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A New Tool for Design and Certification of Aircraft Turbine Rotors

This paper summarizes recent enhancements to a probabilistic damage tolerance software code, DARWIN™, that can be used for design certification of aircraft jet engine titanium disks/rotors that may contain melt-related anomalies. Evaluations of DARWIN™ by engine manufacturers are also discussed, including comparisons with existing codes for accuracy and time efficiency. In addition, relevant test results, including various fatigue tests on material containing melt-related anomalies, are summarized.
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Introduction

A probabilistically based damage tolerance software code called DARWIN™ (Design Assessment of Reliability With Inspection) has been developed to supplement the current safe-life approach for low-cycle fatigue design of titanium disks/rotors in aircraft gas turbine engines. DARWIN™ is a computer program that integrates finite element stress analysis, fracture mechanics analysis, nondestructive inspection simulation, and probabilistic analysis to assess the risk of rotor failure. It computes the probability of fracture as a function of flight cycles, considering random defect occurrence and location, random inspection schedules, and several other random variables. Both Monte Carlo and advanced, fast integration methods are integral to the probabilistic driver. A fracture mechanics module, called Flight_Life, is also incorporated in the code. In addition, a user-friendly graphical user interface (GUI) is available to handle the otherwise difficult task of setting up the problem for analysis and viewing the results.

Previous papers, [1–3], and a report, [4], have reported on the detailed ingredients contained within DARWIN™ and the methodology used in performing a probabilistic analysis with this code. With the Federal Aviation Administration (FAA) having recently stated that DARWIN™ is an acceptable tool to conduct risk analyses for certification of new titanium rotor designs in compliance with Advisory Circular 33.14, the purpose of this paper is to describe several recent enhancements to DARWIN™ that ensure risk convergence and substantially reduce the total engineering time needed to reach convergence; to summarize the results to date of industry evaluations of the code; and to describe several supplementary tasks that address fatigue crack growth (FCG) behavior from hard alpha (HA) anomalies in titanium.

The developments summarized in this paper represent the collective contributions of the program team: Southwest Research Institute, General Electric, Honeywell, Pratt & Whitney, and Rolls-Royce as well as the Rotor Integrity Subcommittee (RISC) of the Aerospace Industries Association.

Enhanced DARWIN™ Capabilities

Previous versions, [5,6], of DARWIN™ provided the capability to predict the risk of fracture associated with hard alpha defects in titanium disks. The risk solution obtained from the zone-based methodology, however, is dependent upon the discretization of the risk zones (i.e., size and number of zones). A zone refinement methodology was recently implemented in DARWIN™ (version 3.5) to assist the user with zone discretization. The methodology, shown in Fig. 1(*a*) can be summarized as follows:

1. Define initial zones (initial discretization).
2. Execute DARWIN™ risk assessment code.
3. Evaluate results. If total risk is less than or equal to design target risk or if a converged solution (i.e., small change in disk failure probability) is obtained, analysis is complete (code terminated).
4. If further analysis is required, the user selects zones to be refined based on zone risk contribution factors (i.e., relative contribution of each zone to the total risk of the disk). Selected zones are automatically subdivided based on the centroid of each zone.
5. User defines fracture mechanics parameters associated with newly subdivided zones (return to step 2).

Since the zone-based risk methodology requires that hard alpha defects be placed in the life-limiting location of each zone, the total disk risk decreases with increasing discretization (i.e., probability of fracture decreases as the number of zones is increased) because the location of the defect in most of the subdivided zones is less severe than the original life limiting location in the parent zone.

The red zones in Fig. 1(*a*) indicate the zones whose contribution to the disk risk exceeds a specified percent threshold, e.g., 2%. When a zone is subdivided, its percent contribution is reduced because the volume of the zone is reduced, thus, the probability of the zone containing a defect is reduced. Also, as mentioned above, the location of the defect in most subdivided zones is less severe than the original life limiting location. Typically, refinement continues until all zones fall below the threshold value.

When using a zone-based risk method, the zone boundaries often conflict with the existing element boundaries defined in the original finite element (FE) mesh (e.g., optimum zone smaller than a single finite element). The solution is to refine the mesh for setting zone boundaries for risk integration. The refined mesh is not used for further analysis; the FE results are merely interpolated for the new mesh. Several new features are provided in DARWIN™ (version 3.5) to assist the user with element discretization. Two of these new features, element refinement and onion skinning, are shown in Figs. 1(*b*) and (*c*), respectively. The element refinement feature allows the user to subdivide any element(s) into a 2×2 set of four elements. Onion skinning divides any element on the surface of the model into two elements—an element of user specified depth normal to the surface and an element containing the remaining material.

