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Application of the Extended Finite Element Method (XFEM) to Model Fatigue Crack Growth Behavior of Some Aluminium Alloys

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ABSTRACT

Fatigue crack growth is a critical concern in the structural integrity of aluminum components used in aerospace, automotive, and industrial applications. This research investigates the fatigue crack growth behavior of 2024-T3, AA2060, and 7075-T73 aluminium alloys using the Extended Finite Element Method (XFEM). Numerical simulations were conducted in ANSYS 19.1 to analyze the crack propagation, stress intensity factors, and fatigue life under a constant tensile load of 40 MPa across and stress ratio (R = -1). The results showed that the lowest FCGR was recorded for the 2024-T3 alloy, while the highest was for the AA2060 alloy. The lower FCGR gives the highest (Nf); 2024-T3 had the longest number of cycles to failure. This study validates XFEM as an effective tool for modeling complex fatigue crack growth scenarios and provides valuable insights for fatigue life assessment in Aluminum alloy components.

تطبيق طريقة العناصر المحدودة الممتدة (XFEM) لنمذجة سلوك نمو شقوق التعب لبعض سبائك الألومنيوم

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الكلمات المفتاحية:
طريقة العناصر المحدودة الممتدة (XFEM)
نمو شقوق التعب (FCG)
دورات الفشل (Nf)
الأنسز (ANSYS)
سبائك الألومنيوم 2024-T3
AA2060
7075-T73

الملخص

نمو شقوق التعب (FCG) هو مصدر قلق بالغ الأهمية فيما يتعلق بالسلامة الهيكلية لمكونات الألومنيوم المستخدمة في تطبيقات الطيران والسيارات والصناعة. يبحث هذا البحث في سلوك نمو شقوق التعب لسبائك الألومنيوم 2024-T3 وAA2060 و7075-T73 باستخدام طريقة العناصر المحدودة الممتدة (XFEM). أجريت عمليات محاكاة عددية في ANSYS 19.1 لتحليل انتشار الشقوق وعوامل شدة الإجهاد وعمر التعب تحت حمل شد ثابت قدره 40 ميجا باسكال عبر نسبة الإجهاد (R = -1). أظهرت النتائج أن أقل معدل نمو شقوق تعب (FCGR) تم تسجيله لسبائك 2024-T3، بينما كان الأعلى لسبائك AA2060. يعطي (FCGR) الأقل أطول عدد دورات الفشل (Nf)؛ كان لدى 2024-T3 أطول عدد من دورات الفشل. تثبت هذه الدراسة صحة (XFEM) كأداة فعالة لنمذجة سيناريوهات نمو شقوق التعب المعقدة وتوفر رؤى قيمة لتقييم عمر التعب في مكونات سبائك الألومنيوم.

1. Introduction

Fatigue crack growth is a critical phenomenon in engineering structures, leading to catastrophic failures if not accurately predicted and managed. Traditional Finite Element Method (FEM) often face challenges in modeling crack propagation, particularly in complex geometries and under dynamic loading conditions. The need for frequent re-meshing and the difficulty in capturing the singular nature of the stress field near the crack tip can limit the accuracy and efficiency of FEM simulations. The Extended Finite Element Method (XFEM) offers a promising alternative by incorporating enrichment functions to represent the crack discontinuity without explicit mesh modification. This approach eliminates the need for re-meshing, significantly reducing the computational cost and improving the accuracy. XFEM has been successfully applied to various fracture mechanics problems, including crack propagation analysis.

Faisal K. et al. investigated the fatigue crack growth behavior of 2024-T3 Aluminum alloy as a function of the stress ratio,

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compressive peak stress, and maximum stress level. They found that as the stress ratio and the magnitude of the compressive peak stress increased, the threshold stress intensity range decreased linearly [1]. **Omer G. et al.** published research on the effect of the stress ratio on the growth rate of fatigue cracks in 1100 AL alloy. Experimental fatigue crack propagation data were analyzed using Paris-Erdogan stress intensity analysis. The test data at different stress ratios showed that two regions were present: region I and region II [2]. **E. Donnelly et al.** studied the small crack growth in the aluminum alloy 7075-T6. The study revealed that the growth rates of cracks at different locations around the circumference of the rotating bending specimens varied little despite the different microstructural orientations of the various locations [3]. On the other hand, **Vidit Gaur et al. i**nvestigated the fatigue life and crack growth behavior of post-welded Aluminium 5183 alloy; the study revealed that the fatigue-crack growth tests on CT specimens at different R-ratios (0.1, 0.5, and 0.8) showed a reduction in crack growth rates (and in threshold values) with increasing R-ratio [4]. **Ouf A. Shams et al.** Performed a Comparative Analysis of the aluminum alloys 2024 and 7085 under Thermal Fatigue and Crack Propagation. The results showed that the maximum deformation reached 0.56 mm in the case where the sample thickness was 5 mm and the type of metal was aluminum alloy 7085. The value of bone deformation at a thickness of 5 mm is 0.66 mm, the highest deformation value compared to the other cases. [5]. **M. Adarwish et al.** studied the stress Intensity factor evaluation at the tips of multi-site cracks in an unstiffened 2024-T3 aluminium panel using XFEM. The concluded analysis showed that XFEM is an efficient tool for simulating of the crack propagation even in the case of the 3D configuration with MSD. In addition, the obtained results can be used for the predicting of SIFs. [6]. **M. Adarwish et al.** studied Stress Numerical assessment of stress intensity at tips of multi-cracks in unstiffened panel, the computations are carried out in FRANC2D software, which is FEM, based and with superposition based approximate method. The comparison of the results has shown that the obtained solutions can be used for SIF predictions with acceptable accuracy [7].

