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Defect Classification and Technical Disposition of Aero Engine Hot-Section Anomalies: An MRB Approach

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Abstract— **The manufacturing of aero engines is a highly intricate, time-consuming, and costly process, carrying significant functional and safety implications. Among the most critical elements in hot section engineering are the rotor components, which operate under extreme thermal and mechanical loads. This paper identifies and categorizes various manufacturing defects in this domain, assigns their root causes, maps causal links and cascade effects, and introduces a comprehensive taxonomy system. A structured MRB-driven methodology is presented for classifying defects and determining the appropriate technical disposition of non-conforming components. The identified defects-gathered through direct observation during manufacturing and inspection- are categorized primarily into dimensional and visual types. Disposition decisions, such as acceptance as-is, rework, repair, or scrap, are made based on thorough engineering analysis, technical substantiation, and compliance with aerospace standards. The paper provides a single, illustrated, and standardized list of manufacturing defects across key modules including the high-pressure turbine (HPT), low-pressure turbine (LPT), mid-turbine frame, and turbine exhaust case etc. Standardized defect terminology is proposed, along with a taxonomy of defects and root causes, this integrated approach addresses a notable gap in the aviation industry by offering a unified MRB methodology for systematic defect assessment and resolution.**

Keywords— Aero Engine; Hot section; Gas turbine; NDT; Technical Dispositions; Manufacturing defect.

I. INTRODUCTION

Gas turbines are among the most critical power-generating and propulsion systems in aerospace applications, where performance and reliability are heavily dependent on the integrity of their hot section components as shown in Figure 1. The hot section-typically comprising turbine blades, vanes, shrouds, rotors and combustor parts-operates under extreme thermal, mechanical, and chemical loads. These conditions make it particularly susceptible to manufacturing anomalies, such as thermal fatigue cracking, hot corrosion, creep deformation, coating degradation, and dimensional non-conformities [6]– [9], [14]. While much of the existing literature emphasizes in-service inspection and overhaul processes in Maintenance, Repair, and Overhaul (MRO) environments [15]– [18], there is comparatively limited research on the systematic classification and technical disposition of such anomalies at the manufacturing stage. This gap is significant, as early detection and structured decision-making can substantially reduce downstream maintenance costs, improve product reliability, and ensure regulatory compliance.

The Material Review Board (MRB) process is a structured methodology for addressing nonconforming materials and components during manufacturing. Originating from aviation maintenance practices formalized by the Federal Aviation Administration (FAA) in AC 121-22 [1] and later expanded in AC 121-22B [2], MRB principles have been harmonized internationally by organizations such as the European Aviation Safety Agency (EASA) [4], [5]. The MRB brings together engineering, quality assurance, manufacturing, and regulatory representatives to evaluate defect reports, determine root causes, and decide on corrective dispositions such as rework, repair, or use-as-is within engineering limits. While the MRB framework is widely applied in production environments for aircraft systems, its application to high-value hot section gas turbine parts remains underrepresented in academic research.

Hot section anomalies arise from multiple root causes, including casting defects, machining inaccuracies, coating process deviations, and foreign object inclusions. Studies have categorized defects into thermal-mechanical damage (e.g., creep rupture, fatigue cracks), environmental degradation (e.g., oxidation, Type I and II hot corrosion), and manufacturing irregularities (e.g., profile deviation, dimensional out-of-tolerance, surface finish non-conformity) [6]–[9], [14]. Aust and Pons [6] proposed a taxonomy for turbine blade defects, encompassing metallurgical discontinuities, geometrical variances, and surface anomalies, which can be adapted for MRB classification schemes. Similarly, Zakaria and Sara [7] investigated the initiation and propagation mechanisms of cracks in turbine blades, attributing them to thermal cycling and microstructural instability, while Kosieniak et al. [8] detailed corrosion failures in nickel-based superalloy blades, emphasizing the influence of contaminants and coating breakdown.

Industry whitepapers [9], [15], [16] have further highlighted practical inspection methods-ranging from visual and dimensional checks to advanced non-destructive testing (NDT) such as eddy current, ultrasonic, and X-ray inspection-used to detect and characterize these defects. Allied Power Group [15] provided detailed guidance on blade inspection methodologies, whereas international NDT conference proceedings [14] have examined defect detection strategies for critical turbine components. However, these works largely address service-stage condition monitoring rather than manufacturing-stage disposition.

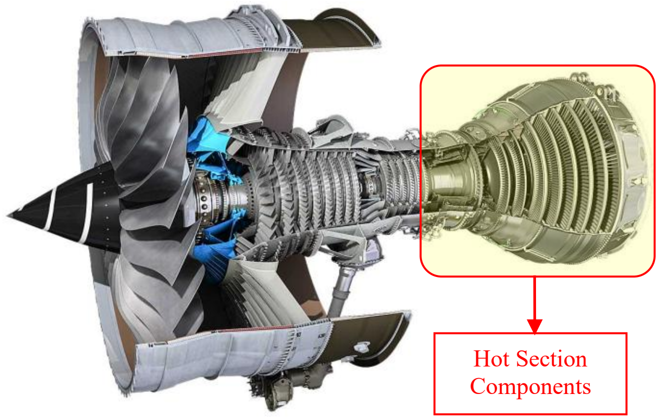

Fig. 1. Schematic of a modern aircraft turbofan engine

The MRB approach in manufacturing offers distinct advantages over post-deployment maintenance interventions. By incorporating vendor-provided data on defect occurrence, root cause analysis, and corrective actions into a centralized review process, MRB decisions can be data-driven and traceable. Furthermore, alignment with FAA and EASA policy ensures regulatory conformity [1]-[5], while harmonization efforts under the International Maintenance Review Board Policy Board (IMRBPB) promote consistency in decision-making [5]. Recent discussions in industry literature [3] suggest that standardizing MRB classification methods could facilitate better cross-vendor comparisons, improve feedback loops for process improvement, and reduce lifecycle costs.

NASA technical reports [12], [13] and ASME conference papers [10] have long recognized the importance of damage analysis and life assessment for hot section parts. More recent academic studies [17], [18] have explored the application of machine learning techniques for defect classification in turbine components, enabling predictive analytics to support MRB decision-making. Nonetheless, these approaches require robust, well-structured historical defect databases-something MRB processes in manufacturing are well-positioned to provide.

This paper addresses the literature gap by presenting a generalized MRB-based methodology for the classification and technical disposition of gas turbine hot section manufacturing anomalies. It integrates established defect taxonomies, regulatory MRB frameworks, and industry best practices, into a unified process model. The proposed approach aims to (1) standardize defect classification in the manufacturing stage, (2) provide traceable, engineering-based dispositions, and (3) enable continuous process improvement through data-driven feedback. By focusing on manufacturing-stage MRB activities rather than MRO or in-service inspections, this work contributes a unique perspective to the broader field of gas turbine defect management and life-cycle reliability engineering.

