Dielectric Failures Reduction: A Mechanical and Process Engineering Approach

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Abstract

Dielectric failures account for approximately 65% of total defects in the Main Stator Cell of an aerospace manufacturing facility. This study identifies mechanical interaction during manual forming operations as the primary root cause, rather than purely electrical phenomena. Contact mechanics analysis using the Hertzian model reveals that conventional steel pliers generate contact pressures of approximately 1.10 GPa, far exceeding enamel insulation tolerance. A dedicated Delrin forming tool reduces contact pressure by 99.5%, friction forces by 75%, and bending stress by 75.2%. Complementary process improvements—including standard work updates, dedicated dielectric test operations, and operator training—achieved a 37% reduction in Scrap, Rework, and Repair (SRR) costs and a 30% reduction in Parts Per Million (PPM) defect rate, surpassing the established 35% SRR target. Key Terms: Contact mechanics, Dielectric failure, PPM, SRR.

Introduction

The aerospace manufacturing industry demands extremely high precision and strict compliance with engineering specifications to ensure the reliability components. A significant portion of these processes rely on manual forming operations, making part handling a decisive factor in product quality. No prior initiative had been exclusively dedicated to their systematic root-cause elimination. This project addresses that gap by combining contact mechanics modeling with structured manufacturing process improvement.

Background

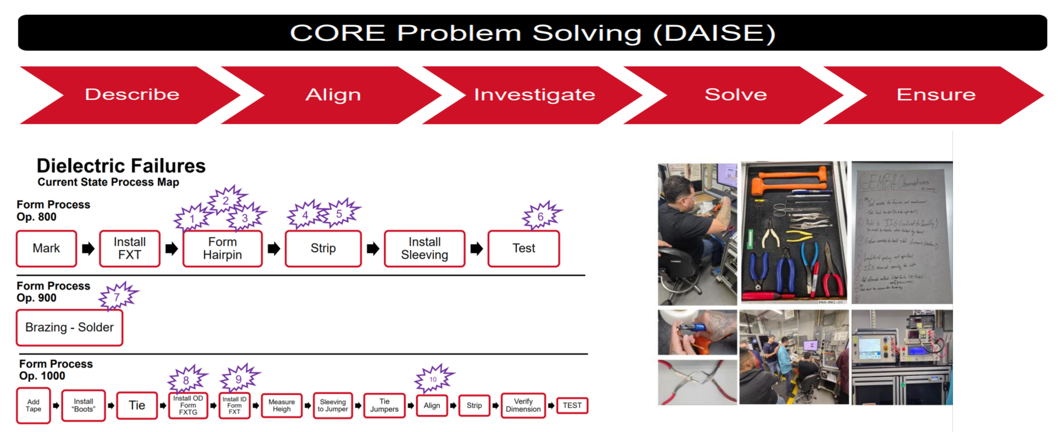
Dielectric failures—ground faults and phase-to-phase shorts—represent the dominant defects in aerospace stator manufacturing. The Hertzian contact model for cylindrical bodies provides the theoretical framework for quantifying contact pressure, friction, and bending stress at the wire-tool interface. Delrin offers an elastic modulus fundamentally altering the contact stress regime and providing the theoretical basis for the proposed tool redesign.

Problem

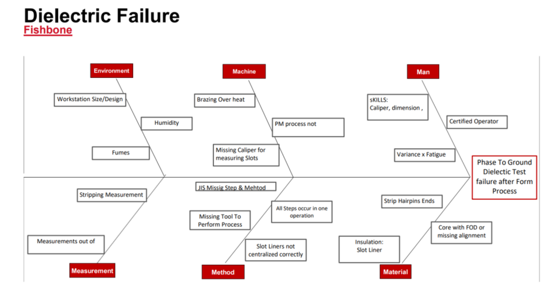
Dielectric failures producing: (1) SRR costs of $200,000 (2) PPM defect rate of 622,042 ppm; (3) delays to Manufacturing Date (DTM); (4) delays to On-Time Delivery (OTD); (5) increased process variability; (6) A critical quality escape. Standard work was incomplete, no root cause analysis existed, and no forming training program was available. Given the aerospace application and long service life under predictive maintenance programs, these failures were unacceptable.

Methodology

A multidisciplinary engineering approach integrated manufacturing process analysis, root cause identification, and quantitative mechanical modeling. (1) Current State Analysis: assessed forming process, inspection methods, and operator practices to identify inefficiencies.