This study aims to investigate the application of XFEM for modeling the fatigue crack growth in notched Aluminum plates made from 2024-T3, AA2060,and 7075-T3, Subject to cyclic loading. The primary objective is to evaluate the accuracy and efficiency of XFEM compared to traditional FEM in predicting the crack path, crack growth rate, and fatigue life. By incorporating XFEM's capabilities, we provide a more robust and reliable approach for fatigue life assessment of engineering components.

2. Material

This study investigated 2024-T3, AA2060, and 7075-T73 Aluminum alloys. Table (1) shows the alloys' Mechanical properties:

Table 1: Mechanical and fracture properties of the studied alloys, [8].

Alloy / Mechanical properties	2024-T3	7075-T73	AA2060
UTS, MPa	455.1	482.6	550
Yield, MPa	365.4	406.8	485
Modulus of elasticity (E) MPa	73.1	70	70
Poisson'sratio	0.25	0.5	0.33
Paris law constant, C	2.382e-12	1.e-10	1.e-10
Paris law constant, m	3.2	2.9	3

3. Methodology

The tensile specimen is commonly used to assess the FCG and material fracture toughness. This study conducted simulation work using XFEM in Ansys. Mechanical (version 19.1, Ansys, Inc., Canonsburg, PA, USA) on four tensile Aluminum specimens to demonstrate the ability to predict crack propagation trajectories and fatigue life under constant amplitude load conditions. The geometric dimensions of the modified tensile specimen are shown in Figure (1).

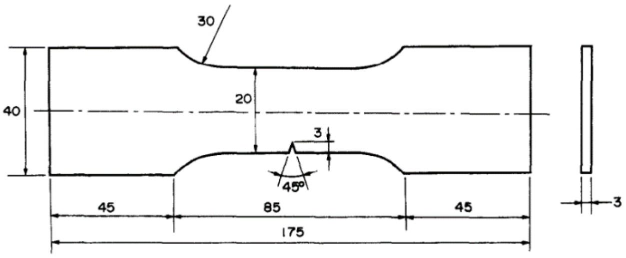

Fig. 1: Fatigue crack growth test specimen.

(ANSYS 19.1) defines the initial crack with no element mesh, and the first step in the 3D analysis of crack propagation is crack "opening" followed by the calculation of stresses. (ANSYS 19.1) uses XFEM solutions to calculate stress intensity factors in nodes of the crack front and generates a file with K_I, K_{II}, and K_{III} results. At the same time, (ANSYS 19.1) calculates the number of loading cycles necessary to grow a crack by a given length using the Paris law. Many stages must be done to perform the modeling and analysis for the numerical simulation of the crack growth within the structure:

1. Creating a 3D model (shape and dimensions), Fig. (1).
2. Defining the material properties for the model.
3. Applying the boundary conditions. In the structural analyses, the boundary conditions BCs apply to the model's regions (nodes - edges -faces - cells) where the displacements and rotations are known. Such areas may be constrained to remain fixed (zero displacement and rotation) during the simulation or may have specified non-zero displacements and rotations.
4. Applying the load, including its intensity, type, and location within the structure.
5. Introducing the initial crack within the structure, including its location.
6. Generating the final mesh. The mesh must be refined around the initial crack and in the regions where the crack is expected to grow.
7. Analyzing the results obtained.

All simulation analyses were performed using ANSYS 19.1 software. The calculations obtained, including the stress intensity factors and the crack growth data, are a function of the load cycles N and crack length [4], [5], [6]. It can be seen that the mesh was refined around the cracks at the crack's edge, and a uniform template of elements around the crack front was used. The characteristics of the final mesh are summarized in Table (2).

Table 2: Characteristics of the specimen's final mesh

No. of nodes	No. of elements	Method
24915	16696	Tetrahedrons

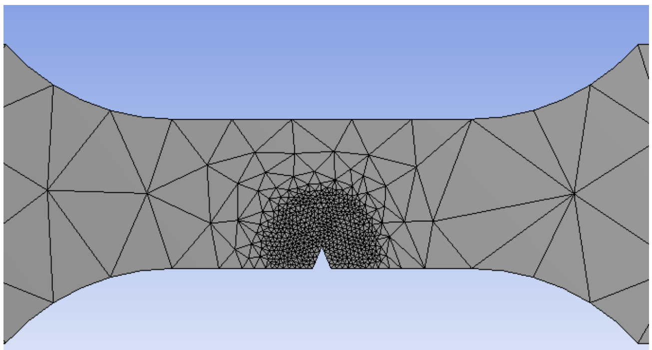

Fig. 2: FE model with the final mesh.

