U.S. Department
of Transportation
Federal Aviation
Administration

Advisory Circular

Subject: Manufacturing Processes for Premium Quality Nickel Alloy for Engine Rotating Parts

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Initiated by: ANE-111

AC No: 33.15-2

1. Purpose. This advisory circular (AC) provides information and guidance on compliance with the nickel materials suitability and durability requirements in part 33 of Title 14 of the Code of Federal Regulations (14 CFR part 33). The AC provides detailed guidance on the requirements of § 33.15 regarding the manufacture of premium quality nickel alloy for high-energy rotating parts for aircraft engines.

2. Applicability.

a. The guidance provided in this document is directed to engine manufacturers, modifiers, foreign regulatory authorities, part manufacturers who hold Parts Manufacturer Approval (PMA) authority, and Federal Aviation Administration (FAA) engine type certification designees.

b. This material is neither mandatory nor regulatory in nature and does not constitute a regulation. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. We (“the FAA”) will consider other methods an applicant may present to demonstrate compliance. Terms such as “should,” “shall,” “may,” and “must” are used only in the sense of ensuring applicability of this particular method of compliance when the method in this document is used. While these guidelines are not mandatory, they are derived from extensive FAA and industry experience in determining compliance with the relevant regulations. If we find that following this AC would not result in compliance with the applicable regulations, we will not be bound by this AC, and we may require additional substantiation as the basis for finding compliance.

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

3. Related Guidance.

a. AC 33-3, Turbine and Compressor Rotors Type Certification Substantiation Procedures, dated September 9, 1968.

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

4. Definitions. The following definitions apply to this AC:

a. Annulus. The nominal gap between a conditioned electrode and the Vacuum Arc Remelting (VAR) or Electro Slag Remelting (ESR) crucible wall.

b. Bar. Converted material with a cross section less than or equal to 16 square inches (103 cm^2) and a width less than five times the thickness.

c. Billet. Converted material with a constant round cross section greater than 16 square inches (103 cm^2).

d. Bottom Charge (or Starter Material). Material placed in the ESR or VAR crucible to protect the crucible during arc initiation.

e. Conversion. The hot working of a cast ingot to refine the grain structure and provide an intermediate shape (billet or bar) which becomes input material for subsequent forging production.

f. Crucible. A water-cooled copper vessel that contains the remelted ingot in the ESR or VAR.

g. Electric Arc Furnace/Argon-Oxygen Decarburization (EAF/AOD). EAF melting plus the AOD refining process—commonly used to process low-grade or contaminated materials to produce alloys. EAF/AOD may be used to refine contaminated nickel-base alloy scrap such as grindings for reuse as a Vacuum Induction Melting (VIM) charge material.

h. Electrode. The consumable feedstock form for ESR or VAR.

i. Electrode Forge-back. The practice of reducing the cross-sectional area of an intermediate ingot by open die forging prior to remelting.

j. Electrode Holder/Stub. Material that is joined to the top of the electrode, or the electrode stub (or stinger), to hold the electrode and to provide the connection between the electrode and the ESR or VAR furnace electrical supply.

k. Electrode Marker. An alloy 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.

l. Electrode Mold. A metal mold into which the VIM charge is poured to form an electrode.

m. Electro slag remelting (ESR) (also referred to as "electro flux remelting"). A remelting process comprised of a conditioned consumable electrode, an electrical resistance heated refining slag, and a solidifying ingot contained in a water-cooled crucible. The ingot may be an intermediate form for subsequent VAR or a final form for conversion to product.

n. ESR Starter Material. Solid material in the form of a plate or wafer that is used to strike an arc and develop a molten pool at the start of the ESR process.

o. Established Procedure. A procedure that is subject to purchaser approval and is found in a controlled document. An established procedure includes limits, controls, and standards.

p. Flux (slag). A precisely defined mixture of metal oxides and fluorides used in the ESR process. The composition is selected for a combination of melting point, viscosity, electrical resistivity, refining capability and ability to produce a uniform ingot surface.