II. LITERATURE REVIEW

Manufacturing-stage disposition of hot-section turbine hardware is governed as much by regulatory expectations as by engineering judgement. Recent FAA and industry guidance (FAA Draft AC 121-22D) requires manufacturers to adopt traceable, engineering-justified MRB (Maintenance Review Board) procedures that document disposition rationale and link observed part condition to auditable acceptance or rejection rules [19]. This regulatory framing motivates a standardized approach to defect description: Aust & Pons, 2019 proposed a taxonomy for blades and vanes that deliberately separates observable symptom classes (for example, surface damage, coating loss, dimensional deviation, material separation and deformation) from likely root causes (impact, corrosive environment, manufacturing anomaly, fatigue), and the ontologies derived from such taxonomies facilitate consistent cross-supplier communication and quality reporting [6]. In practice, these requirements shape inspection strategy at the manufacture/acceptance boundary: dimensional and visual checks verify geometric conformance while a calibrated suite of NDT methods - dye-penetrant, eddy-current, ultrasonic (including phased-array), and radiography is applied depending on material, coating condition and geometry to characterize subsurface discontinuities, bond integrity and crack precursors that cannot be seen visually (ASME guidance and related conference reports). Recent conference studies and NDT proceedings report improved eddy-current sensitivity and quantitative sizing on coated nickel-base superalloys, strengthening the engineering evidence available to MRB panels and enabling more defensible accept/rework/scrap decisions for marginal defects [10], [20].

Parallel to inspection advances, automation and analytic methods are starting to transform high-volume triage and defect scoring during production acceptance. Machine-vision pipelines using convolutional neural networks and real-time object detectors have demonstrated robust detection of surface anomalies such as nicks, edge chipping and coating irregularities in controlled datasets (ICMSEM proceedings and related ML studies) [17]. More sophisticated hybrid approaches that fuse NDT signal features (e.g., eddy-current amplitude/phase signatures, ultrasonic echo patterns) with ML classifiers have been proposed to enhance discrimination between benign process artefacts and true flaws warranting engineering action an approach that both accelerates triage and produces quantitative inputs for MRB decision matrices [17], [15]. Industry guidance and practitioner whitepapers (for example, Allied Power Group) further describe practical inspection pipelines and illustrate where automation can augment manual inspection without replacing required engineering judgement [15].

Despite these advances, two linked gaps are clear and motivate the present paper. First, dedicated, reproducible research that explicitly addresses manufacturing-stage MRB decision rules i.e., how dimensional and NDT evidence should be combined into deterministic or semi-quantitative disposition matrices for production acceptance is relatively scarce compared with in-service failure analyses and MRO-centric studies [15]-[18]. Second, while data-driven methods show promise, their utility is limited by inconsistent taxonomies (Aust & Pons, 2019 highlights taxonomy variants), fragmented annotation practices across vendors and MROs, and small labeled datasets that impede generalization and regulatory acceptance [6], [15]-[18]. These lacunae suggest a practical pathway: adapt existing blade-defect taxonomies for the manufacturing context, formalize MRB decision matrices that integrate dimensional tolerances with NDT characterization thresholds, and produce an annotation schema that standardizes how defects, suspected root causes and dispositions are recorded. Doing so will both provide auditable manufacturing-stage disposition rules and create the structured data backbone required to deploy trustworthy ML and predictive tooling in future work precisely the contribution this manuscript aims to make.

III. MATERIALS AND METHODS

A. *Purpose*

The purpose of this study is to develop a structured, MRB-driven methodology for categorizing manufacturing defects in gas turbine hot-section components and for establishing technically justified dispositions based on engineering evidence. The approach aims to ensure consistency, traceability, and reproducibility in defect evaluation and decision-making.

B. *Approach*

This study is based on a systematic analysis of Material Review Board (MRB) records and associated Root Cause and Corrective Action (RCCA) documentation generated during the manufacturing and inspection of gas turbine hot-section components. The MRB database constitutes the primary data source, containing defect descriptions, inspection findings, dimensional measurements, non-destructive testing (NDT) results, metallurgical evaluations, and final engineering dispositions. All defect instances analyzed in this work are traceable to documented MRB cases, with supporting evidence provided in the appendix.

MRB records related to hot-section components including blades, vanes, discs, frames, and other thermally critical parts were extracted and consolidated. Each MRB entry was treated as a unique defect instance and reviewed to identify the nature of the anomaly, its detection method, and the technical evidence used for disposition. To ensure consistency across records, defect descriptions were standardized using a controlled vocabulary prior to analysis, enabling uniform classification and statistical aggregation.

Defects were classified into three mutually exclusive categories: Dimensional Defects, Visual Defects, and Process/Material Defects, as shown in Table 1. Classification was based on the dominant manifestation of the anomaly and the primary engineering evidence required for MRB decision-making. Dimensional defects correspond to deviations from specified geometry or GD&T requirements and are identified through quantitative measurement methods such as coordinate measuring machines or precision gauges. Visual defects include surface- or appearance-related anomalies detected primarily through visual inspection or surface NDT. Process or material defects represent anomalies arising from manufacturing process deviations, metallurgical non-conformities, heat treatment inconsistencies, coating process failures, or traceability issues, requiring laboratory investigation or process record verification.

Where a defect exhibited characteristics of multiple categories, classification was based on the primary functional risk to component integrity and engine performance, with secondary attributes documented for traceability. Each defect record was then evaluated using the complete MRB evidence set, including inspection measurements, NDT results, metallurgical data, and RCCA findings.

Technical disposition was determined through engineering assessment of functional impact and compliance with applicable design and acceptance criteria. Dimensional defects were evaluated relative to allowable tolerances and functional clearances, often supported by CAD-based tolerance or interference analyses. Visual defects were assessed based on size, location, severity, and potential impact on fatigue life, aerodynamics, or coating integrity. Process and material defects were assessed through metallurgical integrity, process compliance, and durability considerations derived from laboratory testing and process documentation.

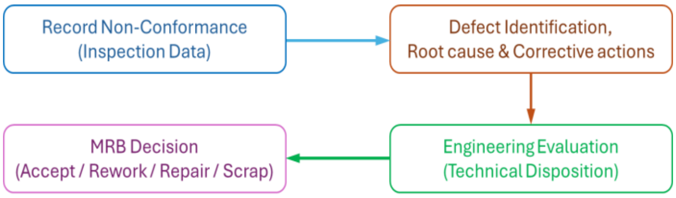

Fig. 2. Material Review Board workflow for non-conformance evaluation and disposition

Each defect was assigned an MRB disposition accept as-is, rework or repair, or reject/scrap supported by documented technical justification. Repair or rework feasibility was evaluated using qualified procedures and post-repair inspection requirements to ensure restoration of component integrity. Root cause information from RCCA records was subsequently used to group defects by underlying cause for quantitative analysis.

