidation practices should be established by the supplier and approved by the PAH. Proper preparation, blending, and consolidation practices not only minimize HID and HDI introduction sources, but can also assist in the elimination of HIDs from sponge type input materials.

9.1.1 Multiple VAR Process.

Double or triple VAR processes typically use blended input materials consolidated either by compaction and welding, or by consolidation melting.

9.1.1.1 **Blending**.

The supplier should establish procedures for selecting and preparing the input materials with respect to size and shape. Blending practices should demonstrate acceptable chemical homogeneity in the final ingot product. Procedures should also be established to preclude excessive deblending during handling and compaction prior to the first melt. Caution and inspection, as required, should be applied to preclude fires from material crushing, handling and blending, and to exclude any material exposed to such a fire.

9.1.1.2 **Compaction**.

Procedures should be established for compacting the input materials in a form that facilitates the supplier's consolidation practice. Compact size and shape, and compaction pressure, should be a fixed practice. Caution and inspection, as required, should be applied to assure no local fires are created during compaction, and to exclude any material exposed to such a fire.

9.1.1.3 **Primary Electrode Fabrication Welding**.

When a primary electrode is fabricated by welding, all welding should be conducted in an inert gas filled or a vacuum chamber. Tungsten Inert Gas or graphite electrode weld processes should not be used for the electrode construction. Welds should be visually inspected at a minimum for atmospheric contamination; contaminated welds should be removed and replaced prior to primary melting. When appropriate, limits and procedures for the chamber weld should be established for the following:

- chamber leak-up rate,
- chamber pressure,
- plasma torch gas, and purge,
- metal-inert gas (MIG) weld wire,
- electrode cooling before venting chamber.

9.1.1.4 **Consolidation Melt Fabrication**.

Charge material may be prepared using an established consolidation melt procedure before the primary VAR step. Effective controls and limits for the consolidation process should be maintained for producing material free from contamination known to cause HIDs and HDIs. The consolidation melt should be performed in an inert gas-filled or vacuum chamber. For the non-consumable electrode melting processes, the electrode should be constructed to avoid the introduction of HDIs or other deleterious materials into the melt. Tungsten or graphite electrodes should not be used. When a CHM refining process is used as the consolidation melt, additional practices, procedures, and limits should be established as identified in 9.1.2, CHM Plus VAR Process. The consolidated ingot should be inspected prior to VAR for surface contamination caused by coolant or air leaks. Limits and procedures should be established for the consolidation melt chamber with respect to the following:

- chamber leak-up rate,
- chamber pressure, and
- input material feed system.

9.1.1.5 **Electrode Mechanical/Electrical Attachment**.

When the possibility exists that the electrode attachment material may be consumed during melting, the attachment material should have the same nominal composition and quality level as the electrode. It should be prepared and inspected using established procedures. The attachment should be joined to the electrode using established inert gas in-chamber welding procedures, or plunge-arc welding in a vacuum chamber. Limits and procedures for weld chamber leak detection should be established. When appropriate, limits and procedures for the chamber welds should be established for the following:

- leak-up rate,
- chamber pressure,
- plasma torch gas and purge,
- metal inert gas (MIG) weld wire, and
- weld cooling prior to venting chamber.

When plunge welding is used, procedures should be established for the following:

- depth of plunge,
- voltage and amperage,
- rundown, and
- leak-up rate.

All welds should be visually inspected to established standards.

9.1.2 CHM Plus VAR Process.

EBM or PAM CHM processes typically use blended input materials compacted as small briquettes for particulate feed or consolidated using either VAR or one of the non-consumable electrode melting processes. Input material requirements for CHM are the same as the multiple VAR process, except that turnings may not require X-ray inspection because the CHM process effectively removes HDIs and the multiple VAR process prohibits use of bulk weldables.

9.1.2.1 **Blending**.

The supplier should establish procedures to select and prepare the input materials with respect to size and shape. Blending practices that achieve acceptable chemical homogeneity in the final ingot product should be demonstrated. Procedures should also be established to preclude excessive deblending during handling and compaction prior to the first melt. Caution and inspections should be applied to prevent fires during material crushing, handling, blending, and to exclude any material exposed to such a fire.

9.1.2.2 **Compaction**.

Procedures should be established for compacting the input materials into a form that facilitates the supplier's consolidation melt or CHM practice. Compact size and shape, and compaction pressure, should be a fixed practice. At a minimum, the sponge, master alloy, elemental additions, titanium dioxide and turnings should be compacted. Caution and inspections should be applied to assure no local fires are created during compaction, and to exclude any material exposed to such a fire.

9.1.2.3 **Consolidation Melt Prior to CHM.**

Some or all the charge material may be prepared using an established consolidation melt procedure before charging the CHM furnace. Effective controls and limits for the consolidation process should be maintained for producing material free from contamination known to cause HIDs and HDIs. The consolidation melt should be performed in an inert gas filled or a vacuum chamber. For the non-consumable electrode melting processes, the electrode should be constructed to avoid the introduction of high density or other harmful materials into the melt. Tungsten or graphite electrodes should not be used. For the VAR consolidation process, procedures identified in 9.1.1, multiple VAR process for input material consolidation, and for melting, should be followed. The consolidated ingot should be visually inspected prior to CHM for surface contamination caused by water or air leaks.