q. Freckle. Macroscopic region of positive segregation created during solidification of an ingot. This is often an area containing brittle intermetallic phases that cannot be resolutioned by homogenization and a potential site for fatigue crack initiation in a component.

r. Heat/Cast. Ingot and ingot product produced from the final VAR or ESR of a single consumable electrode.

s. Hot Topping. Adjustments of process parameters during the latter stages of a melt or remelt process to minimize pipe, shrinkage porosity, and segregation.

t. Hot Top Marker. A visual marker put on the top end of an electrode to allow the operator to determine when to initiate the hot top cycle (i.e. hot topping)

u. Inclusions. Particles of impurities or foreign materials present or introduced during any stage of alloy processing. Examples include, but are not necessarily limited to, metallic (steel, tungsten, etc.) and ceramic particles (oxides, nitrides, and oxy-carbonitrides).

v. Jet Engine Titanium Quality Committee (JETQC). Formed under the auspices of the FAA, with members including all North American and European aircraft engine producers, for the purpose of rapid dissemination of titanium (raw material and parts) and nickel (parts only) alloy melt-related defect issues and data.

w. Macroetch. Chemical treatment of a metal surface to accentuate structural details and anomalies for visual observation. Macroetch surfaces are usually reviewed and rated visually with no magnification.

x. Master Alloy. Refined product used for some raw materials to aid in VIM melting. For example, a high melting point metal such as niobium may be alloyed with nickel to produce a nickel-niobium master alloy with a melting point near that of the superalloy being produced.

y. Pig. Consolidated and refined scrap cast in the form of a small metal bar for ease of charging.

z. Plates. Material converted by hot working and delivered into straight lengths of constant rectangular cross section, having a width greater than five times the thickness.

aa. Premium Quality. Material produced under special process and quality control requirements and used primarily for critical rotating parts.

bb. Production Approval Holder (PAH). Holder of a production certificate (PC), approved production inspection system (APIS), parts manufacturer approval (PMA), or technical standard order authorization (TSOA), who controls the design and quality of a product or part thereof.

cc. Raw Material. Generally used to refer to elemental additions to a VIM charge.

dd. Refining Agent. Element such as a deoxidant that is added to tie up impurities and, to the extent possible, remove them entirely from the metal bath.

ee. Segregation. Region in the alloy product containing an abnormal content of alloying elements.

ff. Sonic Shape. The intermediate machined forging shape that is ultrasonically inspected. Shape and envelope relative to the finished component should be controlled.

gg. Supplier. Person or organization that furnishes materials, parts or related services (at any tier) to the manufacturer of a product or part.

hh. Swarf/Turnings. Material produced as a result of machining disc or billet material.

ii. Tungsten Inert Gas (TIG) Welding. Process that employs a tungsten electrode to transmit the welding arc.

jj. Vacuum Arc Remelting (VAR). Process comprised of a conditioned consumable electrode and a solidifying ingot in an enclosed water-cooled crucible with an applied vacuum. An electrical arc generates the heat that melts the electrode.

kk. Vacuum Induction Melting (VIM). Process used to melt, homogenize and refine raw materials and convert them to cast consumable electrodes for subsequent remelting by the ESR or VAR processes.

ll. Void (Clean). Cavity constituting a structural discontinuity related to solidification and/or conversion conditions of the ingot.

mm. White Spot. Region of negative alloy segregation generated during the remelting process—often defined as a characteristic light etching spot during the macroetching process. Such areas may be detrimental to properties, especially if they contain concentrations of inclusions.