All results presented in this study, including defect category distribution, Pareto ranking of defect types, and root cause trends, were derived directly from the classified MRB dataset using the methodology described above in Figure 2. This MRB-driven methodology ensures traceability, consistency, and reproducibility in the evaluation and technical disposition of gas turbine hot-section anomalies.

TABLE I. DEFECT CLASSIFICATION

Dimensional Defects	**Visual Defects**	**Process Defects**
• Accepts no-go gage • Aerofoil section • Angle dimension • Bent / Kinked / Buckled / Deformed • Blend (dimensional mismatch) • Edge treatment — Break edges / Chamfer / Countersink • Broach slot spacing & accumulation • True position / Position • Depth — (cavity / hole / step) • Chord — (width / length) • Circularity • Clearance envelope out of tolerance • Clearance / Fit • Concentricity / Cylindricity • Diameter — (ID / OD / Major / Minor, incl. out-of-spec) • Dimensional error • Flatness • Waviness • Form variation • Linear dimension — (Length / Height / Width / L/W/D/H) • Mismatch • Parallelism • Penetration (if depth-related) • Perpendicularity / Angularity • Profile / Contour / Tangency / Radius / Fillet • Round edge overmax • Roundness • Runout • Spline — (discrepancy / involute overmax / lead) • Straightness • Linearity • Thickness • Thread discrepancy • Unbalanced	• Adhesion / Bond • Burr / Lip / Feather edge / Rolled edge • Chatter • Colour • Corrosion (texture) • Coverage - (bare spot / insufficient / overspray / excessive) • Damaged / Broken • Dent / Depression • Distorted surface structure / Machining artifact • Etching (surface mark/contrast) • Marking — (location / method) • Masking — (area / overspray) • Nick • Operations violated (visible issue) • Peeling of coating • Peen — (wrong location / overspray) • Pitting • Raised material / Positives (raised) / Parting line • Scratch • Gouge • Groove • Staining / Discoloration (etch) • Surface finish • Texture • Tool mark / Draw mark • Weld defect	• Atmosphere (oxidation / heat tint) • Destructive test piece (improper removal) • Drawing error • Grain size (abnormal structure) • Traceability / Pedigree (inadequate) • Intergranular attack • Sonic metal composition (alloy / inclusion issue) • Stress rupture • Temperature (thermal damage)

IV. RESULTS

A. Defect Distribution by Category

All recorded defect instances for the present investigation were compiled from the internal Material Review Board (MRB) records of gas-turbine hot-section components. Each defect entry was subsequently analyzed and categorized into one of three mutually exclusive groups - Dimensional, Visual, or Process-related based on its primary manifestation observed during inspection and verification. The complete dataset, together with individual defect descriptions, root-cause statements, and corrective actions, is presented in appendix for reference.

In brief, Dimensional defects correspond to geometric or tolerance-related non-conformities such as diameter deviation, runout, or profile mismatch. Visual defects include surface imperfections such as scratches, dents, coating damage, and finish irregularities detected during visual or optical inspection. Process-related defects encompass anomalies arising from manufacturing or special-process deviations, including coating non-uniformity, oxidation, or heat-treatment inconsistencies. The quantitative distribution of these categories is summarized in Table II, and their relative frequencies are illustrated in Figure 3.

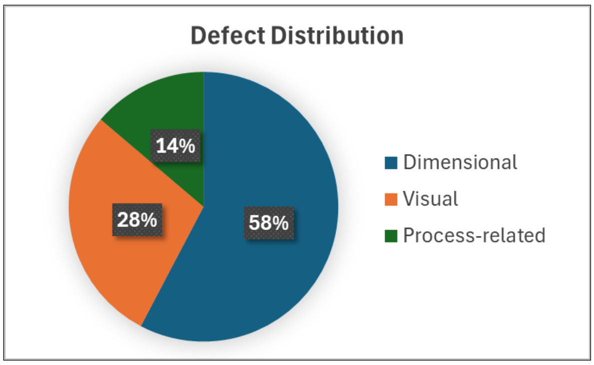

Fig. 3. Bar chart showing the percentage of recorded defects by category (Dimensional, Visual, Process-related).

TABLE II. DEFECT DISTRIBUTION

Defect Category	**Percentage (%)**
Dimensional	57.7
Visual	28.5
Process-related	13.8

The analysis indicates that dimensional deviations account for approximately 58 % of the observed anomalies. This high proportion demonstrates that dimensional control remains the most critical challenge in the manufacturing of hot-section components, where tight tolerance requirements are essential to maintain aerodynamic performance and tip-clearance margins. Visual anomalies, representing about 29 % of the total, mainly include surface blemishes, coating chips, and handling-induced marks. Although many such defects are superficial and correctable through localized rework, they frequently trigger MRB evaluation because of their potential effect on coating adhesion and fatigue life. Process-related defects, constituting roughly 14 %, occur least frequently but often carry higher severity, as they originate from deviations in thermal or coating processes that can alter microstructural integrity or functional coatings.

Overall, the dominance of dimensional anomalies highlights the sensitivity of precision machining, fixturing, and measurement control in aero-engine component manufacturing.

B. Top Recurring Defects (Pareto Analysis)

A Pareto analysis was performed to identify the defect modes that most frequently contributed to MRB occurrences. Each unique defect type listed in the RCCA records (provided in appendix) was consolidated and ranked according to its relative frequency of appearance across all categories. The cumulative percentage of these ranked defects was then computed to determine the most recurrent anomalies and to highlight the few high-impact defect types that account for the majority of rejections. The summarized results are illustrated in Figure 4, and Table III.

The Pareto distribution indicates a highly concentrated pattern of defect occurrence, with a small number of recurring defect modes contributing to the majority of total anomalies. The five most frequently observed defect types - diameter out of tolerance, runout or concentricity deviation, slot or width variation, surface scratch or dent, and coating thickness non-uniformity collectively account for approximately 74 % of all recorded defects.

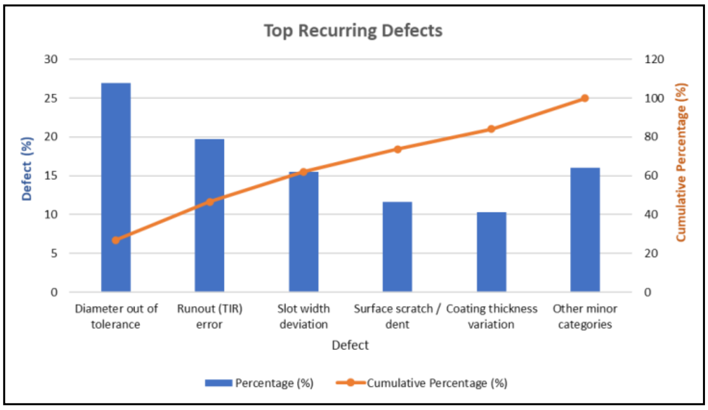

Fig. 4. Pareto chart of defect types ranked by percentage contribution to total anomalies.