9.1.2.4 **Mechanical Attachment.**

When the possibility exists that the pushrod mechanical attachment may be consumed during melting, the push rod should have the same nominal composition and quality level as the charge material and should be prepared and inspected using established procedures. If welding is used, the push rod should be joined to the consolidation melt using established inert gas in-chamber welding procedures or plunge arc welding in a vacuum chamber. Limits and procedures for weld chamber leak detection should be established. When appropriate, limits and procedures for the mechanical attachment chamber welds should be established for the following:

- leak-up rate,
- chamber pressure,
- plasma torch gas and purge,
- metal-inert-gas (MIG) weld wire, and
- procedures for venting chamber.

When plunge welding is used, procedures should be established for the following:

- depth of plunge,
- voltage and amperage,
- rundown, and
- leak-up rate.

The weld should be visually inspected to established standards. Since electrical contact of the push rod is not required, mechanical methods of joining the push rod may be employed.

9.1.3 Skull Plus VAR Process.

The skull process typically uses revert material in the form of solid and scrap which is placed in the hearth prior to sealing the melting chamber. Input material requirements for the skull process are the same as the multiple VAR process, except that turnings may not require X-ray inspection because the skull process effectively removes HDIs. In addition, blended and compacted virgin material may be used to balance the chemistry of the heat.

9.1.3.1 **Charging**.

The supplier should establish procedures to select and prepare the input materials with respect to size and shape. Melting practices, including the positioning of charge materials in the hearth, should be demonstrated to achieve acceptable chemical homogeneity in the final ingot product. Caution and inspections should be applied, as required, to prevent fires during material crushing, handling, blending, and excluding any material exposed to such a fire.

9.1.3.2 **Compaction**.

Procedures should be established for compacting the input materials into a form that facilitates the supplier's skull melt practice. Compact size and shape, and compaction pressure, should be a fixed practice. At a minimum, the sponge, master alloy, elemental additions and titanium dioxide should be compacted. Caution and inspections, as required, should be applied to assure no local fires are created during compaction, and to exclude any material exposed to such a fire.

9.2 **Primary Melting**.

Primary melting may be accomplished by either the VAR of an electrode which has been consolidated as described in 9.1.1, Multiple VAR Process, by the CHM of input materials which have been processed as described in 9.1.2, CHM Plus VAR Process, or by the skull melting of input materials which have been processed as described in 9.1.3 Skull Plus VAR Process.

9.2.1 Multiple VAR Process.

The first melt for the multiple VAR process should be conducted using a fixed melt practice established by the supplier and approved by the PAH. A consumable electrode process should be used, which incorporates effective controls and limits shown to minimize the occurrence of HIDs and HDIs. Care should be taken to terminate melting before any non-premium material is melted.

9.2.1.1 **Critical Parameters.**

When using the VAR process to produce primary melt ingot, processing procedures, parameter limits and verification methods should be established by the supplier to control the following–

- bottom charge (initial charge),
- pressure/leak rate,
- power levels,
- melt rate/gap control,
- arc focusing controls,
- end of melt control/indicators,
- crucible cooling,
- annulus control,
- interruptions (power, pressure),
- chamber, crucible and base plate cleaning,
- coolant leaks, and
- electrode orientation practice.

9.2.1.2 **Multiple Electrode Melting – Precautions.**

Multiple electrode melting is an acceptable, but not preferred, practice. When multiple electrode melting is used to produce a primary ingot of sufficient size for subsequent melts, care should be taken to assure cooling to appropriate temperatures prior to any furnace opening. Piggyback melting of a second electrode on top of the first ingot should be avoided. The primary ingots should be removed from the VAR furnace, cleaned, and chamber-weld joined prior to the second VAR step. Multiple electrode melting should not be used beyond the manufacture of the primary ingot.

9.2.1.3 **Primary Electrode Post-Melting – Precautions.**

The potential risk related to primary VAR electrode burning during air exposure following melting should be minimized, and subsequent primary electrode cleaning methods should be sufficiently robust to remove any contaminated surface to prevent HID(s) remaining in the final product.

9.2.2 Cold Hearth Melting.

When the CHM practice is used to produce a primary melt ingot, a fixed melt process should be established at the CHM supplier and approved by the PAH. During the CHM melting process, the heating source should be designed to preclude it from being the source of HDIs or other deleterious materials entering the melt.

9.2.2.1 **Critical Parameters for EBM and PAM.**

When using either a well-controlled EBM or PAM CHM method to produce a primary melt ingot, processing procedures, parameter limits and verification methods should be established by the CHM source to control the following:

- hearth design and assembly and set up of the associated equipment,
- method of removing the skull from the hearth, storage of the skull to prevent contamination, provisions for retiring the skull and traceability of the skull back to previous melts,
- molten pool dimensions during steady-state melting,
- molten pool temperature during steady-state melting,
- chamber leak-up rate,
- chamber pressure,
- melting (ingot casting) rate,
- cooling cycle and atmosphere,
- melt interruptions,
- chamber and raw material feed cleaning,
- input material feed practice, and
- precautions to prevent accidental transfer of unmelted material into the refining hearth or withdrawal mold.

9.2.2.2 **Additional Electron Beam Melt Parameter Controls.**

In addition to the controls listed in 9.2.2.1, Critical Parameters for EBM and PAM, the EBM CHM source should also establish procedures to control the following:

- electron beam power, deflection pattern, beam diffusion and scanning frequency,
- duration of beam interruption, and the restart procedure, and
- condensate control and fall-in.

