# IMPACT OF CRACK PROPAGATION MECHANISM ON AIRCRAFT DESIGN DEVELOPMENT

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## Abstract

The goal of this review is to examine the possible use of ex-post quantitative fractography in development of aircraft design concepts. The resent investigations using quantitative fractography for the reconstitution of fatigue process history indicated limitations of fatigue crack growth and material toughness-based tests in interpreting fatigue behaviour. Inevitable deviations in the in-service load histories, changes in mission types, increase in weight and severity of service conditions resulted in fatigue problems that could not be foreseen by the initial Safe-life and Damage-tolerant designs. However, to ensure the validity of results, there is a need for standardization and unified methodology in fractographic analysis, particularly when it comes to failure analysis.

**Keywords:** Transportation industry, Aircraft design concepts, Fatigue failure mechanisms, Fractography

## 1. INTRODUCTION

Recent advantages in industrial technology and the pursue for high efficiency and productivity are paralleled with requirements for cost reduction, necessary economics in energy and labour as well as process emissions [1]. Although, from the aspect of technological development and industrialization such progress is considered imperative, the social science investigations indicated that these demands could result in increasingly rigorous working environments and reduced employment [2]. It was also observed that in Industry 4.0 the increase in productivity and flexibility is achieved at the expense of sustainability, social sensitivity and fairness. This led to the introduction of Industry 5.0 as well as the "Age of Augmentation", "Society 5.0" [3], "Produktion 2030", Made in China 2025" and "Smart Working" concepts [4]. In the age of 5th Industrial Revolution, it is no longer sufficient to fully relay on digitalization and Artificial Intelligence-driven technologies, but to support the industry through research and innovations [5]. Given its contradictory goals, the innovations in transportation industry, especially in aircraft, aerospace, and space technology, must be conceived to follow Safe-life design, Fail-safe design, or Damage-tolerant design. While the Safe-life design is characterized by the absence of failure and traditionally used to develop and utilize structural materials, the Fail-safe design allows for failure but ensures safety through load redistribution between multiple stiffening elements. Damage-tolerant design is considered to be an extension of the fail-safe design representing the ability of the structure to sustain anticipated loads in the form of fatigue, corrosion or accidental damage till detection and repair [6]. This literature review emphasizes the impact of crack nucleation and growth mechanisms on aircraft design development and importance of fractographic analysis when failure already occurs.

## 2. TRANSITION FROM SAFETY BY RETIREMENT TO SAFE-LIFE AND INFINITE-LIFE DESIGNS

The concept of damage-tolerant design was added to the Civil Air Regulations in 1965 as an additional option to assess the airframe fatigue strength. This regulations' update derived from the series of accidents involving the first commercial jet airliner de Havilland DH 106 Comet in 1954. The crash investigation indicated the limitations of the earlier Safety by Retirement design and resulted in the introduction of uneconomically short inspection intervals of major airframe components. The basic deficiency of the Safe-life design is represented by the structures with multiple load paths. This type of loading behaviour needs to be considered during aircraft design and allow for the structural integrity to be maintained even if an individual component fails [7]. The prediction of structural damage onset during load or environmental exposure is obtained through failure analysis. Initially, the failure analysis of a single component was based on fatigue load or stress spectrums that were proposed in 1935, verified in 1945 and standardised for aerospace applications in 1970. The standardization was based on commonly accepted practices in the aircraft industry concerning mission profiles, load factor exceedances of individual components, and calculation of the load factor for the structural elements during flight sequences [8]. The need to assess the repeatability of inspection intervals resulted in the application of stress to the number of cycles till failure (S-N) curves. These curves represent the relationship between stress and fatigue life and can be measured using a fatigue testing machine on the standardized samples. By interpreting the curves, it is possible to estimate the stress-induced elastic and strain-induced plastic behaviour of the material as well as the fatigue endurance limit below which the fatigue life of the material is infinite [6]. Consequently, the Infinite-life design was recognized as a subset of the Safe-life methodology. This approach is generally used to design systems that are difficult to maintain and repair. Initially, the effect of stress-controlled cyclic loadings on the fatigue life was studied by August Wöhler in 1893 for railroad wheel-axile failure systems. The experiment that began with the testing of two half axles for cantilever rotational bending under elastic loading enabled engineers to apply the theoretical knowledge of notched sample behaviour to the structural components subjected to fatigue failure [9]. Correlation of various technical factors with fatigue failure and crack occurrence was essential for understanding and development of fatigue failure mechanism.