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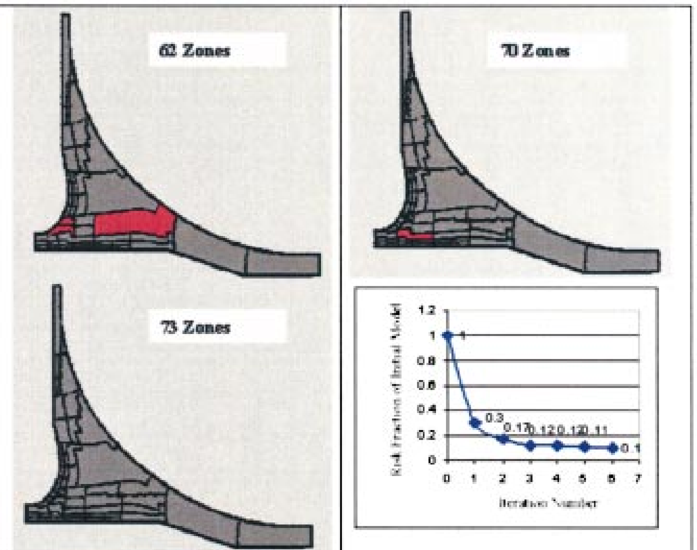
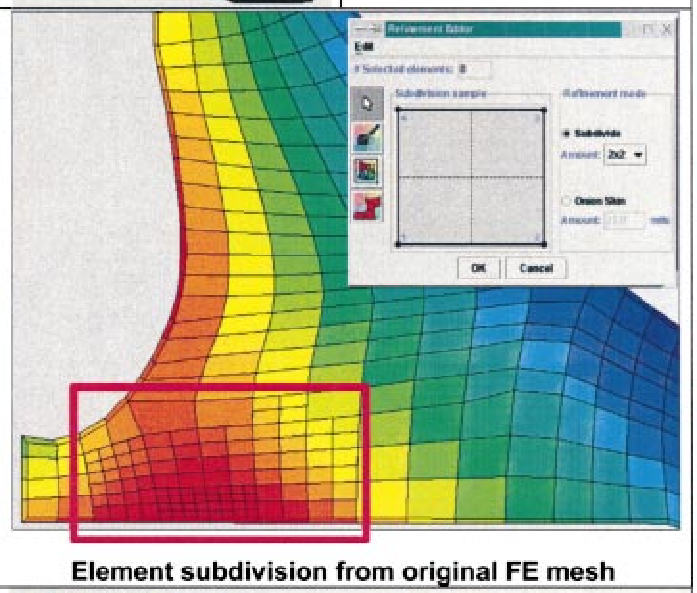
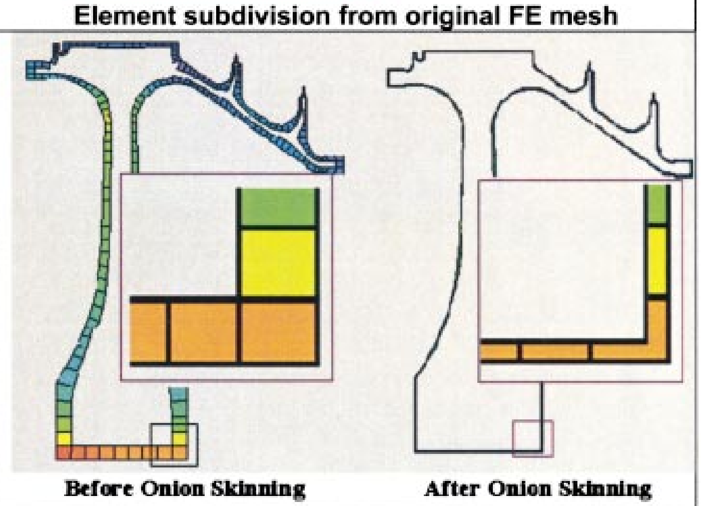
(a) Zone Refinement	• A methodology and tools to ensure a converged solution are provided. • A results database is used to retrieve the solution for zones that have not been modified.	
(b) Element Refinement	• Capabilities to modify the FE mesh are provided.	
(c) Onion Skinning	• Surface zones require a thin layer of elements on the surface of the disk. • Capabilities to generate the required elements are provided.	

Fig. 1 Summary of element and zone discretization features associated with DARWIN™ (3.5 release)

Further details on the zone and element refinement capabilities are contained in Ref. [7].