9.2.2.3 **Additional Plasma Arc Melt Parameter Controls.**

In addition to the controls listed in 9.2.2.1, Critical Parameters for EBM and PAM, the PAM CHM source should also establish procedures to control the following:

- torch gas type and flow rate,
- torch voltage, current, motion pattern, velocity, and position,
- hydrogen, oxygen and moisture control in the chamber and torch gas, and
- duration of arc interruption, and the restart procedure.

9.2.3 Skull Melting.

When the skull practice is used to produce a primary melt ingot, a fixed melt process should be established at the skull supplier and approved by the PAH.

9.2.3.1 **Critical parameters for Skull Melting.**

When using a well-controlled skull melting method to produce primary melt ingot, processing procedures, parameter limits and verification methods should be established by the skull melt source to control the following:

- chemistry of consumable electrode,
- charge materials, including positioning,
- pressure/leak rate,
- current,
- voltage,
- end of melt control/indicators,
- electrode cooling,
- interruptions (Power, pressure), including duration and restart,
- chamber, hearth, mold and associated fixturing cleaning, and
- coolant leaks.

9.3 **Intermediate and Final Melts**.

The final melt should be by the VAR process following either a primary melt by (1) VAR process, (2) CHM process, (3) skull process, or (4) an intermediate VAR melt in the case of a three VAR process.

9.3.1 Multiple VAR, CHM Plus VAR or Skull Plus VAR Process.

Controls should be applied to the melting process to ensure consistency in the melting parameters and, hence, in the ingot product. It is advisable to restrict furnaces and crucibles used for primary melt from being used for the second and third melt. Cleaning and inspection of crucibles is important for all VAR melts and should be performed to established procedures (reference 9.5.4, VAR Furnaces, and 9.5.5, CHM Furnaces).

9.3.1.1 **Weld Joining of Electrodes.**

Melting through a weld should not be permitted in final melting. Therefore, if two ingots are welded together to form a longer electrode, that material shall be melted twice. Controls on welding should be per paragraph 9.2.1.2, Multiple Electrode Melting – Precautions.

9.3.1.2 **Electrode Cleaning/Descale/Crown.**

Prior to remelting, all electrodes should be visually inspected and cleaned. The cleaning method used should thoroughly remove all loose material, foreign material, or any evidence of burnt titanium. In addition, any crown or splatter at the top of the electrode should be removed. Identification and recording of electrode orientation for each melt should be maintained.

9.3.1.3 **Electrode Mechanical/Electrical Attachment.**

It should be in accordance with 9.1.1.5, Electrode Mechanical/Electrical Attachment or 9.1.2.4, Mechanical Attachment, with the exception that the push rod should be joined to the primary electrode, or intermediate electrode in the case of triple VAR process, instead of a consolidation melt per 9.1.1.4.

9.3.1.4 **Critical Melt Parameters.**

The melt supplier should establish a melting sequence to minimize the chemical segregation of the ingot. Once a sequence has been adopted, it should be consistently applied.

All parameters listed in 9.2.1.1, Critical Parameters are applicable to the intermediate and final melts. In addition, for final melting, a hot topping procedure should be established. Input power should be reduced in a controlled fashion over a period of time, and the hot top sequence should be recorded. The hot topping should be consistently applied from heat to heat for each alloy.

1. A system should be established to identify the start of the hot topping sequence. If electrode markers are attached to the electrode, or in any manner introduced into the furnace, they should be manufactured

using premium quality titanium of a similar composition and melting point to the alloy being melted. Attachment should prevent electrode markers from falling into the melt. Welding of electrode markers for final melt should be prohibited. If machined grooves are used, the tools should be selected to avoid HDIs.

2. The hot topping sequence for the final melt should be arranged to terminate before the introduction of any non-premium material into the melt and consumption of any welds. This could be done by ensuring that a ‘wafer’ or ‘platter’ of the electrode is always left unmelted. The furnace should be opened in a controlled manner to avoid surface contamination.

9.3.2 Inclusion Risk Comparison for CHM Plus VAR versus Multiple VAR Processes.

A well-controlled CHM Plus VAR process has demonstrated the capability of reducing HID and HDI rates compared with a well-controlled triple VAR process. The presence of the hearth melt step in a well-controlled CHM Plus VAR process allows for a significantly longer residence time during CHM to dissolve inclusions and allow HDIs to density separate compared with a well-controlled VAR process.

9.3.2.1 **Seeded Heat Inclusion-Elimination Trial to Qualify a New Hearth.**

It has been demonstrated that designing the cold hearth process to be capable of removing select inclusion sizes, types, and quantities is an important contributor to the overall success of the much lower inclusion rates in well-controlled CHM Plus VAR materials. New hearths should be qualified per PAH direction.

9.3.2.2 **Streamlined Post-CHM PQ-Focused VAR Melt Shop.**

It has been demonstrated that having and maintaining a PQ-focused VAR melt shop is important to preserve the quality benefits associated with a well-controlled CHM process.

9.4 **Inspection**.

Ingot inspection procedures should be established by the supplier and approved by the PAH. Inspection procedures relevant to the possible introduction of HIDs during the melt procedure are discussed below. It should be noted that at the ingot stage, inspection methods are relatively limited and simple. Therefore, the primary emphasis should be placed on melt process control. Detailed billet and final forging inspection procedures are covered in Section 10, Billet Conversion, Disk Forging, and NDT.