## 3. THE FATIGUE FAILURE MECHANISM

The fatigue failure comprehends nucleation, formation, and propagation of cracks due to a repetitive or cyclic load significantly lower than yield strength of the material (**Figure 1**).

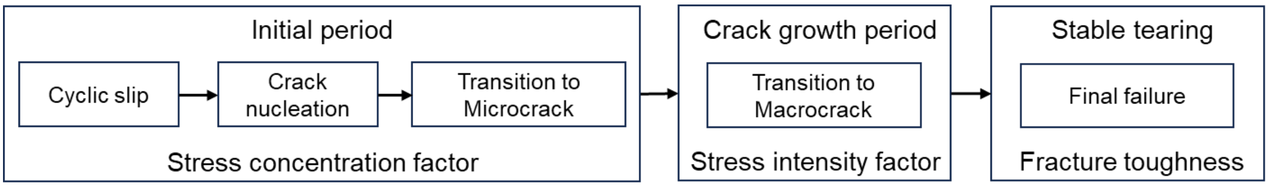
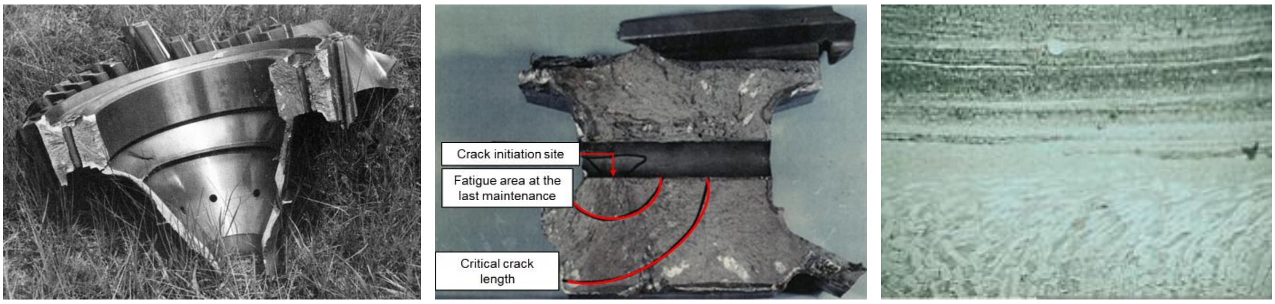


**Figure 1** Fatigue failure mechanism [10]

The repetitive nature of the load causes formation of slip bands on the preexisting material defects and nucleation of crack at microscopic level (**Figure 1**, initial period). Afterwords, the microcracks can transition to a visible crack (Figure 1, crack growth period) and propagate to a critical size. The crack propagation results in structural or pressure boundary failure of the component (**Figure 1**, stable tearing period). Besides microstructural discontinuities, the fatigue cracks can also propagate on the existing macroscopic cracks or be superimposed to a corrosion mechanism [11]. **Figure 2 a** show the engine fan hub of the McDonnell Douglas MD-88 passenger airplane after engine failure during the initial part of the take-off. The fatigue failure was initiated by an inadequate drilling of tie rod holes in the hub web (**Figure 2 b**). During machining abuse, a temperature of 640 °C was reached along the fan hub surface. Since it is a critical temperature for titanium-based alloys (Ti6Al4V alloy), it caused the phase transformation and the appearance of three zones of altered microstructure (**Figure 2 b and c**). The altered microstructure initiated adjacent to the hole wall surface with the layer of recrystalized α-grains. The second zone consisted of the heavily deformed α- and β-grains elongated parallel to the surface, followed by the microstructure with curved texture (**Figure 2 b and c**) [12].



a) b) c)

