Qualifying of Metallic Materials and Structures for Aerospace Applications

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The U.S. Navy's certification and qualification process for materials and structures is undertaken to ensure the flight safety and full mission capability of naval aviation weapon systems. A building-block process is practiced in which validated engineering data and concepts provide the foundation for continued technological development and innovation. For example, prior to developing material-property standards, the manufacturing process is frozen and fully characterized. The customer's cost, schedule, and performance requirements must be carefully considered. Technologies are selected for immediate use or further R&D based upon a risk assessment that takes into account many factors, including technological maturity, lessons learned, the sponsor budget and schedule constraints, affordability, return on investment, and life-cycle cost impact. This paper explores the process that the navy uses to qualify its airframe alloys and structures.

INTRODUCTION

Naval aircraft routinely operate in the harshest environments in the world. The catapult take-off and arrested landings are conducted on a moving airstrip 305 meters long, that is, one-tenth the size of conventional runway. Salt water, stack gases, jet exhaust, and austere maintenance conditions (i.e., little fresh water) combine to form a highly corrosive environment. Figure 1 shows a salt-water washed U.S. Navy aircraft secured to the deck of an aircraft carrier in heavy seas. Although protected with corrosion inhibitors and paints, the structural alloys used must have intrinsic corrosion resistance. Resistance to general corrosion, galvanic corrosion, pitting, exfoliation, stress-corrosion cracking, and corrosion fatigue must be considered. The use of environmentally sensitive alloys, such as high-strength steels, magnesium alloys, and peak aged 7000 series aluminum alloys are closely managed.

The principle objective of the qualification process is to deliver a quality product, fit for use,[1] to the warfighter. The navy designs its aircraft structures to maintain a single-flight probability of catastrophic failure of less than 1×10^{-7}, and uses crack initiation as the primary measure of airframe life for metallic structures. The navy philosophy is to design to a severe usage spectrum and maintain its aircraft with the intention of repairing or replacing primary airframe structures prior to crack initiation. This philosophy impacts every aspect of how an aircraft is managed, including its design, certification, in-service monitoring, and life re-evaluation. The latter is especially important as the navy seeks to extend the useable life of its aging fleet of aircraft. Today, the average age of a navy aircraft is 17.2 years; this figure is expected to continue to rise and stabilize at 20 years.[2] Importantly, many of the navy's types, models, and series of aircraft are significantly older.

Because the nondestructive evaluation (NDE) of alloys and structures is essential to the navy's process, structural components and alloys are designed with NDE in mind. Consideration must be given to the manufacturing process used, types of defects present, the effect of defects, and the compatibility and sensitivity of NDE techniques.

Figure 1. Bow wave washes aircraft in salt water.

THE DESIGN AND CERTIFICATION DRIVERS

The design and certification drivers for structures and materials[3] are inexorably linked together with virtually all material and structural design and certification requirements stemming from a few basic drivers.

Fundamental airframe design and certification drivers applied to naval aircraft include[4–7]

- Performance comparable/superior to land-based aircraft
- Single-flight probability of failure $< 1 \times 10^{-7}$
- No planned structural repairs during aircraft service life
- No planned structural non-destructive inspections during aircraft service life
- No corrosion repair during aircraft service life

THE MATERIALS CERTIFICATION PROCESS

The safe operation, readiness, and support of naval aviation systems rely on a disciplined approach (see Figure 2) that establishes strong linkages between fleet needs, program needs, and materials technologies. Fleet and program needs are continually identified and translated into performance-based technical requirements. Candidate materials technologies are then identified to address those needs. Preferred materials technologies receive certification at that point at which a complete characterization of the technology has been documented.

A systems-engineering design approach is utilized to translate the customer's performance-based requirements into certified materials technologies.[8] The process for the certification of materials technologies follows:[7,9,10]

- The identification of customer requirements and expectations.
- The translation of customer requirements and expectations into materials technologies.
- The prioritization and selection of candidate materials technologies.
- The development, standardization, characterization, and demonstration of materials technologies.
- The transition of preferred materials technologies.

Essential to the process are thoughtful consideration and affirmative answers to three important questions:

Has the Materials Technology Been Developed and Standardized?