Enhanced Fracture Mechanics Capabilities. The Flight_Life fracture mechanics module in DARWIN™ currently contains a limited but sophisticated set of stress intensity factor (K) solutions focused on rotor geometries. In addition to the original polynomial formulations, the code now contains new weight function formulations for semielliptical surface and elliptical em-

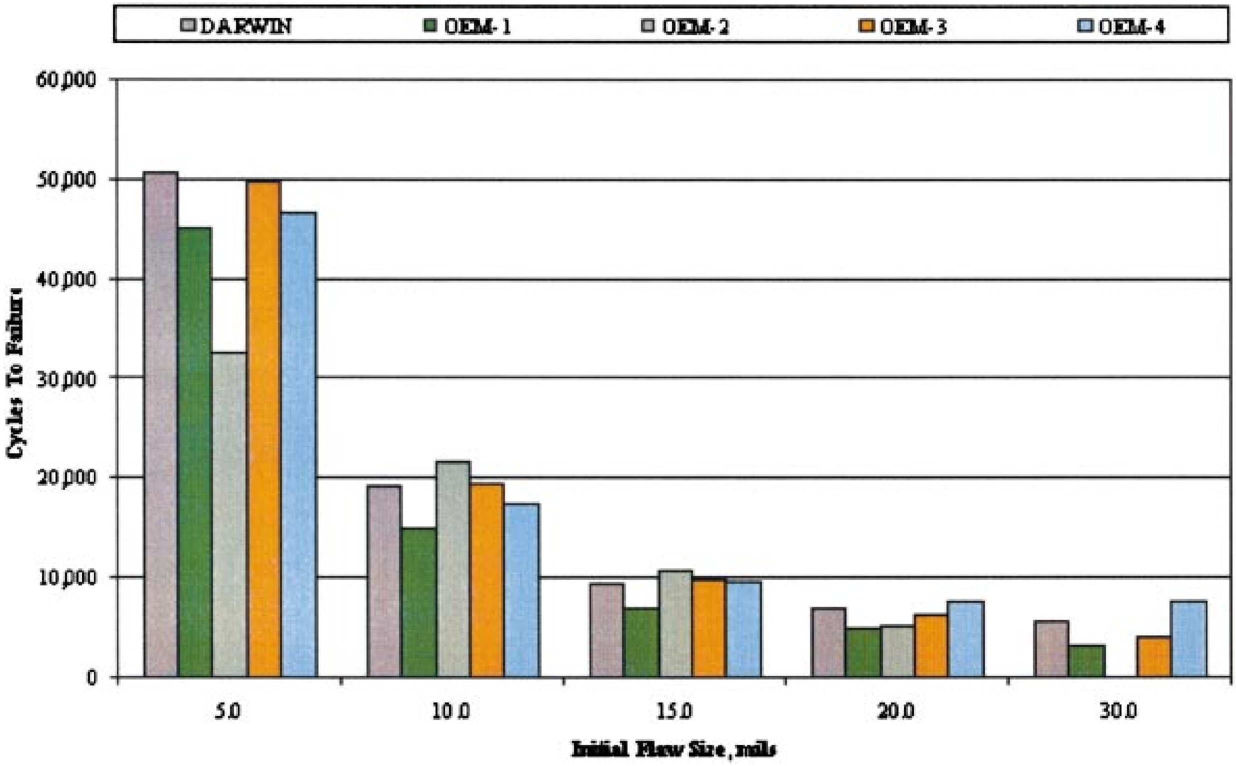


Fig. 2 Cycles to failure vs. initial flaw size for the Flight_Life fracture mechanics module in DARWIN™ compared to OEM fracture mechanics codes

bedded cracks in rectangular plates under univariant stress gradients. Both sets of solutions can address off-center cracks with crack aspect ratios from near 0 up to 2.0. A corner crack plate solution for uniform and linear bivariant stress gradients is also available.

Extension of DARWIN™ to address surface damage issues required implementation of K solutions for corner, surface, and through cracks growing from holes. A new set of weight function solutions for univariant stress gradients have recently been developed, based on a large matrix of reference solutions generated with the FADD-3D boundary element code, [8]

DARWIN™ Evaluation by Industry

Various DARWIN™ capabilities have been independently evaluated by aircraft gas turbine manufacturers (OEMs) that are members of the program team or members of the AIA Rotor Integrity Subcommittee. The evaluations included one-to-one comparisons with their own codes as well as assessments of DARWIN™ predictions compared to actual field experience.

