Review Article ISSN 2832-9384

Journal of Materials and Polymer Science

Analysis of Crack Growth Patterns from Initial Defects in Aircraft Structural Elements under Cyclic Loading

A. Kh. Janahmadov[1,2*], M. Ya. Javadov[2] and P. A. Suleymanova[2]

[1]*Azerbaijan National Aviation Academy, Azerbaijan.*

[2]*Azerbaijan Engineering Academy, Baku Azerbaijan.*

***Corresponding author**

A. Kh. Janahmadov,
Azerbaijan National Aviation Academy, Azerbaijan.

Submitted: 16 Oct 2026; **Accepted:** 30 Oct 2026; **Published:** 24 Nov 2026

Citation: Janahmadov, A. Kh., Javadov, M. Ya., & Suleymanova, P. A. (2026). Analysis of crack growth patterns from initial defects in aircraft structural elements under cyclic loading. *J mate poly sci, 6*(3) :1-5. DOI : https://doi.org/10.47485/2832-9384.1088

Abstract

The study demonstrates that fatigue failure of metals under service conditions, at the stage of initiation and growth of mesodefects, represents a set of sequentially occurring damage accumulation mechanisms at three scale levels, with a transition from the micro- to the meso- and subsequently to the macroscopic level through regions of unstable behavior that act as bifurcation points. The concept of microstructural fracture mechanics is introduced to characterize the development of cracks whose dimensions are comparable to those of structural elements. In the bifurcation regions corresponding to the service life of components, as the stress level increases, the probability of realization of the damage accumulation mechanism at the preceding scale level decreases, whereas the probability of manifestation of the mechanism at the subsequent scale level increases.

The study also analyzes the crack growth patterns originating from initial defects in aircraft structural elements under cyclic loading, with the aim of detecting and recording defects at the early stage of their development using the acoustic emission (AE) method. AE signals were recorded sequentially in terms of their intensity during the half-cycles of the loading and unloading branches.

Keywords: Aviation equipment, cyclic loading, acoustic emission, crack growth, safe defect, bifurcation point.

Introduction

The fundamental principle underlying the design of machines whose components are subjected to cyclic loading is to prevent their failure within the specified service life. In practice, this principle is implemented by incorporating safety factors into the design calculations and is complemented by a monitoring system developed for use during operation.

At present, the level of damage accumulation in a material prior to the initiation of a fatigue crack cannot be assessed with the degree of reliability required for practical applications. Experimental data for structural materials exhibit considerable scatter with respect to the determined point of crack initiation. Such scatter is observed both during inspections and as a result of experimental testing procedures, including the manufacturing technology used to produce the specimens (see photographs).

This is associated with the behavior of the material itself, which exhibits a non-uniform condition in the most highly stressed regions of the structures of different aircraft (Bishop & Sherrat, 1990; Kollinz, 1984; Pashaev et al. 2025).

Once a complex structure has exhausted its specified service life, the problem of extending its operational life arises. For such complex and costly systems as aircraft, extending the service life by just one year can result in savings of hundreds of billions of dollars across an entire fleet. At the same time, the reliability of the structure must be maintained in the event of the possible or probable initiation of fatigue cracks in individual structural elements. Such cracks must be detected in a timely manner using non-destructive testing methods before the critical condition is reached, which is characterized by a transition to rapid and uncontrollable failure.

However, it should not be assumed that cracks do not occur in structural components before service-life extension is considered. The first group of cracks, and in some cases even instances of component failure, may appear after a relatively short period of structural operation. This is attributable to material defects of manufacturing or metallurgical origin (Lindley et al., 1978; Wang et al., 1993; Lich, 1979).

The ultimate goal of all studies of fatigue fracture behavior is to control the process of crack initiation and propagation through its modeling, by introducing justified monitoring in crack propagation zones and comparing the predicted behavior with the actual process (Shanyavskij et al., 1993).

Consequently, neither within the specified service life of a structure nor, especially, during service-life extension is it possible to ensure safe operation without taking into account the occurrence and development of fatigue cracks.