The process by which a material is produced must be fully developed and standardized. That is, the material must be produced according to a fixed process specification and have been registered in accordance with an industry or military standard (e.g., an aerospace material specification). These standards contain material and process specification requirements consistent with conditions representative of the processing and manufacturing environment. The contents of a typical standard (e.g., AMS 2759/2C or AMST81915) include the scope of the standard, reference to applicable documents, technical requirements, provisions for quality assurance, preparation for delivery, and notes.[11,12]

Has the Materials Technology Been Fully Characterized?

Statistically substantiated, mechanical property minimum data (consistent with requirements of *Military Handbook 5 [MIL HNDK 5],* "Metallic Materials and Elements for Aerospace Vehicle") must be generated for the materials and processes used.[13] For metallic materials, the navy prefers the use of A Basis Allowables. Ninety-nine percent of the population exceeds minimum property data reported with a 95% confidence level. The product used to determine mechanical properties must be from production material using production facilities and standard fabrication and processing procedures. To ensure consistency, the test population must include ten lots of material from at least two production heats, casts, or melts for each product form.

Because it determines the physical, mechanical, and chemical property requirements of the alloy, the operational environment of the candidate alloy must be considered. Typically, these material property data exceed the scope of *MIL HNDK 5.*[13] Therefore, test data sufficient to statistically substantiate the alloy's behavior in its operational environment must be developed.

Some material factors to consider are static-strength requirements, fatigue-crack initiation, fracture toughness, fatigue-crack growth, corrosion and embrittlement, environmental stability, producibility, availability, repairability, costs, fabrication characteristics, inspectability, erosion and abrasion, wear characteristics, compatibility with other materials, thermal and electrical characteristics, hard coating to improve wear resistance, and metallic plating to provide galvanic compatibility.

Furthermore, NDE techniques must be shown to be capable of detecting representative defects, and the effect of defects on materials properties must be understood and characterized. Also, the limitations of the NDE techniques being applied must be understood, along with the probability of detecting processing and manufacturing defects.[14,15]

Has the Materials Technology Been Demonstrated?

The candidate materials technology must be demonstrated on sub-components specimens representative of those contemplated for use. Verification that an alloy can be satisfactorily produced in the form and size of the intended application is required. NDE techniques for detecting alloy and manufacturing defects found in the product must be demonstrated—defects may be intentionally introduced into the material to assess their effect on alloy properties and the ability of NDE techniques to detect them.

STRUCTURAL DESIGN AND CERTIFICATION PROCESS

The U.S. Navy airframe fatigue philosophy is to design, certify, monitor, and maintain aircraft with the intent to repair or replace all airframe parts prior to crack initiation.[4,16] The development of widespread crack initiation sites in the structure defines the upper limit of airframe fatigue life.[17] The navy's operational experience indicates that cracks initiate from initial flaws, poor design details, or from the exceedance of design Kts Allowables. The Naval Air Systems Command structural integrity policy may be divided into three phases: design and certification, in-service monitoring, and life re-evaluation. Important factors to consider include service goals and