9.4.1 Wafer/Platter Inspection.

The residual electrode ‘wafer’/‘platter’ should be inspected for thickness and color after each VAR melt and compared to physical or photographic standards. Melting through a weld during the final melt should not be permitted. Any indication of abnormal color due to oxidation should be investigated, and sources of furnace leaks identified and repaired before processing additional material in the affected furnace. The heat of material from the abnormally discolored wafer should not be used for premium quality applications.

9.4.2 Ingot Inspection.

9.4.2.1 All electrodes and final ingots should be inspected for color and surface condition and processed as detailed in 9.3.1.2, Electrode Cleaning/Descale/Crown. Ingots exhibiting abnormal surface condition (excessive oxidation) indicative of furnace coolant or air leaks, should not be released for premium grade applications, and additional material should not be processed in the affected furnace until the leak source has been identified and repaired.

9.4.2.2 Exposed pipe should not be permitted on final ingots. The location of internal pipe should be determined by an inspection technique or by process history to allow appropriate inspection and disposition of the pipe-affected material during or following the subsequent conversion/cropping process.

9.5 **Equipment Maintenance and Cleaning**.

TIG (Tungsten Inert Gas) welds, original or repair, are considered undesirable on equipment surfaces in contact with sponge, raw materials, or other in-process material.

9.5.1 Blending.

Equipment used for blending should be maintained in areas isolated from potential sources of contamination likely to cause HDIs or HIDs (e.g., carbide tools, welding operations, etc.). All processing equipment should be regularly cleaned and inspected to established procedures. Procedures should specify methods of cleaning and frequency.

9.5.2 Compaction.

Compaction equipment (e.g., tooling, handling, etc.) should be maintained in a clean contamination-free environment. Tools should be regularly cleaned and inspected to established procedures.

9.5.3 Electrode Fabrication.

Procedures should be established for thoroughly cleaning and inspecting the interior of the welding chamber, fixtures, welding equipment, etc., to assure all surfaces are free of all contaminants known to cause HDIs and HIDs. Procedures should be specific to what is cleaned, how, at what frequency, and how it is inspected. At a minimum, chambers should be visually inspected before the electrode is welded.

9.5.4 VAR Furnaces.

9.5.4.1 **Furnace Cleaning**.

Procedures should be established for thoroughly cleaning and inspecting the interiors of all melt furnaces. Base plates, stubs, covers and seals should be free of all contaminants known to cause HIDs and HDIs.

Procedures should specify cleaning frequency, method of cleaning, and methods of inspection.

9.5.4.2 **Crucible Cleaning**.

Procedures should be established to clean and inspect the inside surfaces of crucibles before each melt. Examples include tumbling with some hard medium, wire brushing, water jets, etc. The system chosen should be capable of removing any surface contaminant which could cause an HID or HDI. Each crucible should be inspected to a written procedure prior to release for assembly into a furnace melt sequence. After cleaning and inspection, crucibles should be stored in a manner to minimize possible contamination, and a final visual inspection is prudent prior to sealing the furnace for melting.

9.5.4.3 **Leak-Up Rate Checks**.

After the furnace assembly is sealed, but prior to melting, the system should be checked to established procedures to ensure that the requirements for leak-up rate will be met. Results should be recorded.

9.5.5 CHM Furnaces.

9.5.5.1 **Furnace Cleaning.**

Procedures should be established by the CHM source for thoroughly cleaning and inspecting the interior of the melt furnace, the hearth, barriers, spray shields, and all associated equipment used on the interior of the furnace prior to use, to assure that they are free of all contaminants known to cause HDIs and HIDs. Procedures should be specific as to what is cleaned, how it is cleaned, and the frequency of cleaning. At a minimum, cleaning should be done when the melt chamber is exposed to air, between alloy type or alloy quality changes, and after a contaminated melt.

9.5.5.2 **Ingot Mold Cleaning.**

Procedures should be established to ensure that the mold and base/puller assembly is thoroughly cleaned and inspected prior to each melt.

9.5.5.3 **Feed Mechanism.**

Procedures should be established to ensure that all raw material feed mechanisms are cleaned and inspected to preclude contamination prior to melting.

9.5.5.4 **Skull Maintenance.**

Procedures should be established to assure that skulls that are going to be reused are cleaned and not contaminated during removal, storage or reassembly. Only skulls of like alloy and quality from a non-contaminated melt should be reused. The skulls should have traceability to previous melts and should be inspected prior to reuse to assure that no loose contaminants are present.

9.5.6 Skull Furnaces.

9.5.6.1 **Furnace Cleaning.**

The skull source should establish procedures for thoroughly cleaning and inspecting the interior of the melt furnace, the hearth casting chute, protective chamber cover, electrode holder furnace roof, mold and any other associated equipment used on the interior of the furnace prior to use, to assure that they are free of all contaminants known to cause HDIs and HIDs. Procedures should specify what is cleaned, how it is cleaned, and the frequency of cleaning. Cleaning should be performed between every heat.

9.5.6.2 **Skull Maintenance.**

Care should be used, and procedures should be established to assure that skulls to be used as consumable electrodes for a following skull heat are cleaned and not contaminated during removal or storage.

9.5.6.3 **Leak-Up Rate Checks.**

After the furnace assembly is sealed, but before melting, the system should be checked to establish procedures to ensure that requirements for leak-up rate can be met. Results should be recorded.

9.6 **Housekeeping**.

It is important to ensure a high standard of housekeeping in all areas associated with the premium quality titanium manufacturing processes.