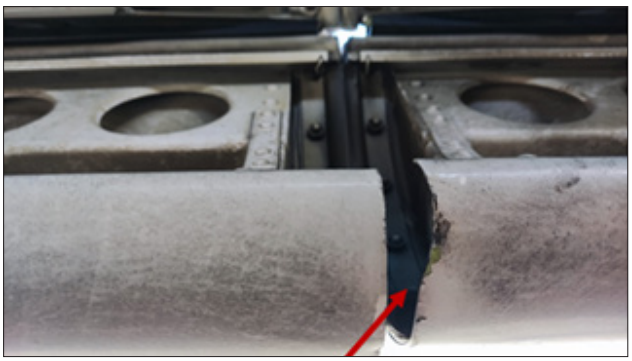

Figure 1: The crack observed in the forward cargo compartment of a Boeing 747-400F aircraft



Figure 2: The wing crack in a Boeing 747-400F aircraft (slat)

The Aim of The Study

Analyze the crack growth patterns in structural elements of aircraft under cyclic loading in order to detect and record defects at the initial stage of their development using the acoustic emission method, as well as to analyze the threshold behavior of small cracks.

Problem Statement

The study is based on the development of acoustic emission methods for detecting and recording the crack growth patterns originating from initial defects in aircraft structural elements under cyclic loading, as well as on investigating their effect on the fatigue properties of the material.

Solution to the Problem

The progressive development of a fatigue crack in metals is accompanied by a successive increase in the complexity of the evolutionary processes occurring near the crack tip. This is associated with a sequence of discrete transitions through bifurcation points resulting from changes in the dominant fracture mechanisms (Fig. 3). Initially, the fracture develops with the formation of surface relief features reflecting the predominance of slip processes, which is characterized by typical elements of a pseudo-striation relief. Subsequently, upon transition through the bifurcation point to the second stage (Stage II) of crack growth, the formation of fatigue striations takes place (Janahmadov, 2024).

As noted above, the propagation of fatigue cracks occurs with the involvement of all three modes of crack-face opening.

Obviously, the theoretical framework of mesomechanics is also applicable at the nano- and microscale levels without any modifications, since it is based on the principle of symmetry in physics (Janahmadov, 2022).

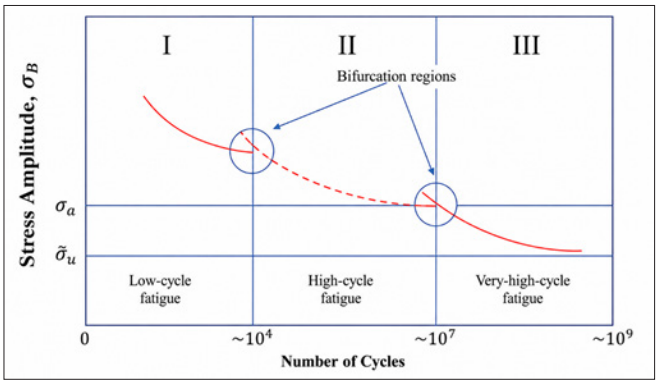

Figure 3: Multi-mode model of the complete fatigue life of materials with the identification of bifurcation regions (Janahmadov, 2024)

However, the crack growth process at Stage II is described based on the assumption that slip processes play a dominant role in the fracture of the material.

A change in the conditions of crack-face opening – from predominantly shear at Stage I to predominantly tensile opening at Stage II – following a reduction in the crack growth acceleration is usually accompanied by a change in the dominant fracture mechanism of the material. This transition corresponds to a shift from slip processes to processes of rotational instability.

At the same time, a limited number of areas exhibiting fatigue striations can already be observed at Stage I as the transition to Stage II is approached.

Crack formation initiates in the transition zone from the slip process to the process of rotational instability; in other words, it occurs before the bifurcation point.

The presence of discontinuities of various depths and shapes in the material provides a basis for assessing the behavior of a material containing a fatigue crack. In aluminum-based alloys, the depth of such a defect may be as small as 5–10 μm. Nevertheless, the service life of the structural element should already be assessed taking into account the presence of such a small material defect (Aboulkhair et al., 2019).