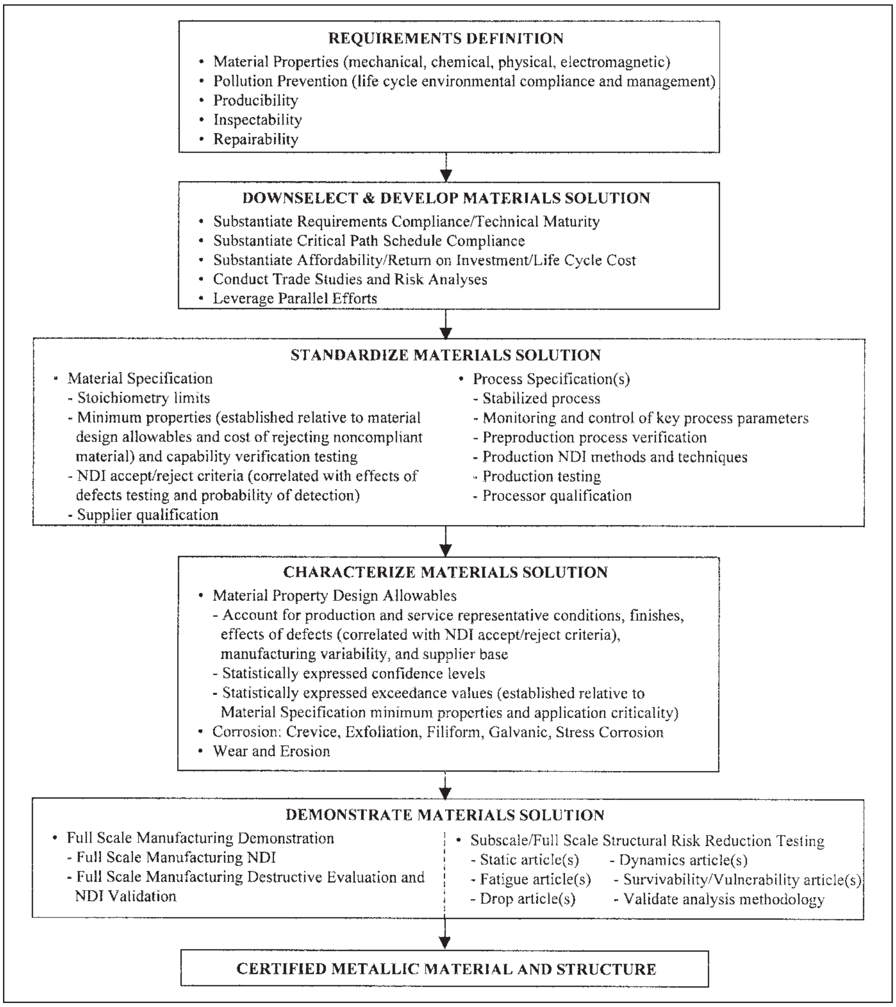

Figure 2. A building-block approach to materials qualification and certification.

usage, identification of critical areas, fatigue and stress analysis, developmental testing, airplane and component testing, fatigue performance analysis, design and manufacturing processes, aircraft in service experience, and inspection intervals.

Structural Design and Certification

The certification consists of three steps: design iteration, ground verification test, and flight tests. The following design criteria are applied for static strength properties. For metallic materials, the design criteria are A Basis Allowables, and for composite materials, B Basis Allowables are used. For metallic structures, no gross section yielding at 115% of the design limit load (DLL) is permissible, and no catastrophic failure at 150% of the DLL is acceptable. For the landing-gear assembly, no gross section yielding is permitted to occur at the peak design load.

The criteria for fatigue properties of metallic structures prohibit crack initiation in one lifetime of the aircraft. Typically, in order to ensure the latter, the design analysis must demonstrate that no cracks will form in 2.7–4 lifetimes. The design spectrum used is robust. The test spectrum is established in the aircraft specification and, except for point-in-the-sky, is based on the usage experience of similar type aircraft. The points-in-the-sky (Mach and altitude) for the overall test spectrum are required to be a combination that provides at least 80% of the maximum possible fatigue damage for each sub-component. The maximum damage is the amount of damage a sub-component would sustain assuming that all aircraft maneuvers occurred at the most critical point in the sky for that component. The spectrum employed is for an aircraft with 60% internal fuel and representative mission stores.

To further ensure structural integrity, a damage-tolerant design criterion is also applied. For metallic structures, cracks of 0.25 mm in size must not propagate to its critical flaw size (a_c) in one lifetime. The critical flaw size must be equal to or greater than 6.4 mm at the DLL, and the maximum stress intensity must be less than the threshold for K_{ISCC} with 0.25 mm flaw. Airframe members suffering significant cross-section-area reduction from a 6.4 mm crack are to be assumed as severed and a fail-safe criteria applied. The entire primary structure, with the exception of horizontal stabilizer spindles and wing pivots, must demonstrate fail-safe capability to limit load.

Ground tests are conducted on the airframe and airframe sub-components (Figure 2) to verify the aircraft design criterion are satisfied and to ensure structural integrity. Verification includes static, fatigue, and drop tests. Static tests also ensure that buckling occurs at the predicted load levels and the residual stress in the landing gear does not exceed the K_{ISCC} threshold. Fatigue-test verification entails testing to two (three is preferred) lifetimes of design spectrum. A successful test means that no cracks 0.25 mm long initiate.