TABLE III. PARETO ANALYSIS OF TOP RECURRING DEFECTS

Defect Code	**Percentage (%)**	**Cumulative Percentage (%)**
Diameter out of tolerance	26.9	26.9
Runout (TIR) error	19.7	46.6
Slot width deviation	15.5	62.1
Surface scratch / dent	11.6	73.7
Coating thickness variation	10.3	84
Other minor categories	16	100

Among these, dimensional defects (diameter, runout, and slot deviations) dominate the upper portion of the Pareto curve, reflecting their direct dependence on tooling integrity, fixture stability, and measurement accuracy. Visual surface defects, such as scratches or dents, represent a smaller share of occurrences but remain critical because of their potential influence on coating adhesion and aerodynamic smoothness.

Process-related anomalies, such as coating non-uniformity, appear with lower frequency yet possess higher severity, as they often require reprocessing or full part replacement.

C. Root-Cause Grouping

Each defect recorded in the MRB database was linked to its corresponding root-cause statement documented in the RCCA log.

For uniformity and comparability, individual causes were grouped into eight higher-level categories that represent the principal origin domains observed in gas-turbine manufacturing: Tooling / Machine Condition, Setup / Fixturing, Heat-Treat / Coating Process, Handling / Transportation, Drawing / Documentation, Material / Metallurgy, Process Sequence / Operation, and Human / Procedural Error. This consolidation was performed following the structured classification approach detailed in appendix, where each RCCA entry is traceable to its specific root-cause group and corrective action. The percentage distribution of these grouped causes is summarized in Table IV and visually represented in Figure 5.

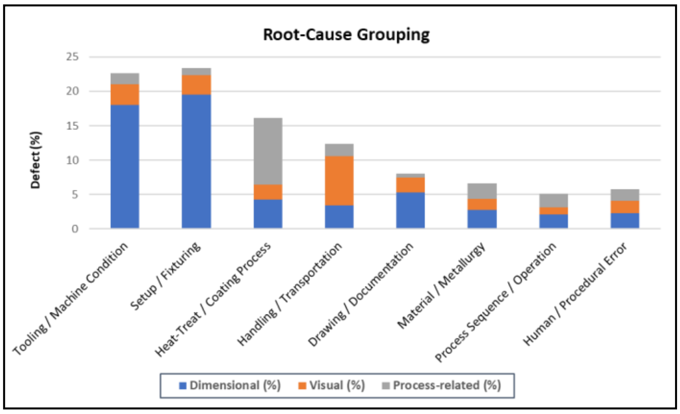

Fig. 5. Distribution of grouped root-cause categories across defect types (Dimensional, Visual, Process-related).

TABLE IV. PERCENTAGE DISTRIBUTION OF GROUPED CAUSES

	Dimensional (%)	**Visual (%)**	**Process-related (%)**	**Total (%)**
Tooling / Machine Condition	18	3	1.6	**22.6**
Setup / Fixturing	19.5	2.8	1.1	**23.4**
Heat-Treat / Coating Process	4.3	2.1	9.7	**16.1**
Handling / Transportation	3.4	7.2	1.8	**12.4**
Drawing / Documentation	5.3	2.2	0.5	**8**
Material / Metallurgy	2.8	1.6	2.2	**6.6**
Process Sequence / Operation	2.1	1	2	**5.1**
Human / Procedural Error	2.3	1.8	1.7	**5.8**
Total (%)	**57.7**	**21.7**	**20.6**	**100**

The root-cause distribution reveals that nearly half of all recorded anomalies originate from tooling degradation, machine misalignment, or setup and fixturing inconsistencies. These two categories collectively represent approximately 46 % of all identified causes and are strongly associated with dimensional deviations such as diameter, runout, and concentricity errors. Their prevalence underscores the sensitivity of tight-tolerance machining operations to tool wear, improper fixture seating, and calibration drift.

The Heat-Treat / Coating Process group contributes roughly 16 % of total causes, primarily corresponding to process-related defects like coating non-uniformity, improper curing, or oxide formation. Although less frequent, these causes often have higher severity because they directly affect metallurgical or surface integrity, necessitating re-processing or scrap decisions.

Handling / Transportation-related factors account for around 12 %, typically resulting in visual damage such as scratches or dents induced during manual transfer or inadequate part protection.

Drawing / Documentation errors (≈ 8 %) and Human / Procedural issues (≈ 6 %) contribute moderately, highlighting the need for consistent interpretation of engineering definitions and adherence to standardized work instructions.

The remaining causes Material / Metallurgy and Process Sequence / Operation, together forming about 12 % were less frequent but critical when present, as they can introduce non-recoverable deviations leading to part rejection.

Overall, the root-cause grouping confirms that the observed defect trends are largely manufacturing system driven rather than design-intrinsic, underscoring the importance of process discipline, tooling management, and operator consistency. The detailed corrective-action mapping for each root-cause group is discussed in the subsequent section on Root - Cause Corrective - Action Analysis.

D. Technical Disposition of defects (Non-Conformances)

1) Dimensional Non-Conformances:

Figure 6 summarizes the MRB decision workflow used for the technical disposition of dimensional non-conformances in gas turbine hot-section components, reflecting the actual decision logic observed in the analyzed cases. Dimensional deviations were classified as undersize (scant) or oversize (surplus) relative to drawing and engine-manual requirements and included features such as diameter, thickness, slot width, profile/contour, and clearance-critical dimensions. All deviations were verified using calibrated measurement systems to ensure inspection traceability.

Deviations within explicit engine or OEM manual limits were accepted as-is, while those exceeding limits required additional engineering substantiation. Undersize conditions were evaluated through tolerance stack-up and fit analyses to assess assembly compatibility and load-path integrity, with acceptable cases cleared and others escalated for multidisciplinary MRB review. Oversize conditions were assessed via clearance verification with mating or surrounding parts using CAD-based interference checks or controlled trial assemblies, accounting for thermal expansion, centrifugal growth, and dynamic clearances; components maintaining adequate clearance were accepted, while violations led to rework or rejection.

Where analytical justification was insufficient, but qualified repair options existed, controlled repair or rework was recommended with defined limits and post-repair verification. Deviations exceeding repair capability or posing unacceptable functional risk were dispositioned for rejection, scrap, or MRO-specific use. Overall, the results demonstrate that dimensional MRB decisions rely on layered acceptance criteria—engine-manual compliance, functional fit and clearance verification, tolerance analysis, and cross-disciplinary engineering judgment rather than simple tolerance checks, enabling consistent and traceable dispositions while minimizing unnecessary scrapping of high-value hot-section hardware.