Small cracks have little effect on the fatigue limit until they reach a certain size, as follows from the well-known Kitagawa–Takahashi diagram (Fig. 4) (Kitagawa & Takahashi, 1976).

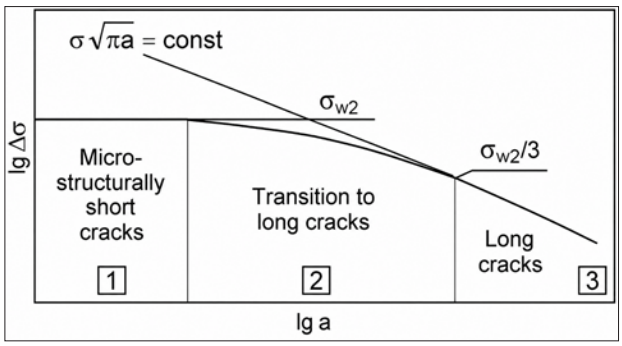

Figure 4: The Kitagawa–Takahashi diagram schematically illustrates the regions of: 1 – independence; 2 – weak dependence; and 3 – strong dependence of the "fatigue limit" σ_{W2} on crack depth (Kitagawa & Takahashi, 1976)

The onset of crack propagation represents a critical situation for the material and, even more so, for a structural element. It corresponds to an instability point, beyond which the scatter in fatigue strength assessments based on the criterion of fatigue crack initiation decreases. However, a degree of uncertainty remains in assessing the service life of an aircraft, partly because once the critical crack length is reached, the fracture process develops rapidly and uncontrollably.

Operational experience with civil aviation aircraft has shown that, within their specified service lives, fatigue cracks can initiate and grow to considerable lengths and depths in individual structural elements. This may occur for various reasons (Lich, 1979; Shanyavskij et al., 1993).

The occurrence of fatigue cracks can lead to various consequences, including aircraft accidents, for example, as a result of the failure of load-bearing elements of the wing structure. Cracks may occur at different stages of operation of aircraft and gas turbine engines (GTEs) and, by their nature, can fundamentally be divided into three classes (Makarevskij & Korchemkin, 1975).

The first class includes cracks that initiate from various types of manufacturing defects. It is extremely difficult to avoid the occurrence of manufacturing defects even with the highest level of production technology.

Obviously, other frequently occurring material defects also arise during the manufacture of aircraft components.

The second class of material damage in components occurs during operation. The most typical service-induced material defect is corrosion.

The third class of service-induced damage leading to premature component failure is associated with incomplete consideration of actual aircraft operating conditions. This corresponds to the case in which the actual operating conditions of the aircraft were not taken into account during its testing.

The propagation of fatigue cracks in materials used in aircraft structures, as an open system, occurs sequentially at different scale levels.

In the bifurcation region near the nominal stress level, the short fatigue cracks that form do not propagate. In this region, the principle of unique correspondence is violated, and the material exhibits a non-unique resistance to the fatigue crack growth in response to the external loading characterized by the equivalent stress level (Fig. 3).

The transition from short to long cracks with increasing nominal stress level is accompanied by a gradual decrease in their growth rate, followed by a subsequent increase. According to the Kitagawa–Takahashi diagram, a defect does not propagate if its size does not exceed the size of a safe defect. As the defect grows and reaches the safe-defect size, the fatigue strength decreases (Fig. 4) (Kitagawa & Takahashi, 1976).

Numerous models of short-crack initiation and growth have been proposed to determine the rate of defect development and to predict the service life of structural elements before the occurrence of a macrocrack. In 1976, Kitagawa and Takahashi were the first to quantitatively characterize the threshold behavior of small cracks, i.e., the decrease in threshold fracture resistance with decreasing crack size. Their work stimulated numerous subsequent studies on the effect of small cracks and defects on the fatigue properties of metals.

Miller and O'Donnell (1999) presented a modified Kitagawa–Takahashi diagram in which three regions corresponding to three crack-growth regimes were identified. These regimes are described using approaches based on microstructural, elastic–plastic, and linear elastic fracture mechanics. Thus, the concept of microstructural fracture mechanics was introduced to characterize the development of cracks whose dimensions are comparable to those of structural elements.