**Figure 2** The engine fan hub of the McDonnell Douglas MD-88: a) after engine failure, b) fracture surface with indicated crack propagation [12], c) microstructure of the Ti6Al4V alloy in the affected area [16]

As indicated in the example, the characteristic morphology of the fracture surface enables identification of fatigue crack nucleation site and crack propagation mechanism using fractographic analysis (**Figure 2**). For the given material and stress conditions, fracture zone and related fatigue stages depend on the stress intensity factor (SIF) defined as a function of applied stress and crack length (**Figure 1**, crack growth period). Below the fatigue crack propagation threshold, the development of microcracks with an average crack growth rate smaller than one atomic lattice period per load cycle occurs (**Figure 3 a**). This initial period is correlated with the fine granular area of the fracture surface. The increase in SIF causes the nucleation of small cracks with a circular crack propagation front and transition of fracture surface from granular to smooth. The surface area of smooth or fisheye morphology is not constant but depends on SIF range and crack length (**Figure 3 a**). Some fractographic investigations have indicate the existence of transition zone between fine granular area and fisheye structure know as smooth area (SA). This area is associated with the transition of a microscopic crack into a physically small one (< 1 mm) [13]. When a crack becomes large enough to satisfy the energy or stress intensity criteria, sudden crack closure occurs (**Figure 3**) [11]. The crack closure mechanism can be induced by plasticity, roughness, oxidation, transition, transformation or grain boundary. The plastically induced closure appears due to the formation of plastic zone ahead of the crack tip. Plastic deformation at each load cycle leads to successive blunting (closing) and sharpening (opening) of a crack tip and formation of striations on the fracture surface (**Figure 3 b**). Roughness-induced closure is characterized by the displacement in the crack propagation direction caused by material anisotropy or microstructural inhomogeneity [14]. Since the volume of oxides and other corrosion products is typically larger than the volume of the corresponding base metal, the formation of the oxide layer on the fracture surface can be interpretated as a wedge insertion [15].

a) b)

**Figure 3** Fatigue fracture surface of the steel shaft: a) crack nucleation and propagation, b) plastically induced crack closure [18]

The transformation induced crack closure is characteristic for alloys with metastable phase transformations. While the phase transformation is induced by the increased stress at the crack tip, the crack closure is a consequence of increase in volume due to phase transformation. The grain boundary closure is associated with newly formed surface cracks, but it can also occur because of the variation in grain size with respect to thickness. Determining the exact mechanism of crack propagation is necessary for the interpretation of experimental results as well as the fatigue failure predictions [14]. From the more practical aspect, correlating different types of materials with a specific crack propagation mechanism is beneficial for innovative material design and application, aircraft structure design and assessment of the inspection interval repeatability [17].

## 4. THE INTERPRETATION OF FRACTURE SURFACE TOPOLOGY

The fracture surface is created by the propagating crack because of the reaction between materials' microstructure and service conditions. By correlating the identified morphological features of fracture surface with physical processes, fractographic analysis enables ex-post determination of different qualitative and quantitative parameters. While qualitative parameters determine the fracture type as static or fatigue, brittle or ductile, transgranular or intergranular, the quantitative parameters represent measurable features of fracture surface such as ductile dimple diameter, striation and beach mark spacing or cleavage factor size [18].

The contemporary approach to fractography in fatigue failure analysis comprehends the reconstitution of fatigue process history, namely determination of the relationship between measurable characteristic of fracture surface with time-dependant variables during service. It is conditioned by the existence and detectability of measurable topological features that can be connected to fatigue crack growth rate at specific cycles or blocks in the loading spectrum. The reconstitution of fatigue process can provide detailed information on the duration of crack initiation period, localized crack growth rates in different fatigue areas, time-dependent and two-dimensional description of fatigue crack growth, chronology of individual features' formation and their interaction, as well as the impact of maintenance and repair on fatigue crack propagation mechanism [19].