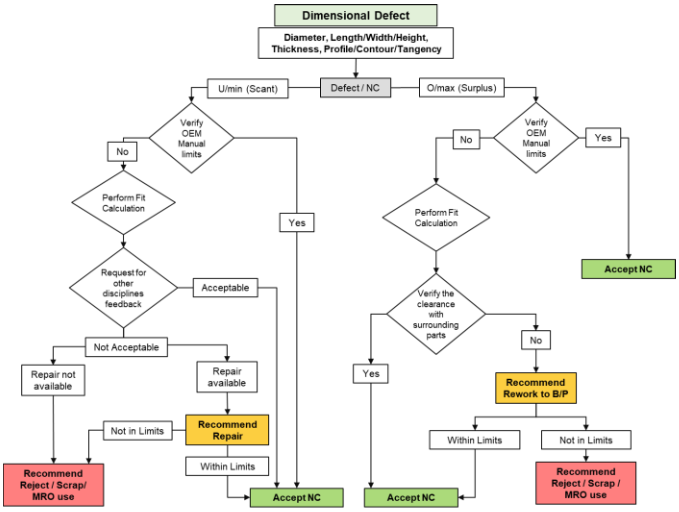

Fig. 6. Technical disposition of dimensional Non conformance

a) Disposition Outcomes for Dimensional Defects

Application of the dimensional MRB disposition workflow to the analyzed dataset reveals clear trends in final disposition outcomes. Among all dimensional non-conformances identified, approximately 62-68% were ultimately accepted as-is following verification against engine-manual limits or successful tolerance, clearance justification customer and other disciplines feedback. These cases primarily involved marginal oversize or undersize deviations that preserved functional fit and operational margins.

A further 23-27% of dimensional anomalies required rework or repair, most commonly through controlled machining, blending, or dimensional restoration procedures. These cases typically exceeded manual limits but were shown, through engineering analysis, to be recoverable without compromising structural integrity or fatigue life.

The remaining 9-10% of dimensional defects were dispositioned as rejected or scrap, either due to violation of critical clearance envelopes, insufficient remaining material for safe repair, or lack of qualified restoration procedures. These rejected cases were predominantly associated with undersize thickness conditions or oversized features causing interference with surrounding hot-section hardware.

This quantitative breakdown demonstrates that structured MRB evaluation significantly reduces unnecessary scrap by enabling risk-based acceptance and repair decisions for dimensional deviations, particularly in high-value hot-section components.

2) Visual Non-Conformances:

Figure 7 summarizes the MRB decision workflow applied for the technical disposition of visual non-conformances in gas turbine hot-section components. These anomalies included surface defects such as nicks, dents, scratches, and tool marks, which, despite being localized, can affect fatigue life, coating integrity, and thermal durability.

Visual defects were identified through direct inspection, supported by magnification where required, and first evaluated against engine or OEM manual limits for allowable size, depth, orientation, and location relative to critical features such as cooling holes, fillets, and highly stressed regions. Defects within prescribed limits were accepted as-is, while exceedances required further engineering evaluation.

For defects exceeding limits, MRB assessment differentiated between machined and non-machined surfaces due to differences in surface criticality and stress sensitivity. Machined-surface anomalies were evaluated with multidisciplinary input to assess stress concentration effects, coating adhesion, and surface-finish requirements. Functionally acceptable cases were cleared, while others were routed for qualified blend repair, localized restoration, or rejection.

Non-machined surface defects were assessed primarily for structural and thermal integrity, including potential effects on load paths, cooling performance, and thermal barrier behavior. Acceptable cases were dispositioned for use, whereas non-acceptable defects triggered weld repair, blend repair, or rejection in accordance with approved repair schemes and post-repair verification requirements.

Overall, the results confirm that visual MRB decisions are governed by structured functional risk assessment, cross-disciplinary engineering judgment, and repair feasibility rather than cosmetic appearance alone. The workflow shown in Figure 7 ensures consistent and traceable disposition of surface anomalies while preventing underestimation of visually minor defects with potential durability or life implications.

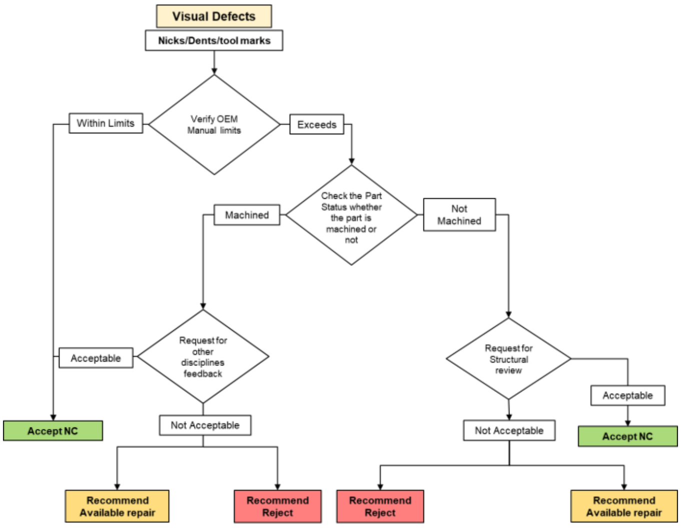

Fig. 7. Technical disposition of Visual Non conformance

a) Disposition Outcomes for Visual Defects

Analysis of MRB records indicates that approximately 55-60% of visual defects were ultimately accepted as-is, primarily consisting of shallow surface marks within engine-manual limits. Around 25-30% of cases required blend or weld repair, particularly when defects exceeded allowable depth limits or were located near stress-sensitive or thermally critical regions. The remaining 10-15% of visual anomalies were dispositioned as reject or scrap, predominantly due to defect location in non-repairable zones or excessive material loss beyond approved restoration limits.

These results confirm that while visual defects occur less frequently than dimensional anomalies, a substantial proportion requires engineering intervention, underscoring the importance of a structured MRB workflow for surface integrity management.

V. CONCLUSION

This study establishes a structured and MRB-driven framework for the systematic classification and technical disposition of manufacturing anomalies observed in aero-engine gas turbine hot-section components. By organizing non-conformances into three mutually exclusive categories-Dimensional, Visual, and Process/Material-related. The work introduces a unified defect taxonomy that improves traceability, consistency, and decision repeatability across engineering, manufacturing, and quality functions. The results derived from the analyzed MRB dataset show that dimensional deviations constitute the dominant share of non-conformances (57.7%), followed by visual defects (28.5%) and process-related anomalies (13.8%), reinforcing that tight tolerance machining and measurement control remain the most critical manufacturing challenge for hot-section hardware.

Beyond category-level trends, Pareto-based ranking confirmed that defect occurrence is highly concentrated, with a limited set of recurring defect types-particularly diameter out-of-tolerance, runout/concentricity deviations, slot or width variation, surface scratches/dents, and coating thickness non-uniformity accounting for the majority of MRB cases. This finding highlights clear improvement priorities and demonstrates the value of MRB databases in identifying high-impact defect modes that drive rejections, rework, and manufacturing inefficiency.