9.6.1 Raw Materials and Melting Facilities Process Flow.

The layout of raw materials areas and melt shops should be designed to minimize the potential cross-contamination of the in-process premium quality material with inclusion-forming material generated from other processes related to the production facilities.

9.6.2 Raw Materials and Melting Facilities Cleanliness.

The raw materials areas and melt shops should be maintained with a high standard of cleanliness to prevent cross-contamination of in-process premium quality material with inclusion-forming material associated with poor housekeeping.

9.6.3 Internal and Customer Product Hazard Reviews.

Both internal and customer product hazard reviews should be conducted to ensure all employees remain vigilant against the possibility that a reduction in housekeeping standards might lead to an increase in the occurrence of melt-related inclusions and the associated risks with the premium quality titanium material in aircraft engines.

10 BILLET CONVERSION, DISK FORGING, AND NDT.

10.1 Control of Billet Conversion Process.

Specific detailed procedures should exist for the conversion of ingot to billet and bar products. These include but are not necessarily limited to:

10.1.1 Billet Conversion.

Ingot to billet conversion should be performed using controlled, consistent, and detailed procedures.

10.1.1.1 Forge Parameter Control.

Documented procedures to control ingot and billet products should be developed and used. These procedures include, but are not limited to:

- forge furnace temperatures/atmospheres,
- soak times,
- amount of draft,
- reduction schedules/sequences,
- quench time, media, and methods,
- die type,
- single or double end procedures,
- off-die procedures, and
- traceability of material during loading and withdrawal into and from pre-heat furnace.

10.1.1.2 Forge Practice.

Forge practices which preclude the formation of strain induced porosity (SIP) or clean voids and contamination associated with material cutting should be developed. In addition to the potential of creating SIP during billet forging, it should be noted that billet forging may also act to seal residual ingot microporosity.

10.1.1.3 Cropping.

Any ingot conversion should incorporate a crop of the ingot extremities to remove undesirable end material. Limits for crop lengths from the ingot top and bottom should be established to account for the hot topping procedures and bottom charge used for the final melting.

10.1.1.4 MTR – Billet Forge Processing.

Sub-beta transus billet forge practices for alpha/beta processed and heat-treated alloys should be developed to minimize MTR formation, size, frequency, and intensity by controlling the following processing parameters below (refer to the first bullet of appendix A, paragraph 5.

1. Beta Recrystallization. Initial beta work combined with a subsequent alpha/beta pre-strain and a beta recrystallization step will set-up a smaller recrystallized prior beta grain size. A smaller prior beta grain size will minimize the size of the subsequent MTRs. A minimum deformation ratio is necessary in this temperature domain to break down the solidification structure and obtain a uniform, relatively small prior beta grain size. Minimizing the time at temperature for the beta recrystallization step results in a smaller recrystallized prior beta grain size.
2. Post-beta-recrystallization Cooling. Cooling after beta recrystallization results in the formation of alpha colonies; these colonies are the origin of MTRs. A faster cooling rate minimizes the alpha colony size and the thickness of the lamellae within the colonies. Smaller colonies and thinner alpha plates increase the ability of MTRs to be broken-up during subsequent billet and component forging processing. Metal temperature, transfer time and temperature of the water tank prior to quenching along with section size should be controlled to maximize the cooling rate.
3. Final Alpha/beta Work. The degree of sub-beta-transus work imposed on the billet following the last quench from the beta phase field is important in reducing MTRs through the breaking up of colonies. Increased levels of final alpha/beta work generally lead to a reduction in MTR size and a decrease in MTR intensity.
4. Temperature of Final Alpha/beta Work. A higher final alpha/beta work temperature decreases the MTR intensity. The temperature for initial and reheating sequences should be controlled to mitigate variations in bar length, reduction per pass, and bites per pass with associated surface chilling and adiabatic heating.
5. Reheat Time for Final Alpha/beta Work. Longer reheat times between the final alpha/beta forge operations (provided the prior forge operation imparted a sufficient level of strain) may decrease the MTR intensity. This should be balanced with the need to retain a refined, spheroidized primary alpha structure.
6. Type of Press Work. Billet forging work should be conducted using a press that is capable of imparting strain through the entire billet cross-section enabling refinement of the microstructure, including MTRs, through to the center of the billet.
7. Redundant Work for MTR Break-up. A combination of upset and draw should be conducted to improve work in the billet material to reduce MTRs. Working in multiple directions imparts strain on all MTR orientations and subsequently reduces the MTR size and

intensity. In addition, intermediate billet cross-section shape should be considered to ensure uniformity of microstructure.

8. Billet End Effects. It is known that forging and conversion of cast ingots to billets results in strain variation between the near steady-state region and ingot/billet ends. The variation of strain within the ends of ingots and billets will influence the evolution of MTRs. Strain non-uniformity during initial ingot upsetting and processing can result in specific zones of undesirable MTR conditions. Any ingot conversion should incorporate a crop of the ingot extremities to remove undesirable end material. Limits for crop lengths from the ingot top and bottom should be established to account for initial upset strain variations, the hot topping procedures and bottom charge used for the final melting. It is also believed that the level and the intensity of MTRs may be increased at the end of individual billets due to the potential for less uniform deformation conditions during billet conversion. When cropping billet ends, the potential for increased MTR size and intensity should be considered.