5. Background.

a. The manufacture of nickel-base alloy forged rotating components can introduce component life limiting anomalies at all stages of material processing. To limit these anomalies, the manufacturing process must be established so that, at each stage, appropriate controls and inspections minimize occurrence and maximize detection, of such anomalies. Further, only through using the best available technologies, can the goals of adequate prevention and detection be met.

b. The conventional melting process for nickel-base alloys has been the VIM process, followed by the ESR and/or VAR processes. Triple melt (VIM + ESR + VAR) INCO 718 rotor material has demonstrated significantly fewer melt-related anomalies than double melt (VIM+VAR) INCO718 material, and we recommend using triple melt processes in critical rotating components. Improvements in all stages of melt, remelt, and conversion have resulted in a significant reduction in the occurrence of melt-related defects since the mid-1980's.

c. Section 33.15(b) requires that materials used in the engine conform to specifications that ensure they have the strength and other properties assumed in the design data. To achieve this goal, inspection practices must advance in step with the best available technologies. The frequency and size of the anomalies tolerated in the rotating component design and lifing analysis must also be consistent with the levels observed in the materials.

d. Advisory Circulars 21-1B, 21-6A, 21-9A, 21-27, and 21.303-2H provide a means to obtain and maintain production approvals. These ACs, however, do not fully describe the manufacturing processes used in the manufacture of premium quality, nickel-base, 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 the manufacture of premium quality, nickel-base, alloy-forged rotating components, such as disks, spacers, hubs, shafts, spools and impellers (not blades).

6. General.

a Sections 139 and 143 of 14 CFR part 21 require that production approval holders establish and maintain, as appropriate, quality control systems that ensure that products used in type certificated engines conform to the FAA-approved type design.

b. PAHs should also ensure, through appropriate agreements with their suppliers, that effective process control documents are developed that identify significant process control points, parameters, and control limits.

c. The PAH and its suppliers must establish a method to document and approve changes to the process control documents and the means of handling violations of any control limit(s). Manufacturing process steps where inclusions could be formed or entrapped, segregations generated, or porosity induced, should be particularly detailed for methods of control, monitoring, and detection.

d. Records of the following should be maintained and available for review as long as the parts made from this material are in service:

(1) material and component inspection;

(2) disposition results;

(3) property test results;

(4) traceability of forged components to ingot/billet location;

(5) material heat; and

(6) raw material ingredient lots making up the heat.

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

f. The PAH and its suppliers must establish a system of handling deviations and non-conformances with respect to product or part limits.

g. Each supplier must establish and document a system for conducting internal self-audits.

7. Raw Materials and Storage. Melt suppliers must maintain effective specifications and procedures for procurement, identification, storage, and processing of charge materials for Vacuum Induction Melting. The raw material supplier must inspect its raw material on a sampling plan sufficiently to ensure compliance with melt supplier raw material procurement specifications. The melt supplier should also inspect sufficient raw material to verify conformance to its procurement specifications and should maintain those inspection records for an appropriate period of time.

a. Charge Composition. The charge materials must be composed of only approved raw materials, such as elemental additions, master alloys, refining agents and recycle material. The weight percent, chemical composition, batch or lot number, and sequence of addition of each type of raw material used in the charge materials must be recorded and maintained for each heat of material.

b. Elemental Additions. Process elemental additions to preclude or remove contaminants considered to cause deleterious inclusions or to adversely affect the properties of the alloy.

c. Master Alloys. Master alloy suppliers must have established procedures and limits for the production of high-purity master alloy. Master alloys must be inspected to established standards to identify and remove detrimental foreign material, oxides, nitrides, and other contaminants considered to cause deleterious inclusions. Ceramics used in VIM crucibles, tundishes, etc., must be controlled. The melt supplier and the PAH must establish and agree upon chemistry for each master alloy grade.

d. Refining agents. Both metallic and nonmetallic additions must meet established chemistry specifications and should be inspected for conformity.

e. Recycle Material. All recycle materials must be cleaned and free from contamination. The following limitations must be considered when recycling previously melted alloy:

(1) Solid scrap may be used directly in the VIM furnace charge, providing the solid scrap has been cleaned (as necessary) and checked for alloy identity.

(2) Chips and turnings may be charged either in loose or consolidated form if they have been previously cleaned to a defined standard and the scrap processor has certified them as to their chemistry.