(2) Root Cause Analysis: a Fishbone (Ishikawa) Diagram developed during a Quality Kaizen event revealed three root cause categories—inadequate tools (Machines), incomplete standard work (Methods), and insufficient operator skill (Man).



(3) Mechanical Modeling: Hertzian contact model applied to AWG 16 magnet wire (d=1.25 mm, enamel t=0.025 mm) under forming conditions (F=150 N, θ=15°). Contact half-width, maximum contact pressure, friction force, bending moment, and safety factors were computed for steel plier vs. Delrin tool.

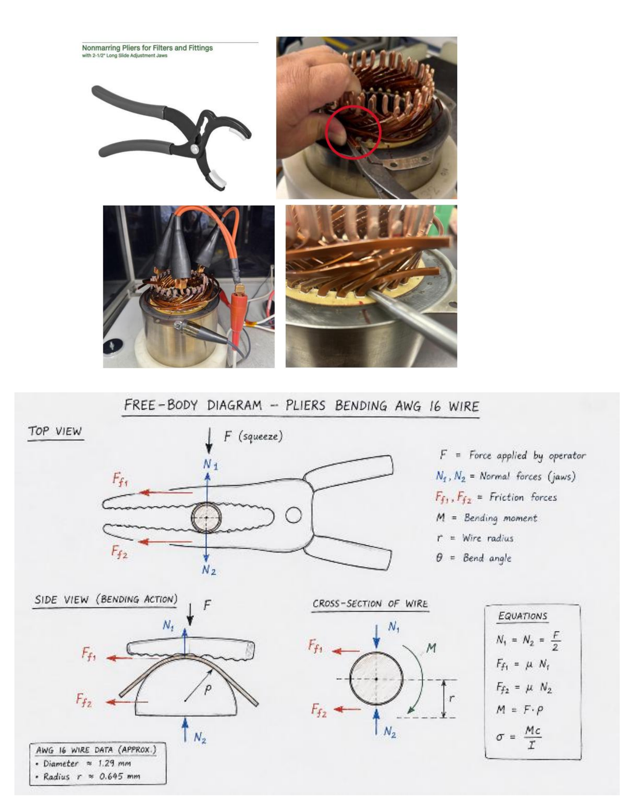
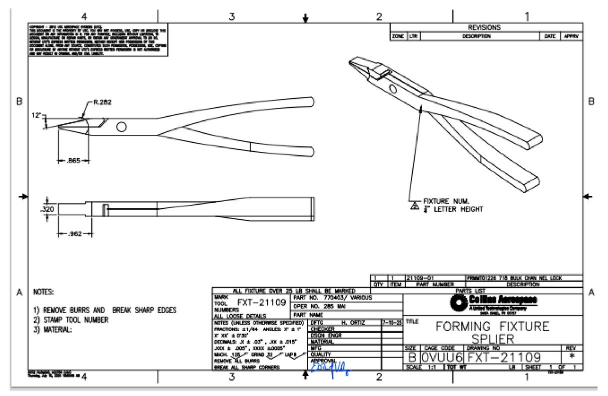


Figure 1. Free Body Diagram

(4) Process Improvements: standard work (JIS) updates, new dedicated dielectric test operation, operator training program and dedicate tool design (Delrin).