10.1.1.5 **There are many attributes of MTRs that can be quantified as noted in appendix A, paragraph 5(1), including the following:**

- size,
- shape,
- density,
- intensity,
- frequency,
- orientation,
- orientation spread,
- neighboring region characteristics, and
- volume fraction.

10.1.1.6 **Records**.

Reduction sizes, sequences, and temperature records should be maintained.

10.1.1.7 **Traceability**.

Traceability of billet to exact ingot location should be maintained. The identity and orientation of the billet within an ingot is important for material-related problem-solving and risk reduction.

10.2 **Control of Disk/Component Manufacture.**

10.2.1 Forging/Heat Treatment Process.

Specific detailed procedures should exist for the production of finished rotating components from billet product. These should include but not necessarily be limited to:

10.2.1.1 **Forging Controls.**

Controlled, consistent, and detailed procedures should be established for the control of the forging press/hammer processing.

10.2.1.2 **Thermal Controls.**

Documented procedures for control of forge/soaking furnace temperature and times should be established.

10.2.1.3 **Heat Treatment Controls.**

Documented procedures should be established for the control of heat treatment furnaces, atmospheres, times, and temperatures.

10.2.1.4 **Quenching.**

Quench practice and cooling rates should be controlled to ensure freedom from quench related cracking.

10.2.1.5 **Records.**

Forging and heat treatment records should be maintained, including traceability of forgings to exact billet location.

10.2.2 MTR – Forge Processing and Heat Treatment.

Forging and heat treatment parameters for alpha/beta processed and heat-treated alloys should be developed to minimize MTR size, frequency, and intensity by controlling the following processing parameters:

10.2.2.1 **MTR levels in billet used to manufacture parts.**

Billet that has been processed to minimize MTR size, frequency and intensity is less susceptible to retaining MTRs in forgings.

10.2.2.2 **Alpha/beta versus beta forging practice.**

Alpha/beta forged parts may retain MTRs from the billet processing, whereas beta-forged parts erase MTRs from the billet processing. Beta forging followed by cooling through the beta transus can lead to the generation of colonies that may adversely impact CDF capability of the material.

10.2.2.3 **Forge strain, strain rate and temperature.**

A sufficient level of strain and associated strain rate and temperature will reduce remnant MTRs carried over from billet for alpha/beta forged parts. Strain path should also be considered relative to modification of location-specific MTR characteristics within the final part. Note that high levels of strain along a consistent strain path may increase the macrotexture within the forging and that alpha/beta forge practice should avoid excessive adiabatic heating that may locally reduce primary alpha volume fraction in the overheated region leading to the formation of a beta fleck. Note, increased levels of strain at higher rates and lower temperatures may lead to SIP formation.

10.2.2.4 **Number of re-heats.**

Time at temperature associated with multiple re-heats should be minimized to retain a finer primary alpha grain size.

10.2.2.5 **Heat treatment temperature for alpha/beta processed alloys.**

Selecting a heat treatment temperature closer to the beta transus for alpha/beta-processed alloys will reduce the primary alpha volume fraction and size, resulting in a reduction in MTR size and intensity. Note, if the selected temperature is too close to the beta transus, areas of remaining local ingot segregation of beta stabilizing elements may result in the formation of beta fleck.

10.2.2.6 **Post-solution cooling rate for alpha/beta-processed alloys.**

Increasing the post-solution cooling rate for alpha/beta-processed alloys will reduce the primary alpha volume fraction and grain size and will reduce the secondary alpha plate thickness as well as increase the likelihood that the secondary alpha plate morphology will change from a colony to a basketweave morphology.

10.2.2.7 **Post-forge cooling rate for beta-processed alloys.**

The post-forge cooling rate should be maximized to ensure refined alpha colonies and thinner alpha lamellae.

10.2.2.8 **Post-solution cooling rate for beta-heat treated alloys.**

The post-solution cooling rate should be maximized to ensure refined alpha colonies and basketweave morphology with thinner alpha lamellae.

10.2.3 MTR/Microstructural Features.

The above forge processing and heat treatment parameters will impact the following MTR and other microstructural features that may influence the component CDF life:

- MTR size,
- MTR shape,
- MTR density,
- MTR intensity,
- MTR frequency,

- MTR orientation,
- MTR orientation spread,
- MTR volume fraction,
- MTR neighboring region characteristics,
- colony size for beta processed alloys,
- primary alpha grain volume fraction for alpha/beta processed alloys, and
- primary alpha grain size for alpha/beta processed alloys.

10.2.4 Bulk Residual Stress.

Manufactured-in residual stresses are additive to application stress which make them important relative to component life. Bulk residual stress present after heat treatment will be a function of:

- Size and geometry of heat-treated forging,
- Heat treatment solution temperature,
- Cooling method and transfer time, where applicable, post-solution heat treatment,
- Aging/stress relief temperature and time, and
- Alloy class. Creep-resistant near-alpha alloys have the greatest susceptibility to retaining residual stress with beta alloys having the least susceptibility to retaining residual stress.

10.2.5 MTR – Alloy Class.

It should be noted that different alloy classes are believed to have differing tendencies to form MTRs, and so processes will need to be adjusted between alloy classes in order to minimize MTR formation, size, volume fraction and maximize MTR crystal orientation spread. The alloy classes believed to be susceptible to CDF are:

- Near-alpha alloys such as Ti-6242, Ti-811, Alloy 834, Alloy 685, Alloy 829.
- Alpha plus beta alloys such as Ti-64.