(3) Lower grade scrap such as grindings, furnace skulls, solids contaminated with slag, or heavily oxidized solids may be used provided they are first refined by EAF/AOD or other techniques to produce a solid refined shape, such as a pig or ingot with a certified chemistry.

f. Raw Material Storage. Store all virgin raw material and turnings in covered containers in a secure area immediately after inspection to preclude the extraneous addition of foreign or uninspected material. Stored raw materials must be adequately marked with identification to avoid any inadvertent misuse.

g. TIG welding. TIG welding is a common industrial practice for welding alloy components. Tungsten is a very high melting point metal that may inadvertently be incorporated into the melt/remelt ingot and included in the final part. To avoid this, suppliers must establish procedures for TIG welding used to manufacture or repair equipment used to store or process nickel-base alloys. Do not use TIG welding to attach remelt electrodes to stubs.

8. Melting and Remelting.

a. This section details significant process parameters, controls and procedures recommended in input material consolidation and ingot melting for the production of premium quality nickel-base alloys. These items are recommended guidelines which, when incorporated into a supplier's specific manufacturing method, will minimize freckle and white spot and produce sound ingots with acceptable chemistry and homogeneity. Triple melt (VIM+ESR+VAR) INCO718 alloy contains significantly fewer melt-related anomalies than double melt (VIM+VAR) INCO718, and the FAA recommends triple melt for critical rotating components.

b. Vacuum Induction Melting.

(1) Charge make-up. Establish aim limits for the weight percent and chemical composition of the following types of charge make up materials used in a VIM heat:

- elemental raw materials;
- master alloy;
- solid scrap;
- turnings, and
- pig.

(2) The VIM process must produce electrodes capable of either being remelted directly in VAR or ESR remelted first, followed by a VAR step. The resultant billet/bar product must be free from inclusions, rejectable segregation, and melt-related structural imperfections.

(3) Refractories. Refractory (oxide) materials that come in contact with the molten metal, such as furnace linings, spouts, tundishes, launders and pouring pads, must be procured and processed to specifications that cover material supplier, material composition, handling, method of manufacture, and fabrication. Inspect refractory materials after each heat and replace them when deleterious deterioration is noted.

(4) VIM Crucible. The VIM crucible must be prepared to an established procedure and inspected prior to melting rotor grade material to ensure the crucible is clean and undamaged. Sequence heats in the crucible to an established procedure to preclude contamination of follow-on heats.

(5) VIM Mold Preparation. The VIM mold must be dedicated for nickel-base alloys or have a documented procedure for conditioning the electrode surface prior to ESR. A surface conditioning procedure is required for all VAR electrodes. Materials used in the mold assembly and the method of mold preparation and assembly must be to a documented procedure. Clean and inspect electrode molds prior to use to a documented procedure to ensure they are free from rust, oil, grease, coatings and nonmetallic materials.

(6) VIM Melt Parameter Controls. Chamber pressure, metal temperature and power input must be continuously measured and recorded during the melting cycle. Establish limits at the designated control points for the following parameters:

(a) Leak rate and pressure for the furnace chamber prior to power on.

(b) Furnace pressure during back charging.

(c) Metal temperature during refining.

(d) Furnace pressure and difference between consecutive leak rates to indicate the end of refining.

(e) Furnace pressure while making alloy additions.

(f) Metal temperature and stir time after alloy additions.

(g) The percentage dross coverage on the top of the molten metal after all alloy additions have been made and the stir power is turned off.

(h) Record metal temperature, furnace pressure and stir power input during the addition of volatile elements.

(i) Maximum time from the addition of volatile elements to start of pour.

(j) Metal pour temperature, pour rate, and time from the start to the end of pour.

(k) Molten metal level in the tundish during the pour.

(l) Chemical composition of the VIM heat at the start of pour.

(m) Time from end pour to open mold chamber to the atmosphere.

(n) Time from end pour to strip molds from electrodes.

(o) Record of the introduction of any inert gasses added to the VIM heat.

(p) Time from pouring and stripping of mold to heat treat, cooling pits or boxes.

(7) VIM Tundish. Material must be processed through a tundish that removes, by flotation and/or filtration, non-metallic contamination films and exogenous materials and restricts them from entering the electrode molds.