Drop tests are performed on navy aircraft to simulate the loads experienced during a carrier landing. The airframe is dropped at up to the design-sink rate of 8–9 m/s. The primary purpose is to measure dynamic response and evaluate landing gear load-stroke performance. Finally, flight tests verify load and stiffness predictions, flutter, carrier suitability, and store release loads.

Service Life Management

A detailed review of the manner in which the navy manages its aircraft is beyond the scope of this paper. However, because that process has a significant effect on design and certification, the management philosophy will be delineated. The Aircraft Structural Life Surveillance Program tracks individual aircraft usage employing counting accelerometers or multi-parameter recorders. Accelerometer and parametric recorder data are processed and subsequently converted to fatigue-life expended (FLE) values for each aircraft. On a quarterly basis the Structural Appraisal of Fatigue Effects Report is issued which provides FLE data for each aircraft, along with life projections and other usage information. Component life limits, derived from fatigue testing, are issued in a Service Life Bulletin on an as-required basis. Aircraft or aircraft components that exceed their FLE are removed from service.

A Service Life Assessment Program (SLAP) is typically undertaken after the fleet-average FLE passes 50%. The SLAP is an extensive, destructive, teardown inspection of at least one aircraft combined with a reassessment of service usage and component failure history. This assessment involves extensive use of NDE, fractography, and scanning electron microscopy in order to detect and characterize fatigue cracks. The SLAP provides further confirmation of the accuracy of fatigue life predictions.

References

1. Douglas C. Montgomery and George C. Runger, *Applied Statistics and Probability for Engineers*, 2nd edition (New York: John Wiley & Sons, Inc., 1999).
2. Capt. John Rosa, 4th Int. Aircraft Corrosion Workshop, NAVAIR & ONR, Vinod Agarwala Organizer (Solomons, MD, 22–25 August 2000).
3. "Flight Clearance Policy for Manned Air Vehicles," *NAVAIR Instruction 13034.1B* (Patuxent River, MD: DON, Naval Air Systems Command, 24 October 2000).
4. Donald Polakovics, "Aging Aircraft, the United States Navy Experience" (Paper presented at the Int. Conf. on Aircraft Damage Assessment and Repair, Melbourne, Australia, 27 August 1991).
5. Donald Polakovics, "Structural Certification and Risk Assessment Criteria" (Paper presented to the RAF, NAVAIR, MD, October 2000).
6. "Test Method Standard for Environmental Engineering Consideration and Laboratory Tests," *DoD Standard MIL-STD-810F* (DoD, 1 January 2000).
7. William E. Frazier, "Material Selection and Qualification" (Paper presented at ASM, AeroMat'00, Seattle, WA, 26–29 June 2000).
8. *Defense Systems Management College, Systems Engineering Fundamentals* (Washington, D.C.: U.S. Government Printing Office, December 1999).
9. *Certification of Materials Technologies* (Patuxent River, MD: NAVAIR Team Process Tool Kit, 1997).
10. William E. Frazier, "Materials Engineering Excellence: Quality in Support of the Naval Aviation Warfighter" (Paper presented at ASM, AeroMat'00, Seattle, WA, 26–29 June 2000).
11. "Titanium and Titanium-Alloy Castings, Investment," *Aerospace Material Specification*, AMS-T-81915 (Warrendale, PA: SAE Int., July 1998).
12. "Heat Treatment of Low-Alloy Steel Parts, Minimum Tensile Strength 220 ksi (1517 MPa) and Higher," *Aerospace Material Specification*, AMS 2759/2C (Warrendale, PA: SAE Int., September 2000).
13. "Metallic Materials and Elements for Aerospace Vehicle Structures," *MIL-HDBK*-5 (DoD, March 1998).
14. "Nondestructive Evaluation System Reliability Assessment," *MIL-HDBK-1823* (DoD, 30 April 1999).
15. Alfredo H-S. Ang and Wilson H. Tang, *Probability Concepts in Engineering Planning and Design*, Volume I-Basic Principles (New York: John Wiley & Sons, 1975).
16. "Evaluate Structural Designs" (Patuxent River, MD: NAVAIR Team Process Tool Kit, 30 December 1997).
17. National Research Council, National Materials Advisory Board, Aging of U.S. Air Force Aircraft (Washington, D.C.: National Academy Press, 1997).

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