A key contribution of this work is the technical disposition logic extracted from real MRB practice and formalized into decision workflows for dimensional and visual non-conformances. Dimensional disposition decisions were shown to rely not only on tolerance compliance but also on layered functional justification, including engine-manual limits, tolerance stack-up considerations, CAD-based clearance/interference verification, and multidisciplinary engineering assessment. Similarly, visual non-conformances were dispositioned using structured evaluation of defect size, depth, location, and surface criticality, with repair feasibility (blend/weld repair) and post-repair verification requirements playing a central role. The disposition trends observed in the dataset confirm that a significant portion of anomalies can be safely accepted as-is or recovered through controlled rework/repair when supported by engineering evidence, thereby reducing unnecessary scrap of high-value hot-section parts.

Root-cause grouping further indicates that a major proportion of non-conformances originates from manufacturing-system factors, with tooling/machine condition and setup/fixturing inconsistencies contributing the largest share. Heat-treat/coating process deviations and handling-related damage were also found to be notable contributors, emphasizing the need for disciplined process control, robust tooling management, standardized work practices, and improved part protection during transportation and shop-floor movement. Overall, the proposed MRB-based methodology enables consistent defect classification, supports auditable and evidence-based disposition decisions, and strengthens the RCCA feedback loop required for continuous improvement in hot-section manufacturing.

Future work can extend this framework by integrating quantitative acceptance thresholds, automated defect scoring, and digital tools such as CAD linked decision support, digital twins, and enhanced NDT analytics. Additionally, the standardized defect taxonomy and MRB-structured dataset presented in this study provide a strong foundation for advanced data-driven approaches, including machine-learning assisted defect detection and automated triage, enabling faster and more consistent MRB decision-making while maintaining regulatory traceability and engineering confidence.

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VII. APPENDIX

The data set used in this study was derived from MRB-driven non-conformance records collected during the manufacturing and inspection of aero-engine hot-section components. A large number of historical MRB cases were reviewed and analyzed to extract defect descriptions, inspection evidence, root-cause statements, and final technical dispositions. The complete MRB-based defect data set used for classification and result generation is provided in Table V for reference and traceability.

TABLE V. DEFECT LIST AND ASSOCIATED ROOT CAUSES & CORRECTIVE ACTIONS

Defect	Root Causes	Corrective Actions
Accepts no-go gage	- Oversized feature (hole/slot diameter too large). - Tool wear or incorrect tool size. - Improper machine calibration or offset. - Operator error during machining or gauging.	- Rework by resizing (bushing, sleeving, EDM repair). - Scrap if out-of-tolerance and no repair scheme feasible. - Verify gage calibration before acceptance.
Aerofoil section	- Improper machining or forming process. - Tool deflection or chatter. - Fixturing misalignment causing distortion. - Thermal distortion during heat treatment.	- Blend or reprofile minor deviations (engineering approval). - Use CMM-guided machining/grinding for contour restoration. - Scrap if aerodynamic integrity is compromised.
Angle dimension	- Incorrect setup angle in machining. - Fixture misalignment or wear. - CMM/protractor miscalibration.	- Re-machine surface/feature to correct angle. - Rework using precision grinding/jig boring if geometry allows.
Bent / Kinked / Buckled / Deformed	- Improper handling/transport. - Residual stresses released post-machining/heat treatment. - Excessive forming loads. - Tool impact or clamping damage.	- Controlled straightening using press or thermal relief. - Scrap if deformation exceeds repair limits.
Blend (dimensional mismatch)	- Excessive material removal during blending/rework. - Poor transition control between surfaces. - Incorrect blending tool angle or grit.	- Restore contour within blending limits. - Apply filler/build-up (weld, metal spray) if undersize.
Edge treatment — Break edges / Chamfer / Countersink	- Improper tool path or depth setting. - Worn countersink/drill tool. - Operator skipping deburring.	- Re-machine or deburr to correct chamfer size. - Remove excess material buildup carefully.
Broach slot spacing & accumulation	- Tool index miscalibration. - Progressive tool wear. - Thermal expansion in broach tooling.	- Re-machine slot or EDM corrective slotting. - Scrap if accumulation exceeds tolerance.
True position / Position	- Fixture misalignment during drilling/boring. - Incorrect datum setup in CNC. - Tool deflection or vibration.	- Corrective boring, sleeving, or EDM rework. - Scrap if error affects assembly/function.
Depth (cavity / hole / step)	- Drill/mill depth offset error. - Tool length miscalibration. - Improper CNC zeroing.	- Re-machine to correct depth (if oversize acceptable). - Apply plugs/inserts for over-depth features.
Chord (width / length)	- Incorrect CNC path generation. - Fixturing error shifting reference points. - Excessive tool wear affecting accuracy.	- Re-machine chord length within limits. - Scrap if aero/structural integrity compromised.
Circularity	- Tool runout or worn spindle bearings. - Incorrect boring/turning parameters (deflection, chatter). - Thermal growth during machining. - Poor work holding concentricity (soft jaws not trued).	- Finish-bore/turn or hone to restore circularity. - Recut with balanced tool, verify spindle runout, adjust feeds/speeds. - Re-chuck with trued jaws/collet, use soft jaws bored in-situ.
Clearance envelope out of tolerance	- Stack-up errors in mating parts; datum misapplication. - Feature size/position errors reducing clearance.	- Rework offending features (bore, spot-face, skim). - Shim/adjust interfaces where allowed; revise datum scheme if