(8) VIM Hot Topping. When performing hot topping, VIM ingots must be hot topped to an established procedure using materials and controls specified in the supplier's procedure. Remove all contaminated hot top material or compound prior to remelt. If not hot topped, VIM ingots should have open pipe covered after stripping to prevent contamination.

c. Electroslag Remelting.

(1) ESR Processing. Melting sources must maintain effective controls for the ESR processes to consistently produce uniform ingots that yield billet/bar material free from deleterious voids, segregation, and inclusions and to meet the chemistry requirements of the material specification. The electrode diameter, melting procedures, and acceptance standards must be established and documented.

(2) VIM Electrode Preparation. Electrode surfaces must be conditioned to remove surface irregularities and previous melt contaminants that would affect ESR processing or contaminate the electrode during remelt. If the VIM molds are not dedicated for nickel-base alloys, the electrode conditioning practice must be in accordance with a documented procedure. The ESR melter must establish acceptance criteria that must include provisions to control the annulus. Photographic or written standards for the conditioned surface must be defined and applied.

(3) Electrode cropping. If cropping of the electrode exposes pipe, shield the cut face to ensure no exogenous material enters the cavity prior to melting. Residual pipe diameter and depth dimensions must be established and met prior to remelting the electrode.

(4) ESR Stub Welding. Conduct electrode stub welding in accordance with a documented procedure that prevents exogenous materials associated with the welding process from entering the ESR furnace. Do not use the TIG welding process for stub welding.

(5) Crucible and Stub Cleaning. Examine the crucible and stubs before each use and clean them in accordance with a documented procedure to remove foreign material. The procedure should describe conditions that do not require cleaning.

(6) ESR Slag.

(a) Slag chemistry and weight. Limits for chemical composition and initial weight of the slag must be established for initial slag charge and for any process additions.

(b) Hot slag start. Establish limits for the slag melting time or temperature, chemistry, and weight. The limits must ensure proper slag chemistry and prevent excessive carbon pickup from the slag-melting crucible.

(c) Cold slag start. Establish limits for chemistry and weight. Storage and handling of the slag and its constituents must prevent moisture pickup.

(d) Protective atmosphere. An inert gas cover may be used to prevent loss of oxidizable elements during ESR. Gas type, minimum flow, and the method used to lay the atmosphere over the slag must be to an established procedure.

(e) Slag additions. When used, slag additions must be made continuously at a rate prescribed in the established procedure. Monitor the slag addition system to ensure that blockage, spillage, or surges do not occur.

(7) Starter Material. The configuration for starting a melt must be to a documented procedure. Starter material should be as follows:

(a) Cold start. Same composition as the alloy to be melted.

(b) Hot Start. A different alloy may be used if it can be demonstrated that no starter material is picked up in the final product.

(c) Starter pellets or tablets must not be used.

(d) Take appropriate measures to ensure that the ESR starter material (plate) is in firm contact with the base plate.

(8) Crucible shielding. Shield the open top of the ESR furnace crucible in a manner that prevents exogenous material from falling into the crucible during the remelting process.

(9) ESR Melt Parameter Controls. Current and voltage must be continuously measured and recorded during the melting cycle. Melt rate must be continuously measured and recorded during the melting cycle. Voltage or resistance swing must be used in the electrode position control system. Establish limits at the designated control points for the following parameters:

(a) Current and power voltage/resistance during start up and transient to steady state conditions.

(b) Swing voltage/resistance and melt rate during the quasi-steady state or main segment of the melting program.

(c) Current or power or melt rate voltage/resistance during transient from steady state to the end of the melt.

(10) Ingot Cooling. Establish a procedure to uniformly and consistently cool the solidifying ingot. Also, establish limits for inlet and outlet crucible water temperature and water flow rate.

d. Vacuum Arc Remelting.

(1) Melting Control. The VAR melter must maintain effective controls for consistently producing uniform ingots that yield billet and bar material free from deleterious

voids, segregation and inclusions. The electrode diameter, melting procedures, start up and hot top practices, and acceptance standards must be established and documented.