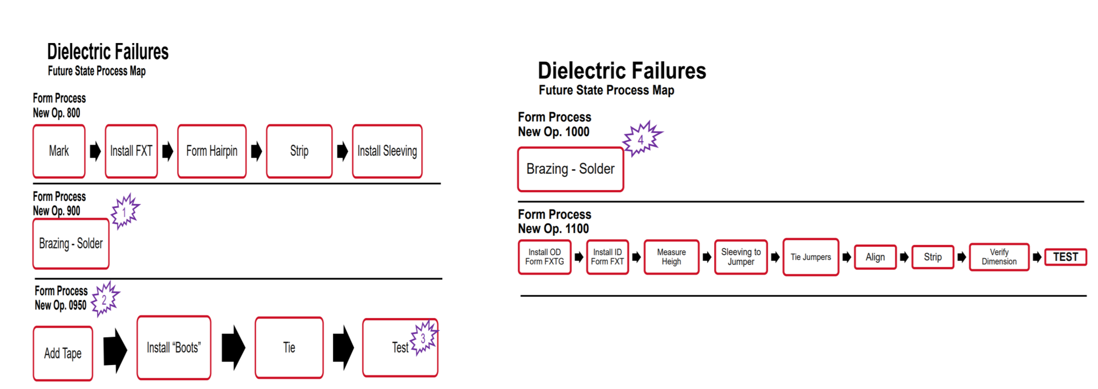
Results and Discussion

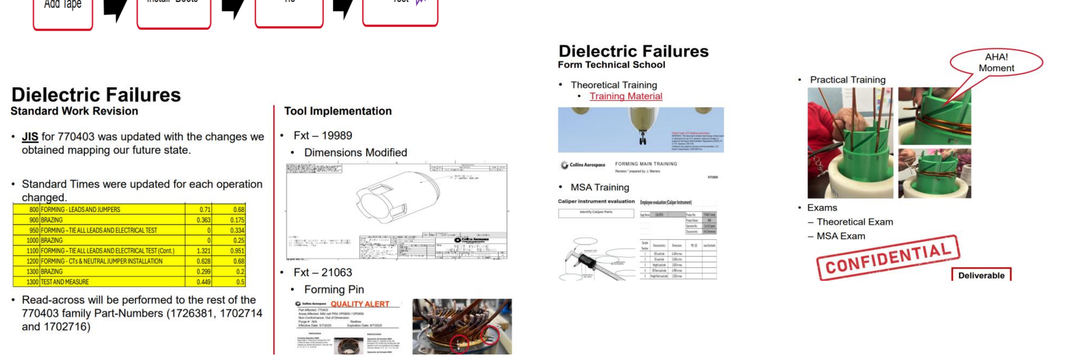
Mechanical Analysis: Steel pliers generate pmax ≈ 1,099 MPa (1.10 GPa), a contact half-width b ≈ 17.37 µm, friction force Ff = 45 N, and bending stress σ ≈ 152.7 MPa—yielding an enamel safety factor of only 0.15 (below 1.0, failure inevitable). The dedicated Delrin tool reduces pmax to 5.12 MPa (99.5% reduction), expands contact half-width to 1,866 µm (uniform load distribution), reduces friction by 75%, bending stress by 75.2%, and raises enamel safety factor to 4.49.



Parameter	Steel Plier	Delrin Tool	Reduction
Equivalent Modulus E*	79.24 GPa	3.434 GPa	≦23 ×more compliant
Contact Half-Width b	17.37 µm	1,866 µm	Uniform load distribution
Max. Hertz Pressure pmax	1,099 MPa	5.12 MPa	99.5%
Max. Shear Stress τmax	334 MPa	1.56 MPa	~99.5%
Friction Force Ff	45.0 N	11.25 N	75%
Bending Moment M	28.13 N·mm	7.031 N·mm	75%
Bending Stress σ	152.7 MPa	37.87 MPa	75.2%
Safety Factor (enamel)	0.15	4.49	Enamel protected
Safety Factor (copper)	0.46	1.85	Core protected

Process Improvements: Operation renumbering (1100→1200, 1200→1300, 1300→1400), JIS updates for Operations 800/900/950, new dedicated dielectric test operation, alternate dielectric fixture (Op. 1000), and jumper brazing operation.





Deliverables Assessment

Deliverable	Before	Target	Final Status
Root Cause Analysis	Not developed	Complete	Completed
Standard Work Review (Forming Area)	Not developed	Complete	Completed
Process Modification (Tools & Fixtures)	Not existing	Develop/Modify	Implemented
Forming Process Training Program	Not existing	Create	Proposed
Dielectric Defect Categorization	Not differentiated	Optimize	Optimized

Performance Outcomes: SRR reduced 37% (target: 35% ✓); PPM reduced 30% (target: 35%—partially met). All 5 planned deliverables completed.

Conclusions

Dielectric failures in the Main Stator Cell are primarily driven by mechanical—not electrical—mechanisms. Conventional steel pliers generate contact pressures (~1.10 GPa) far exceeding enamel insulation limits, with a safety factor below 1.0. The dedicated Delrin forming tool eliminates these conditions, reducing contact pressure by 99.5% and achieving a safety factor above 4.0 for the enamel layer. Complementary process improvements—standard work updates, dedicated dielectric test operations, improved defect categorization, and operator training—collectively achieved a 37% SRR cost reduction (exceeding the 35% target) and a 30% PPM reduction. Tool design and process standardization are decisive factors in dielectric failure prevention for aerospace stator manufacturing.

Future Work

Read-Across Analysis for other Main Stator Cell processes. Expansion of dielectric failure prevention strategies across additional product families. Further optimization of forming tools and operator training programs. Integration of predictive quality analytics for early defect detection.

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