Alloys Ti-17 and Ti-6246 are considered to have low susceptibility to CDF.

10.3 Non-Destructive Testing and Criteria.

10.3.1 Background.

10.3.1.1 Non-Destructive Testing (NDT) of all material used for turbine engine rotating hardware is critical. Common NDT techniques are ultrasonic testing (UT), eddy current inspection (ECI), fluorescent penetrant inspection (FPI), and macroetch. Each of these methods can support the identification of material anomalies such as melt-related features (e.g. inclusions or segregation) and conversion issues (e.g. MTRs). UT is useful for volumetric inspection to ensure the quality of titanium billet, bar, and final forgings, while ECI, FPI and macroetch are surface inspection methods.

10.3.1.2 Ultrasonic inspection relies on the transmission of elastic waves within the material. Discontinuities in the material with large differences in density or elastic properties, like cracks, voids, or inclusions, will result in discrete backscattered reflections of appreciable amplitude indicating the presence of an undesirable defect. These signals are relatively straightforward to detect in material with fine, uniform grain size without any MTRs (or with MTRs much smaller than the incidence wavelength), but the presence of MTRs diminishes the inspectability of bar, billet, and finished components.

10.3.1.3 Two distinct phenomena are observed depending on the size, shape, and orientation of the major axis of the MTR relative to the incident ultrasound. Significant attenuation, leading to decreased signal, occurs when the wavelength is much smaller than the MTR size in the direction of wave propagation, whereas significant backscattering, leading to enhanced noise, occurs when the wavelength is of the order of the MTR size. These phenomena are a result of the elastic anisotropy of the alpha phase. Enhanced attenuation occurs as a result of variations in the local wave velocity inside different MTRs that distort the coherent incident wavefront.

Additionally, the shape of the MTRs resulting from metal flow during the forging process may cause the wave to reflect, refract, or otherwise travel in a path away from the source. The additional backscattering occurs because of the elastic (impedance) mismatch at MTR boundaries. Either of these phenomena decrease the signal-to-noise ratio making it more difficult to detect real flaws. In some instances, when the MTR size is large relative to the wavelength and depending on the attributes of the specific MTR and its neighborhood, geometric scattering can occur resulting in a single, large, discrete reflection to be received. In the same way that MTRs can impede the inspectability of titanium alloys, the presence of MTRs can also be qualitatively inferred from ultrasonic inspection. MTRs can produce both an increased average noise response, quantified by the average root-mean-square of the backscattered signal content, as well as single high amplitude reflections. Depending on size and aspect ratio relative to the incident sound wave, MTRs can also cause a measurable increase in attenuation or backscattering, and hence interrogation in multiple directions can be useful in determining preferred MTR orientation. The use of these effects requires correlation of the ultrasonic parameters with levels of MTR severity, along with consideration of interactions between sound wavelength and microstructure.

10.3.1.4 Finally, the presence of macrotexture may also be inferred from the measurement of ultrasonic wave velocity. Because wave speed is proportional to elastic modulus, the velocity is highest along the C-axis of the unit cell, and slowest perpendicular to it.

10.3.2 NDT.

To obtain further confidence that titanium rotating parts are free from potentially detrimental anomalies, NDT should be performed at appropriate stages throughout billet/bar and component manufacture. NDT requirements will typically include but not necessarily be limited to the following:

10.3.2.1 **Billet/Bar**.

- Ultrasonic.

  Immersion ultrasonic testing of billets that are less than or equal to 10 inches in diameter should be performed using a system with demonstrated inspection sensitivity equivalent to, or better than, a #2 flat bottom hole (FBH) (0.031 in.) at all billet depths. The UT inspection should be performed in accordance with SAE Document AMS 2628 sections 3 and 4 or an equivalent Phased Array accepted procedure. Immersion ultrasonic testing of billets that are greater than 10 inches in diameter should be performed using a system with demonstrated inspection sensitivity equivalent to, or better than, a #3 FBH at all billet depths. The UT inspection should be performed in accordance with SAE Document AMS 2628 sections 3 and 4 or an equivalent Phased Array accepted procedure.

- Macroetch.

  Macroetch inspection of billet/bar ends adjacent to ultrasonic crops should be performed to assure freedom of the remaining material from segregation or other anomalies.

10.3.2.2 Forging.

Ultrasonic.

Immersion ultrasonic testing of forgings should be performed to a sensitivity consistent with the lifing analysis for the component. The inspection should be applied as needed to achieve the required sensitivity, noting that specific regions of a component may require enhanced inspection sensitivity capabilities consistent with part requirements.

- Macroetch.

  Sonic shape or any other intermediate machined forging shape may be macroetched for examination for the presence of surface-connected segregation or other anomalies.

10.3.2.3 **Finish Machined Component.**

- Etch.

  Finish machined, or near-finish machined components should have their surfaces blue etch anodized and inspected to assure freedom from segregates or other anomalies, including abusive machining. Alternate suitable macroetch procedures, although not preferred, may be utilized when agreed with the PAH. Performing an etch as close to the final shape as possible is desired to validate no segregates intersect the finish machined component surface.

- Fluorescent Penetrant Inspection.

  Finish machined components should be fluorescent penetrant inspected.