(2) VIM Ingot Preparation. Electrode surfaces must be conditioned to remove surface irregularities and previous melt contaminants that would affect VAR processing or contaminate the electrode during remelt. The electrode conditioning practice must be in accordance with a documented procedure. The VAR melter must establish acceptance criteria that includes provisions to control the annulus. Photographic or written standards for the conditioned surface must be defined and applied.

(3) ESR Ingot Processing. If the ESR ingot is to be forged to a smaller diameter, the conversion must be performed to an established procedure. Electrode surfaces must be conditioned to remove scale and slag. Acceptance criteria must be established and should include provisions to control the annulus and photographic and/or written standards for the conditioned surface.

(4) Electrode Cutting. Procedures must be established to define cutting method, standard crop head and toe crop lengths, conditions requiring additional cropping and squareness of cut ends, and straightness in the case of forge back electrodes. Residual electrode pipe diameter and depth dimensions must be established and met prior to remelting the electrode.

(5) Electrode Stub Welding. Conduct electrode stub welding in accordance with a documented procedure that prevents exogenous materials associated with the welding process from entering the VAR crucible. Do not use the TIG welding process for stub welding.

(6) Electrode Stub Cleaning. Stubs must be dedicated for nickel-base alloys. A documented procedure for cleaning and inspecting the stub prior to use is required.

(7) Crucible Cleaning. Clean and inspect the crucible prior to each use in accordance with a documented procedure.

(8) Furnace. The furnace must be dedicated for nickel-base alloys unless a procedure for rigorously cleaning and inspecting the furnace head prior to each campaign of nickel-base alloys is established. Clean and inspect the furnace in accordance with a documented procedure. The procedure must describe any conditions that do not require cleaning.

(9) Hot Top Markers. If hot top markers are used, there must be a documented procedure.

(10) VAR Melt Parameter controls. Process parameters such as furnace pressure, current, voltage, ram travel, melt rate, and the frequency and duration of transient over-voltage pulses or transient arc short circuits (pulse rate/drip short) must be continually measured and recorded during the melting cycle. Actual melt rate must be calculated. Establish limits at the designated control points for the following parameters:

(a) Furnace pressure and leak rate prior to power on.

(b) Furnace pressure, voltage, and current profile during start up and transient to steady state conditions.

(c) Furnace pressure, current, voltage melt rate, melt rate excursions, and the frequency and duration of transient over voltage pulses or transient arc short circuits (pulse rate/drip short) during the quasi-steady state or main segment of the melting program.

(d) Electrode weight or length at the start of the hot top sequence.

(e) Furnace pressure, voltage and the current profile during the transient from quasi-steady state to the end of the melt.

(f) Inert gas (i.e. helium) cooling gas pressure and flow.

(g) Water flow rate and inlet and exit temperatures.

(h) Drip short control parameters.

(11) Ingot cooling. The VAR source must develop procedures to uniformly and consistently cool the solidifying ingot. Limits should be established for inlet and outlet crucible water temperature, water flow rate, inert gas type, and pressure or flow rate.

9. Billet/Bar Conversion, Disk Forging, and Nondestructive Testing (NDT).

a. Control of Billet/Bar Manufacture.

(1) Conversion Process. Specific detailed procedures must exist for the conversion of ingot to billet and bar products. These must include, but are not necessarily limited to:

(a) Billet/Bar Conversion. Perform ingot to billet/bar conversion using controlled, consistent, and detailed procedures.

1 Ingot Conditioning. Establish documented procedures for conditioning the ingot surface prior to heating for forging.

2 Forge Parameter Control. Develop and use documented procedures to control ingot and billet/bar products. These procedures must include, but are not limited to:

- Homogenization time and temperature and cooling procedure for preforge soaking
- 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

3 Forge Practice. Develop forge practices which preclude formation of strain induced porosity (SIP) or clean voids.

4 Records. Maintain reduction sizes, sequences, and temperature records.

(b) Traceability. Billet must be traceable to location and orientation in the VAR ingot. Bar must be traceable to the final VAR ingot and at least to the top, or bottom half of the cropped ingot, and to a section of the original ingot not to exceed 3000 pounds.