### 4.1 The basics of fractographic analysis

Anisotropy of materials' microstructure and mechanical properties as well as the interaction between propagating crack and variable service conditions will ensure the uniqueness of each individual fracture surface. To achieve validity and repeatability of results, fractographic analysis must be based on appropriate methodology and follow previously outlined plan with respect to the fractured parts and indicated features of interest [20]. The fractography can be performed on the parts fractured during manufacturing, service or under laboratory conditions with a purpose of identifying fracture type, zones corresponding to three stages of fracture, fracture mechanism and intrinsic and external factors influencing crack propagation. To meet those objectives, the fractographic examination should constitute visual inspection followed by the examinations on macroscopic and microscopic levels. Although there is no universally accepted methodology, the fractographic examination in failure analysis, fatigue failure analysis or scientific research should provide data on overall fractured parts' condition, fracture surface with different topological features, secondary or multiple crack formation, plastic deformation occurrence and the presence of crack closure mechanisms. Additionally, analysis should include information abought service environment, zones closest to the fracture as well as unaffected zones [21].

### 4.2 The fractographic reconstitution methodology

Quantitative fractography in fatigue failure analysis can be performed by striation spacing measurements, beach mark spacing measurements or fracture marking [22]. The striation spacing measurements were used to ex-post reconstitute the LM 200 aircraft's wing spar fatigue process history. The fatigue failure comprehended formation of four cracks initiating at the sharp notches in the rivet hole connecting the spar web with the lower flange plate. All four cracks propagated mostly by striation mechanism. The data was processed by recalculation of the striation spacing into the macroscopic crack growth rate and integration of the crack length as a function of the number of applied cycles. However, the striation spacing, and macroscopic crack growth rate cannot always be considered as identical. The beach mark spacing was used as quantifiable topological features for reconstitution of fatigue failure of small civil aircraft wing loaded by flight-by-flight spectrum simulating real service conditions. The fatigue failure occurred through the propagation and coalescence of three different cracks that have initiated in the bolt hole. Variations in loading amplitude resulted in the formation of clear beach marks in fracture's micromorphology. The beach mark-based observations give information on crack growth rate, crack tip shape and its changes with respect to time and space. This method enables determination of the relationship between microscopic and macroscopic crack growth rate without difficulty [22]. Contrary to previous methods, the fracture marking comprehends insertion of specific cycles or blocks into the testing spectrum leading to the formation of specific features in fracture surface topology. The application of this method requires good detectability of features on the fracture surface and minimal influence on fatigue crack initiation and growth. This testing methodology is of particular importance for the aviation industry where two main types of fracture markings are used [23].

## 5. FRA CTOGRAPHIC APPROACH TO AIRCRAFT DESIGN DEVELOPMENT

Deviation in the in-service load histories, changes in mission types, increase in weight and severity of service conditions can cause the fatigue problems that were not foreseen by the initial Safe-life and Damage-tolerant design. This is especially evident in tactical aircraft (fighter and attack planes) where degression from design assumptions and full-scale test results often leads to costly structural repairs and uneconomically short inspection intervals. A less severe situation is typical for transportation and passenger planes, where fatigue problems occur with prolongation of service life. The unpredictability of those discrepancies shifted the focus of fatigue research from the original design concepts represented by MIL-STD-150A Military Standard: Military Structural Integrity Program, Airplane Requirements, to a more holistic life approach [24]. The application of holistic approach in failure analysis is based on understanding of fatigue crack origins, the length of crack initiation period as well as microscopic and macroscopic crack growth rates. All three aspects require ex-post analysis of the fracture surface topology using qualitative and quantitative fractography. Correlation of identified and quantified topological features occurred under service conditions with the results of full-scale, component or sample/coupon tests will overcome the limitations of fatigue crack growth, linear elastic fracture mechanism, and material toughness approaches to fatigue failure analysis [25].

## 6. CONCLUSION

This paper provided a brief literature review concerning aircraft design concepts, fatigue failure analysis, crack propagation mechanisms and fractography with the aim of considering the possible application of ex-post quantitative fractography in development of aircraft design concepts. The results of recently performed investigations based on reconstitution of fatigue process history emphasized the limitations of Safe-life and Damage-tolerant designs, especially when it comes to the crack nucleation and transition from small to large crack growth rates. Identification and quantification of unique fracture surface features seem to be crucial for understanding material's response to variable service conditions.

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