According to the Smith and Miller (1978) and Taylor and Knott (1981), models, the Kitagawa and Takahashi (1976) diagram can be described by two straight lines corresponding to constant values of threshold fracture toughness and fatigue limit.

The Kitagawa–Takahashi diagram is a fundamental diagram in fracture mechanics and fatigue analysis that relates the fatigue limit of a material to the size of a defect or crack.

Subsequently, we undertook studies of acoustic emission (AE) signals with the aim of detecting and recording defects at the initial stage of their development (Janahmadov, 2019).

The pattern of fatigue crack formation during a loading cycle was investigated in accordance with the pattern of AE signal generation, with the processes of plastic deformation and material fracture being distinguished. AE signals were recorded sequentially according to their intensity during the half-cycles of the ascending and descending branches of the loading curve.

The acoustic emission method was used for the diagnostic monitoring, detection, and recording of defects at the initial stage of their development. This makes it possible to classify defects not by their size but by their degree of danger; to determine the current crack size in a component with an accuracy of fractions of a millimeter; to detect an increase in the size of a defect in the material down to 10^{-6} mm² under the influence of external loads, demonstrating the high sensitivity of the method; and to detect defects regardless of their location within the object or their orientation.

Acoustic emission occurs when the internal structure of a material changes, including the crack initiation and growth, the dislocation movement, the inclusion fracture, and other processes. It makes it possible to detect, analyze, and localize defects in real time.

According to established concepts and definitions, acoustic emission is the emission of elastic waves by a material caused by local dynamic rearrangement of its structure. In the acoustic emission method, the physical field is generated by the material itself within the monitored object and contains comprehensive information about the progress of the process, both at the current moment and over time. The phenomenon of acoustic emission accompanies internal processes occurring in materials and involves the release of energy that propagates in the form of elastic displacements of material particles.

The propagated elastic displacements are detected by a sensor installed directly on the surface of the material of the component or on a waveguide having adequate acoustic contact with the material surface. A schematic representation of defect detection in metal using acoustic emission is shown in Fig. 5.