(2) Cropping. Any ingot conversion must incorporate a minimum crop of the ingot extremities. Limits for crop lengths should be established to account for the bottom charge and hot topping procedures used for the final melting.

b. Control of Disk/Component Manufacture.

(1) Forging/Heat Treatment Process. Specific detailed procedures must exist for the production of finished rotating components from billet product. These should include but are not necessarily limited to:

(a) Forging Controls. Controlled, consistent, and detailed procedures must be established for the control of the forging process. These must include but are not limited to:

- Furnace loading diagram for each operation;
- Strain profile for each part made; strain may be defined through controlled ram speeds and load/stroke parameters;
- Standard die designation for each forging operation;
- Forging mult weight and diameter; and
- To die and off-die transfer times from furnace and to cooling station respectively.

(b) Thermal Controls. Documented procedures must be established for control of forge/soaking furnace temperature and times.

(c) Heat Treatment Controls. Documented procedures must be established for the control of heat treatment furnaces, atmospheres, times and temperatures.

(d) Quenching. Quench practice and cooling rates must be controlled to ensure freedom from quench related cracking.

(e) Traceability. Traceability of forgings and bar products to billet location must be maintained.

(f) Records. Reduction sizes, sequences, and temperature records must be maintained.

c. Nondestructive Testing and Criteria.

(1) To obtain further confidence that nickel-base alloy rotating parts are free from potentially detrimental anomalies, NDT must be performed at appropriate stages throughout billet/bar and component manufacture. These inspections must be chosen based on melting, billet conversion, heat treatment, and forging processes used and part requirements. Controlled procedures must define the inspection processes and acceptance criteria. Consider the following NDT inspections:

(a) Billet/Bar.

1 Immersion ultrasonic testing.

2 Macroetch inspection of billet/bar ends and slices adjacent to ultrasonic crops.

(b) Forging.

1 Immersion ultrasonic testing.

2 Macroetch of sonic or intermediate machined forgings.

(c) Finish Machined Component.

1 Fluorescent Penetrant Inspection.

(2) 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 are not necessarily limited to:

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

(b) Test Blocks. Test blocks must be manufactured using material with fabrication and ultrasonic characteristics similar to those of the billet or forging being tested. Document calibration procedures adequately to verify the proper operation of the ultrasonic inspection system.

(3) Acceptance Limit. When using scanning systems, set the acceptance limit appropriately (at least 3 db) above the noise level to minimize false calls while maintaining detection sensitivity consistent with design requirements.

(4) Records. Retain electronic data (preferred) or equivalent strip charts according to the engine manufacturer's FAA-approved records retention schedule.

d. Actions Following Indication Detection.

(1) Ultrasonic Indication Characterization of unacceptable indications should be conducted on billet/bar, forgings or finished parts, as appropriate. Report unacceptable indications found in the forging and finished parts to the JETQC (Jet Engine Titanium Committee) in accordance with JETQC practices. At a minimum, report the following information for all indications:

(a) Defect type;

(b) Cross-section defect size;

(c) Cross-section void/crack size, if any;

(d) Ultrasonic inspection calibration and test procedures;

(e) Ultrasonic amplitude;

(f) Ultrasonic signal-to-noise ratio (SNR), if available; and

(g) Indication location in the billet/forging.

(2) For metallic inclusions, report the following additional information:

(a) Microhardness; and

(b) Scanning electron microscope and/or microprobe evaluation: nature of constituents, fractography of void/crack.

(3) Indications Detected In Billet/Bar.

(a) Freckle after all Crops. Review any heat which is shown by billet/bar inspection and indication characterization to contain a freckle. Consider rejecting any heat containing a freckle for a critical rotating part application unless a special cause can be determined which would allow only partial rejection of the heat.

(b) Other Anomalies. Evaluate use of heats with any other anomalies on an individual basis.

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

(5) Associated Heats. Associated heats must be identified and investigated for potentially similar defects as appropriate.

for

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