The first set of evaluations involved the prediction of low-cycle fatigue crack propagation lives for different locations in a hypothetical Ti-6A1-4V rotating ring. Comparisons were made between the Flight_Life fracture mechanics code that is embedded in DARWIN™ (but can be run as a stand-alone code) and various fracture mechanics codes in use by the manufacturers. Results of the analyses for one disk location are shown in Fig. 2. It can be seen that the Flight_Life results are typically bracketed by the results obtained by the OEMs

A second set of evaluations for the rotating ring was a comparison of the probability of failure in 20,000 cycles for certain loading conditions. This comparison is shown in Fig. 3 where it can be seen that DARWIN™ compares very favorably with the risk values computed independently by one manufacturer using their own code and by other OEM's using the DARWIN™ probabilistic algorithms with their own fracture mechanics modules.

In addition, one manufacturer assessed the field experiences of over 50 engine disks of varying levels of maturity using DARWIN™. This included various titanium alloys with different disk and hub geometries. The computed probability of fracture predictions for a subset of a fleet involving 2 billion part cycles was combined with the representative fleet population and accumulated cycles to predict the number of fractures and finds (HA detection prior to fracture). The probability of fracture predictions were reasonably consistent with earlier results used by the AIA Rotor Integrity Subcommittee to set the initial HA defect distributions [9].

Another manufacturer performed a one-to-one comparison between their own code and DARWIN™ predictions for a compressor disk. The risk predictions compared favorably, and the DARWIN™ analyses could be completed in less than half the total engineering time required by the corresponding OEM tool.

Characterization and Verification of Material Behavior

Vacuum Fatigue Crack Growth Behavior. DARWIN™ includes a library of FCG rate properties for rotor materials. Only minimal data are provided for air environments, since most DARWIN™ users (engine companies) have their own proprietary databases. However, DARWIN™ will provide more extensive databases for FCG behavior in vacuum environments, which are relevant to embedded cracks growing in isolation from the atmosphere. Because FCG rates in vacuum can be substantially different from FCG rates in air, especially at low ΔK, characterization of vacuum behavior is especially important since most HA defects are in subsurface locations.

Since extensive vacuum data are not commonly available, the TRMD program is conducting a testing program to generate vacuum FCG data on select rotor alloys. Tests are being conducted in engine company labs following their conventional test protocols: surface crack tension and single edge notch button head