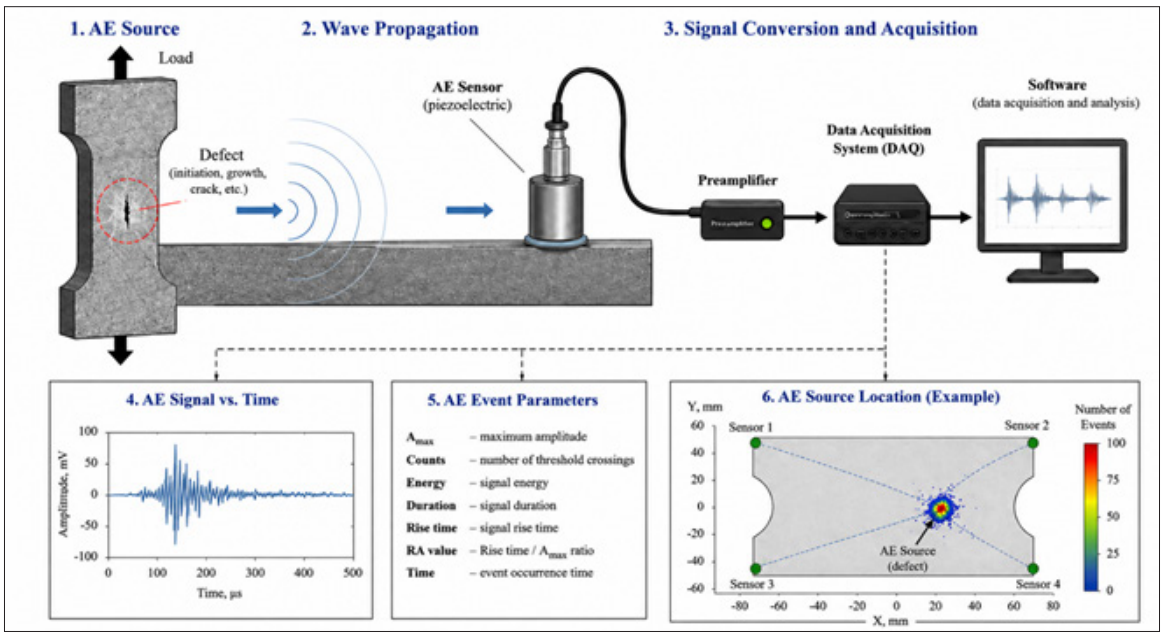

Figure 5: The schematic representation of the defect detection in metal using Acoustic Emission (Janahmadov, 2019)

An acoustic emission sensor converts the elastic displacements of material particles propagating through the material into an electrical signal, which is amplified and processed by electronic equipment based on established concepts. The recorded acoustic emission signal is characterized primarily by its basic parameters, including amplitude, duration, energy, waveform, and time of occurrence. All other parameters used to analyze the acoustic process are considered secondary. The informational value of acoustic emission parameters is determined by the nature of the specific physical processes involved.

The results obtained are used to describe the processes and develop models of the sources generating acoustic emission signals. This makes it possible not only to assess the informational value of their parameters but also to formulate certain requirements for electronic equipment. Most researchers studying the acoustic emission phenomenon have obtained practical results that are generally consistent with regard to the requirements for hardware used for the acquisition and analysis of acoustic information.

The application of acoustic emission methods makes it possible to monitor the kinetics of crack formation in structural components. In this case, emissions associated with microplastic deformation processes must be filtered out. It is known that the stress waves emitted by a crack occur in the frequency range of 2000–6000 Hz, whereas the pulses associated with the crack propagation have frequencies substantially higher than the overall background level. An acoustic emission signal in the form of a longitudinal, transverse, or Rayleigh wave is relatively short, with a duration of approximately 0.03 μs.

This approach can be used to analyze phenomena preceding fatigue failure based on three acoustic emission peaks. The first peak is associated with a high density and velocity of mobile dislocations, which become pinned at barriers or, conversely, accelerate under the action of stresses; the second peak is

associated with the formation of microcracks; and the third peak is associated with the initiation of a macroscopic crack. In one approach to detect a crack, ultrasound and acoustic emission are used simultaneously. One part of this system is an ultrasonic flaw detector operating to determine the crack length at a frequency of 50 Hz, while the second part is the acoustic emission system itself.

Conclusion

It has been demonstrated that fatigue failure of metals under service conditions, at the stage of initiation and growth of mesodefects, represents a set of sequentially occurring damage accumulation mechanisms at three scale levels, with a transition from the micro- to the meso- and subsequently to the macroscopic level through regions of unstable behavior that act as bifurcation points. The concept of microstructural fracture mechanics is introduced to characterize the development of cracks whose dimensions are comparable to those of structural elements. In the bifurcation regions corresponding to the service life of components, as the stress level increases, the probability of realization of the damage accumulation mechanism at the preceding scale level decreases, whereas the probability of manifestation of the mechanism at the subsequent scale level increases.

The identified patterns of AE signal generation make it possible to draw certain general conclusions regarding the deformation and fracture processes occurring in the material during crack development. The continuous nature of the signals during the half-cycle of decreasing load characterizes plastic deformation of the material at the crack tip. In addition, discrete-type signals on the ascending branch of the loading curve indicate a material fracture process associated with the formation of fatigue cracks.