10.3.3 Ultrasonic Testing (UT) Criteria.

The criteria for UT of billet/bar and forgings should consider the operational and control requirements that materials/ultrasonic inspection systems must achieve. The criteria should include but not necessarily be limited to the following:

10.3.3.1 **System Variability.**

Materials systems from billet/bar through forging, heat treatment, and machining should be engineered such that materials-generated ultrasonic noise or boundary (surface finish) ultrasound transmission characteristics do not interfere with the detectability of potentially detrimental anomalies. Periodic system reliability/repeatability studies should be conducted to assure instrumentation and standards are functioning properly and within calibration.

10.3.3.2 **Test Blocks.**

Test blocks used to verify operation of the ultrasonic inspection system should be representative of the billet/bar or forging being inspected, including MTRs and grain flow to the extent possible, and should contain appropriate ultrasonic reference standards (flat bottom holes or side drilled holes). The ultrasonic reference standards should be correlated with potentially detrimental anomalies.

10.3.4 Statistical Assessment.

Statistical assessment of factors responsible for material/ultrasonic system variability should be conducted.

10.3.5 Acceptance Limit.

The acceptance limit should be set appropriately above the noise level to minimize false calls while maintaining detection sensitivity consistent with design requirements.

10.3.6 Records.

The output should be electronic C-scan data, which can be acquired, stored, and retrieved electronically and retained according to the engine-manufacturer's FAA-approved records retention schedule.

10.4 **Actions Following Indication Detection.**

10.4.1 Indication Characterization.
Characterization of unacceptable indications should be conducted on billet/bar, forgings or finished parts, as appropriate, and reported to JETQC in accordance with JETQC practices. This characterization, as appropriate and as a minimum, shall provide the following information (the recommended procedure for 3D inclusion characterization is outlined in appendix B):

- anomaly type,
- 3D anomaly size,
- 3D void/crack size if any,
- microhardness,
- scanning electron microscope (SEM) evaluation: nature of constituents, fractography of void/crack,
- microprobe analysis (currently recommended): chemical composition and nature of anomaly, and
- photomicrographs of anomaly in two perpendicular directions.

10.4.2 Indications Detected in Billet/Bar.

10.4.2.1 **HDI or HID.**
Any heat which is shown, by billet/bar inspection and indication characterization, to contain an HDI or HID inclusion should be rejected for critical rotating part application.

10.4.2.2 **Other**.
HAD's and clean voids are considered potentially detrimental; usage of heats shown to contain any of these anomalies should be evaluated on an individual basis.

10.4.3 Indications Detected in Forgings and Finished Parts.
The PAH should take appropriate action upon finding and characterizing unacceptable indications in forgings and finished parts. Action regarding suspect material should be based on historic experience with the process and may include, but not necessarily be limited to, over-inspections of parts from heats, lots, batches, etc., which contain the forging or part with the anomaly.

10.4.4 Associated Heats. Associated heats shall be identified and investigated for similar potential anomalies.

Appendix A. Additional References

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Appendix B. Minimum Recommended Procedure for 3D Inclusion Characterization

STEP 1: Characterize the ultrasonic indication in the product:

- Angulation,
- Two different frequencies, and
- Exact location (marking).

STEP 2: Cut a sample (approximately 40 mm x 40 mm) out of the product containing the indication (mark each face to maintain orientation).

STEP 3: Conduct an NDT Inspection.

STEP 4: Relocate indication ultrasonically and remark (to maintain orientation).

STEP 5: Cut a cube whose side is approximately 25mm (1 inch). If necessary, relocate the indication ultrasonically.

STEP 6: Consider performing 3D Computer Aided Tomography (CAT) scanning or other NDT technique to assist in determination of the 3D shape and size of the anomaly.

STEP 7: Metallurgical characterization:

1. Approach:
    - Approach the anomaly by the face of the cube perpendicular to face exhibiting the maximum ultrasonic response, and
    - Precut at 2 mm from identified position.
2. Macrographic examination:
    - Any segregation, and
    - Orientation of grain structure.
3. Micrographic examination:
    - Polish in steps from 50 to 500 microns,
    - Determine anomaly type, 3D anomaly size, 3D void/crack size, microhardness, and
    - Take photomicrographs of the anomaly at each polishing step to establish its maximum dimensions in two perpendicular directions.
4. Recommend performing 3D CAT scanning or other NDT technique to assist in determination of the 3D shape and size of the anomaly.
5. Microprobe analysis (currently recommended) (in case of inclusion): Chemical composition of the anomaly.

6. Scanning Electron Microscope (SEM) examination (if necessary):
    - Nature of constituents, and
    - Fractography of void/crack.

This is the minimum procedure recommended for any characterization of inclusion (HID, HDI) on billet/bar, forging, or finished part. Additional Requirements may be established by the PAH.

09/08/2025

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Advisory Circular Feedback Form

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If you find an error in this Advisory Circular, have recommendations for improving it, or have suggestions for new items/subjects to be added, you may let us know by emailing this form to 9-avs-air-directives-management-officer@faa.gov or faxing it to the attention of N/A at N/A.

Subject: AC 33.15-1A, Manufacturing Process of Premium Quality Titanium Alloy Rotating Engine Components

Date: 09/08/2025

Mark all appropriate line items:

☐ An error (procedural or typographical) has been noted in paragraph __________ on page _________.

☐ Recommend paragraph ______ on page be changed as follows:

☐ In a future change to this AC, please cover the following subject:
(Briefly describe what you want added.)

☐ Other comments:

☐ I would like to discuss the above. Please contact me using the information below.

Submitted by: ________________________________ Date: ______________________