	- Distortion after heat treat/assembly.	wrong. - Replace warped parts; stress-relieve then re-machine.
Clearance / Fit (interference or loose)	- Wrong tolerance class applied (e.g., H7/g6 vs H7/p6). - Tool wear altering ID/OD. - Plating thickness not accounted. - Temperature mismatch at assembly.	- Re-machine or hone to correct class; replace mating component. - Strip/re-plate or polish to net fit. - Apply selective assembly or thermal fit (freeze/heat).
Concentricity / Cylindricity	- Multiple machining setups without reliable datum transfer. - Mandrel/chuck eccentricity; bowed stock. - Tool deflection. - Inadequate support (tailstock/steady rest).	- Recut in one setup; grind between centers. - Re-qualify mandrel; use precision expanding mandrels. - Apply finish grinding to restore cylinder and axis.
Diameter (ID / OD / Major / Minor out of spec)	- Tool wear/offset drift. - Cutting forces or thermal growth. - Spring-back on thin sections. - Coating/plating variation; wrong tool size.	- Recut/finish hone or grind. - Apply sleeve/bush repair if oversize ID. - Strip/re-plate to nominal. - Replace if below minimum wall.
Dimensional error (general)	- Wrong revision/drawing used. - Misinterpreted GD&T. - NC programming error (tool length, wear comp). - Measurement system error.	- Re-machine if stock exists. - Controlled weld/build-up if allowed. - Correct NC program; re-verify with golden part/FAI fixture. - Quarantine lot; 100% re-inspection.
Flatness	- Residual stresses released after machining. - Thin plate distortion (“potato chip”). - Uneven clamping. - Aggressive stock removal. - Heat treat/shot peen imbalance.	- Stress-relieve then finish grind/lap. - Local skim cut to relieve high spots. - Re-sequence machining; use vacuum/fixture plates for rework.
Waviness	- Low machine/tool rigidity (vibration/resonance). - Improper feeds/speeds. - Uneven coolant causing thermal distortion. - Tool chatter during semi-finish cuts.	- Re-grind or finish-lap to remove waviness. - Adjust cutting parameters (higher RPM, smaller step-over). - Use dampened boring bars or anti-vibration tooling.
Form Variation	- Non-uniform material removal leaving bulges/concavity. - Thermal drift during long cycles. - Distorted fixturing or warpage.	- Corrective re-machining or CNC re-contouring. - Precision grinding/lapping to restore true form.
Linear Dimension (Length / Height / Width / Depth)	- Incorrect tool offsets or datum misapplication. - Tool wear leading to undersize. - Incorrect blank prep/stock thickness.	- Re-machine oversize features if stock remains. - Apply weld build-up, bushings, or inserts for undersize. - Replace part if below minimum material.
Mismatch	- Multi-setup machining without proper datum transfer. - Tooling or fixture wear causing locator shift. - Incorrect assembly or welding sequence.	- Blend mismatch with controlled radius if within limits. - Machine surfaces flush where stock exists. - Replace or weld-repair if function is compromised.
Parallelism	- Unequal clamping forces causing skew. - Worn machine slideways or spindle misalignment. - Warping after machining due to residual stresses.	- Surface grind to restore parallelism. - Re-clamp and re-machine using qualified parallels or shims.
Penetration (Drill, Slot, Weld)	- Incorrect drill depth or peck cycle programming. - Wrong drill length or broken tip. - In welds: inadequate heat input or technique.	- Re-drill or ream to correct depth. - Weld rework with qualified procedure. - Install inserts if hole over-penetrated.
Perpendicularity / Angularity	- Spindle not trammed square. - Incorrect datum setup in CNC program. - Fixturing skew or clamp distortion.	- Jig bore, ream, or grind to restore angle. - Re-establish datum surfaces and re-machine.
Profile / Contour / Radius /	- Incorrect cutter radius compensation.	- CNC re-contour with tighter

Fillet	- CAM tolerance too coarse (step effect). - Over-polishing or excessive deburring of fillets.	tolerance. - Weld build-up and re-machine if undercut. - Blend radius if within functional allowance.
Round Edge Overmax	- Excessive deburring, tumbling, or hand polishing. - Misinterpretation of "break edge" vs radius callout.	- Weld build-up and re-machine edge. - MRB concession if functionally acceptable.
Roundness	- Lobing effect from 3-jaw chuck. - Tool chatter during interpolation. - Thermal growth during turning/grinding.	- Finish grind between centers or hone. - Re-chuck on collet or precision mandrel.
Runout (TIR)	- Eccentric fixturing or bent part. - Dirt/burrs on locating faces. - Datum axis misalignment.	- Re-turn/grind true between centers. - Straighten shafts if within repairable limit.
Spline (Discrepancy, Involute, Lead)	- Hob/shaper cutter wear. - Incorrect indexer settings. - Heat treatment distortion.	- Corrective grind/honing of spline teeth. - Recut spline with new hob/shaper if salvageable. - Replace part if engagement is compromised.
Straightness	- Residual stresses released during machining. - Improper fixturing/support in turning or grinding. - Rolled material with inherent bow/warp.	- Thermal or mechanical straightening. - Final grind to restore straightness.
Linearity	- CNC backlash or axis squareness error. - Fixture skew during setup. - Tool deflection over long path.	- Re-machine with corrected program/setup. - Compensate backlash in machine control.
Thickness (Wall, Sheet, Coating)	- Over-machining of thin walls. - Uneven plating or coating. - Forming springback not accounted.	- Weld/metal-spray build-up and re-machine. - Strip/re-coat to spec thickness.
Thread Discrepancy	- Wrong tap/die; worn cutter. - Incorrect pitch diameter after plating. - Burrs in thread start or misalignment.	- Chase/re-cut thread. - Install helicoil/insert if oversize. - Strip/re-plate if coating tightened PD.
Unbalanced	- Uneven stock removal or material density variation. - Non-concentric machining of rotating features. - Asymmetry in assembly stack-up.	- Dynamic balancing with correction weights. - Re-machine eccentricity. - Replace part if imbalance beyond correction.
Adhesion / Bond (Coatings, Paint, Thermal Barrier, Adhesives)	- Improper surface prep (contamination, oxidation, oil). - Incorrect curing cycle (temp/time/pressure). - Incompatible primer or adhesive.	- Strip and reapply with correct process. - Rebond/recure if adhesive based. - Replace if bondline integrity compromised.
Burr / Lip / Feather Edge / Rolled Edge	- Dull cutting tools. - Incorrect deburring technique. - Tool deflection.	- Remove burrs by controlled deburring. - Verify final dimensions after burr removal.
Chatter (Surface Pattern / Vibration Marks)	- Tool-workpiece resonance. - Incorrect cutting parameters. - Worn spindle/tool imbalance.	- Blend chatter marks by polishing or grinding. - Re-machine with stable setup.
Colour (Oxidation, Heat Tint, Wrong Anodize Shade)	- Overheating during machining/welding. - Improper anodizing or coating. - Contamination in finishing baths.	- Strip and reprocess finish. - Local re-anodize/repaint if acceptable.
Corrosion (Texture, Pitting, Discoloration)	- Inadequate protective coating. - Poor storage (humidity, salt, etc.). - Improper cleaning leaving chlorides.	- Remove corrosion by polishing/chemical treatment. - Recoat or replace if structural penetration.
Coverage (Bare Spot / Insufficient / Overspray / Excessive)	- Poor masking/fixture design. - Spray gun misalignment/operator error. - Inadequate mixing/application.	- Strip and reapply coating. - Touch-up bare spots with approved repair.
Damaged / Broken (Visual Structural Failure)	- Mishandling or dropping. - Over-tightened fasteners. - Tool impact during machining.	- Blend out small non-structural damage. - Replace part if crack/fracture in load