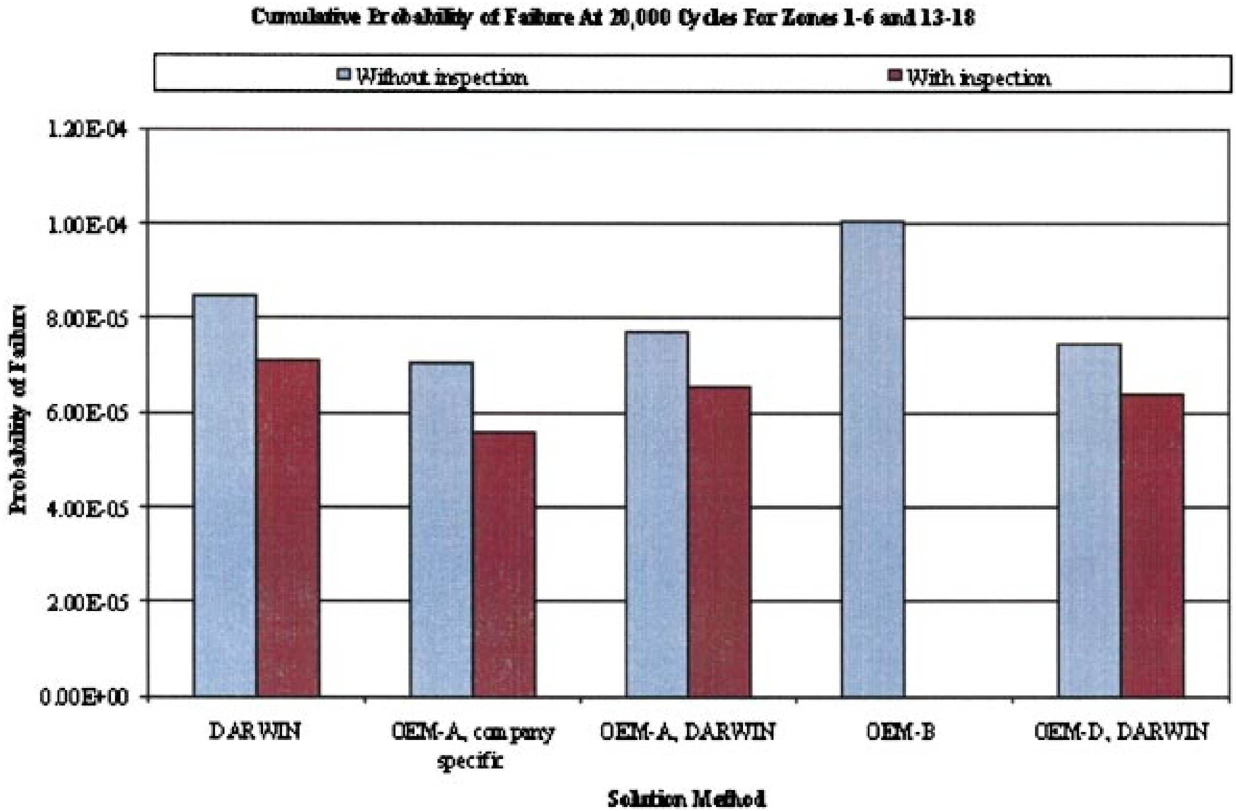


Fig. 3 Summation of the probability of failure for 12 zones computed entirely using DARWIN™ and by OEMs using DARWIN™ in conjunction with their own fracture mechanics codes

specimens, and DCPD crack length monitoring. Vacuum levels are greater than 10^{-7} Torr and test frequencies are 0.33 to 1 Hz. Stress ratios range from 0.05 to 0.75.

Experiments at relevant temperatures have been completed on three titanium alloys, Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo+Si, and Ti-17β. Early results were documented in [10]. Testing is currently underway on two conventional nickel-base rotor alloys, Inconel 718 and Waspaloy, and limited tests are planned on representative powder metallurgy nickel-base alloys.

Static and Fatigue Behavior of Hard Alpha Defects

Laboratory Tests. The AC33.14 risk assessment procedure assumes that HA defects are cracked during the forging process and that FCG from the defect into the surrounding titanium matrix begins essentially on the first cycle of service loading. In order to assess the potential conservatism of this assumption, laboratory tests were conducted on coupons containing artificial or natural HA defects. Test procedures and early results were documented previously, [11]. Acoustic emission methods were used to sense cracking in embedded defects. High stress ratio fatigue marker bands were applied to assist in post-test fractographic interpretation of results.

Static tests showed that HA defect cores and the surrounding diffusion zones exhibited multiple cracking at very low static stresses (5–40 ksi) when the defects were surface-connected. When the defects were embedded, substantial cracking apparently did not occur until static stresses exceeded 90–100 ksi.

Fatigue tests with embedded defects exhibited somewhat longer lives and higher threshold stresses than expected, and this was apparently due to delays in FCG into the matrix. Diffusion zones exhibited some resistance to fatigue crack growth, albeit a lower resistance than matrix material. Marker banding of cracks that had grown into the matrix well beyond the defect showed that crack growth rates agreed with predictions based on vacuum data. Synthetic and natural defects behaved similarly.

Spin Pit Tests. Three forgings with simple sonic shapes that were manufactured for separate studies of the forging deformation process were also spin pit tested in conjunction with evaluation of the fracture mechanics model. All forgings contained a single significant HA defect located by design in a high stress region of the disk. One forging contained a synthetic defect, and two forgings contained natural defects obtained from an independent NDE study of a contaminated billet. As in the coupon tests, the disks exhibited higher threshold stresses than anticipated. After applied stresses were increased, cracks in two of the disks grew to rupture; the third test was halted prior to rupture and the disk sectioned. Crack growth predictions using Flight_Life showed general agreement with measured behavior at these higher stresses.

Analysis of Residual Stresses Around Hard Alpha. HA defects and the surrounding matrix material contain residual stresses due to differential thermal contraction of defect and matrix during cool down from the final heat treatment. A brief analytical study of these residual stresses was conducted to evaluate their potential contribution to the enhanced static and fatigue strengths of embedded defects. The study employed simple elastic models of spherical and cylindrical defects, [12], and values of the coefficient of thermal expansion for both HA and matrix material that were experimentally measured for the program at GE CR&D. The models successfully explained the observed experimental behavior in the laboratory tests. Parameter studies indicated that residual stress effects could be substantial at lower applied stresses but might be negligible at higher applied stresses. Ignoring these residual stresses is conservative.

Summary

Recent progress in the development of a probabilistic damage tolerance software code, DARWIN™, has been highlighted, including a zone refinement methodology for risk convergence, automated creation of thin surface zones, ability to modify the original finite element mesh, and enhancements to the fracture mechanics capabilities. Successful, independent evaluations of DARWIN™ by engine manufacturers were also discussed in terms of comparative crack propagation lives and risk assessments as well as engineering time required to perform an analysis. The fatigue behavior of titanium containing hard alpha (HA) anomalies was also determined to evaluate the assumption that cracks immediately start to propagate from precracked HA on the first flight cycle. It is shown that this is generally a conservative assumption.

Acknowledgments

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