References

1. Bishop, N. W. M., & Sherrat, F. (1990). A THEORETICAL SOLUTION FOR THE ESTIMATION OF "RAINFLOW" RANGES FROM POWER SPECTRAL DENSITY DATA. *Fatigue & Fracture of Engineering Materials & Structures, 13*(4), pp. 311-326. DOI: https://doi.org/10.1111/j.1460-2695.1990.tb00604.x
2. Kollinz, J. (1984). Povrezhdenie materialov v konstrukciyah. M.: Mir.
3. Pashaev, A. M., Janahmadov, A. Kh., & Samedov, A. S. (2025). Analiz i ocenka resursa elementov konstrukcii aviacionnoj tekhniki pri ciklicheskih nagruzkah. // V sb. V Mezhdunarodnogo kosmicheskogo foruma "Sovremennye zadachi inzhenernoj nauk. Problemy promyshlennogo rosta", T. II, Moskva, s. 15–20.
4. Lindley, T. C., Palmer, I. Ç., & Richards, C. E. (1978). Acoustic emission monitoring of fatigue crack growth. *Mater Sci Eng., 32*(1), pp. 1-15. DOI: https://doi.org/10.1016/0025-5416(78)90206-9
5. Wang, Z. F., Li, J., Ke, W., & Zhu, Z. (1993). DEPENDENCE OF ACOUSTIC-EMISSION FOR LOW STRENGTH STEELS UPON THE EMBRITTLEMENT AND THE PLASTIC ZONE REDUCTION AT THE CRACK-TIP DURING CORROSION FATIGUE CRACK-PROPAGATION. Fatigue Frac. Engng. Mater. Struct., 16, pp. 441–451. DOI:https://doi.org/10.1111/J.1460-2695.1993.TB00099.X
6. Lich, S. P. (1979). Mechanisms of Fatigue and Environmentally Assisted Fatigue. In J. T. Fong (Eds.) Fatigue mechanisms (pp. 174–213). ASTM International. DOI: https://doi.org/10.1520/STP675-EB
7. Shanyavskij, A. A., Orlov, E. G., & Karaev, K. Z. (1993). Prognazirovanie razvitiya ustalostnyh povrezhdenij elementov konstrukcij aviatekhniki pri slozhnom napryazhennom sostoyanii. Vozdushnyj transport. – M.: NTICGA.
8. Janahmadov A. Kh. (2024). Synergetic Principles and Regularities of Materials Fracture under Low-Cycle Fatigue Conditions. Journal of Friction and Wear, 45(4). Pp.238-244. DOI: https://doi.org/10.3103/S1068366624700363
9. Janahmadov, A. Kh. (2022). Mezomekhanika frikcionnogo vzaimodejstviya. - Baku: Apostrof-A, 404 s.
10. Aboulkhair, N. T., Simonelli, M., Parry, L., Askcroft, I., Tuck, C., Hague, R. (2019). 3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting. Progr. Mater. Sci ,106, P.100578. DOI: https://doi.org/10.1016/jpmatsci.2019.100578
11. Kitagawa, H., & Takahashi, S. (1976). Applicability of Fracture Mechanics to Very Small Cracks or the Cracks in the Early Stage. In Proc. Second International Conference on Mechanical Behavior of Materials, Boston, USA, pp. 627-631. https://scispace.com/papers/applicability-of-fracture-mechanics-to-very-small-cracks-or-3btlqrvjku
12. Makarevskij, A. I., & Korchemkin, N. M. (1975). i dr. Prochnost samolyota. M.: Mashinostroenie.
13. Miller, K. J., & O'Donnell, W. J. (1999). The fatigue limit and its elimination. Fatigue & Fracture of Engineering Materials & Structures, 22(7), pp. 545-558. DOI: https://doi.org/10.1046/J.1460-2695.1999.00204.X
14. Smith, R. A., & Miller, K. J. (1978). Prediction of fatigue regimes in notched components. *Intern. J. Mech. Sci., 20*(4), pp. 201-206. DOI: https://doi.org/10.1016/0020-7403(78)90082-6
15. Teylor, D., & Knott, J. F. (1981). Fatigue crack propagation behavior of short cracks; effects of microstructure. *Fatigue Eng. Mater. Struct, 4*(2), pp. 147-155. DOI: https://doi.org/10.1111/J.1460-2695.1981.TB01116.X
16. Janahmadov, A. Kh., Volchenko, A. I., Nabizade, K. T., Javadov, M. Ya. (2019.). i dr. Tribologiya (Trenie, iznos, smazka). Baku: «Apostrof-A», – 640 p.

Copyright: ©2026 A. Kh. Janahmadov. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.