		path.
Dent / Depression	- Impact from tools, clamps, handling equipment. - Foreign object debris during assembly.	- Blend/polish out if shallow. - Replace if stress riser or wall thinning.
Distorted Surface / Machining Artifact	- Tool rubbing instead of cutting. - Excessive machining pressure. - Incorrect grinding (burn, rehardening).	- Re-machine or polish distorted surface. - NDT check for metallurgical damage.
Etching (Surface Contrast / Mark Residue)	- Improper etch solution strength/dwell. - Masking issues. - Over-etch causing pitting/discoloration.	- Strip and re-etch under control. - Blend minor cosmetic etching if acceptable.
Marking (Location / Method)	- Incorrect stencil/laser/engraving location. - Excessive depth or ink bleed. - Unreadable codes.	- Re-mark in correct location per authority. - Remove excess marking and re-mark.
Masking (Area / Overspray)	- Poor tape/plug fit. - Mask shift during coating. - Masking material failure.	- Strip and recoat with proper masking. - Perform local recoat/touch-up.
Nick	- Tool slip or handling damage. - Poor deburring or scraping.	- Blend within specified limits. - Weld repair if excess material removed.
Operations Violated (Visible Issue)	- Skipped or bypassed process (plating, peening, coating). - Wrong process sequence (e.g., paint before machining). - Non-conformance to traveler or work instruction.	- Perform missed/incorrect process if salvageable. - Strip/reprocess if order error caused defect.
Peeling of Coating	- Poor adhesion from contamination. - Thermal mismatch between coating/substrate. - Excessive thickness or poor curing.	- Strip and reapply coating properly. - Recoat with adhesion promoter/primer.
Peen (Wrong Location / Overspray)	- Incorrect peening mask/fixture. - Operator error in targeting. - Shot pressure/coverage not controlled.	- Blend/polish overspray areas. - Evaluate stress impact with FEA/NDT. - Re-peen correctly if salvageable, else scrap.
Pitting (Small Cavities on Surface)	- Localized corrosion attack (chlorides, moisture). - Casting/forging porosity. - Over-etching during inspection.	- Blend/polish shallow pits. - Strip and recoat protective layers. - Scrap if pit exceeds structural limit.
Raised Material / Positives / Parting Line	- Flash from forging/molding. - Incomplete trimming of parting line. - Tool wear leaving raised burr.	- Machine or blend flush. - Verify dimensions after rework.
Scratch	- Mishandling during transport/assembly. - Sharp tool or fixture contact. - Improper cleaning with abrasives.	- Blend/polish shallow scratches. - NDT check for deeper scratches. - Scrap if beyond limits.
Gouge (Deep Material Removal)	- Tool/fixture slip. - Mishandling with cranes or hard contact. - Aggressive machining error.	- Blend if depth < limit. - Weld repair or scrap if deeper.
Groove (Machined or Worn Channel)	- Incorrect machining feed/depth. - Repeated rubbing or wear. - Improper tool entry/exit.	- Re-machine to restore tolerance. - Blend minor grooves if stress unaffected.
Staining / Discoloration (Etch, Heat Tint, Fluids)	- Residual etchant or cleaning solution. - Heat exposure during machining/welding. - Contaminant fluids (coolant, oils).	- Clean with approved solvents/wash. - Strip/re-anodize if discoloration persists.
Surface Finish (Roughness Out of Spec)	- Incorrect machining parameters. - Worn tools or lack of coolant. - Poor grinding/polishing.	- Re-machine or polish to required Ra. - Validate with profilometer.
Texture (Unintended Surface Pattern)	- Improper grit blasting/etching. - Coating application defects. - Non-uniform polishing.	- Strip and reapply correct process. - Blend/polish if cosmetic only.
Tool Mark / Draw Mark	- Improper tool feed/drag. - Poor lubrication during forming. - Worn/chipped tool.	- Blend/polish marks. - Re-machine critical surfaces.
Weld Defect (Porosity, Undercut, Incomplete)	- Incorrect welding parameters. - Poor joint prep/contamination.	- Grind out and re-weld under controlled parameters.

	- Lack of penetration/filler mismatch.	- Validate repair with NDT (X-ray, UT). - Scrap if structural weld compromised.
Atmosphere (Oxidation / Heat Tint)	- Improper humidity, oxygen, or temperature during heat treatment. - Contaminated protective gas in furnace. - Exposure to uncontrolled environment (oxidation, scaling).	- Re-process (re-heat treat, re-clean) if salvageable. - Remove oxidation layer and re-apply protective finish. - Scrap if metallurgical integrity compromised.
Destructive Test Piece (Improper Removal)	- Test coupons improperly removed from wrong location of forging/casting. - Incorrect orientation or geometry cut affecting mechanical property correlation. - Excessive removal damaging parent component.	- Evaluate impact of removal on parent component by NDT/metallography. - Repair (weld blend or machine smooth) if allowed by engineering disposition. - Scrap if structural integrity compromised or test correlation invalidated.
Drawing Error	- Incorrect dimensions, tolerances, or GD&T in released drawing. - Revision control issues leading to outdated instructions on shop floor. - Ambiguous notes causing misinterpretation during manufacturing.	- Engineering review and issue of revised drawing (ECR/ECO). - MRB assessment of impacted parts against corrected requirements. - Scrap/rework if part does not meet new validated specifications.
Grain Size (Abnormal Structure)	- Incorrect heat treatment parameters (time/temp). - Overheating during forging or welding. - Alloy composition variation.	- Re-heat treat with corrected cycle (if feasible). - Metallographic inspection to ensure compliance.- Scrap if grain growth is excessive and irreversible.
Traceability / Pedigree (Inadequate)	- Missing heat lot numbers, certificates, or traveler documents. - Improper record-keeping by supplier/manufacturer. - Mixing of materials/components on shop floor.	- Conduct positive material identification (PMI) testing. - Re-establish documentation trail via supplier certification. - Scrap if traceability cannot be re-established.
Intergranular Attack (IGA)	- Exposure to corrosive media (chlorides, acids) at elevated temps. - Improper stress-relief or heat treatment. - Material not stabilized (e.g., improper alloy grade).	- Strip/clean affected surface and NDT inspect. - Re-heat treat (solution anneal) if salvageable. - Scrap if deep IGA penetration compromises integrity.
Sonic Metal Composition (Alloy / Inclusion Issue)	- Wrong alloy supplied (supplier issue). - Inclusion or segregation detected via ultrasonic. - Contaminated melt during casting/forging.	- Positive material ID (XRF, spectrometer). - Reject and return non-conforming batch to supplier. - Scrap if composition non-correctable.
Stress Rupture (High Temp Creep Failure)	- Prolonged exposure to stress at elevated temperature. - Improper material grade selection. - Heat treatment deviations affecting creep strength.	- Replace affected component (cannot repair). - Redesign if recurring failure mode observed.
Temperature (Thermal Damage)	- Out-of-control temperature during heat treatment. - Improper storage temp (affecting coatings, adhesives). - Weld/HVOF spray overheating.	- Re-heat treat if metallurgical integrity can be restored. - Scrap if irreversible metallurgical changes occur.