4. Results and Discussion

Fatigue crack growth in Aluminum alloys is a critical factor in the design and lifespan of engineering components. Due to their unique microstructures and mechanical properties, various Aluminum alloys exhibit different fatigue crack growth behaviors, [4]. The key factors affecting fatigue crack growth:

A constant-amplitude, cyclic loading condition was applied to the panel, including a tensile loading of 40 MPa with a stress ratio of (R = -1). The fatigue cracks in this simulation usually grow in a direction perpendicular to the tensile stress that attempts to open the crack. This type of crack opening is referred to as Mode I. The simulation results show that K_I was the principle domain, as shown in the following figures: Fig. (3) shows the comparison between the crack length and the stress intensity factor for the crack alloys; it can be seen from this figure that the cracks behave and show a linear relation as the crack extends until a specific increment, and then there is a rapid increase in SIF values comparing with crack length, This behavior was confirmed by many researchers, [5], [6].

The following table shows the final step of the simulation at R= -1. The results indicate that the 2024-T3 alloy is the most affected by the stress ratio, followed by the 7075-T73 alloy, and then the AA2060 alloy. The crack length in the 2024-T3 alloy was 40% longer than that of the AA2060 alloy and 23.2% longer than that of the 7075-T3 alloy. Additionally, the K_I value for the 2024-T3 alloy was 48% higher than that of the AA2060 alloy and 33.4% higher than that of the 7075-T3 alloy. In this specific case, the AA2060 alloy exhibited the lowest crack length and K_I value. This is attributed to its superior mechanical properties (as detailed in Table (1)), which makes it a promising modern alloy for aeronautical applications.

Table 3: Final crack length and its corresponding SIFs.

Alloy	Crack length, mm	Stress intensity factor, K_I MPa$\sqrt{mm}$
7075-T73	6.3794	1030.9
2024-T3	8.3021	1547.8
AA2060	4.9676	803.64

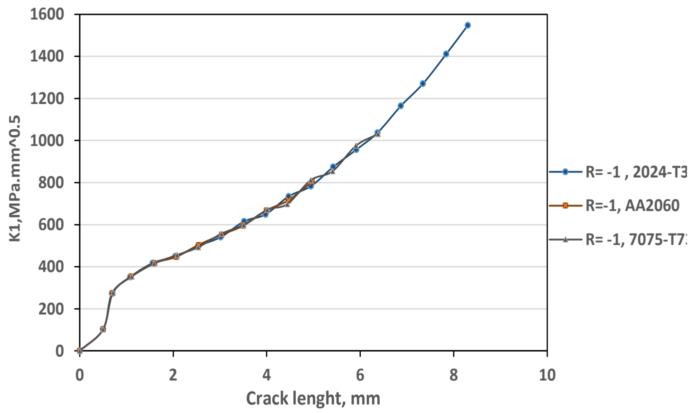

Fig. 3: SIF history for cracks in load case σ=40 MPa, R=-1.

The stress ratio (-1) illustrates a completely reversed cycle of stress in the sinusoidal form. The maximum and minimum stresses are equal for this type of stress cycle. The tensile stress is considered positive, and the compressive stress is considered negative. This type of stress cycle is counted as the most effective, meaning this type gives less specimen fatigue life. The figures below describe the simulation results in this case (R=-1).

Fig. (4) below shows the relationship between the FCGR and the corresponding values of the SIF; it showed that the lowest FCGR was recorded for the 2024-T3 alloy, while the highest was for the AA2060 alloy. The FCGR recorded the maximum difference of 7%; the highest was to the AA2060 alloy and the lowest was 6%, see Fig. (4).

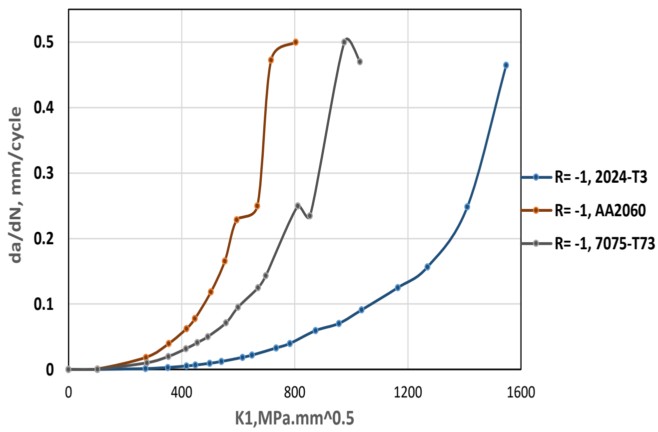

Fig. 4 FCGR histories of the alloys in load case σ=40 MPa, R= -1

The lower FCGR gives the highest (Nf); this is very clear in Fig. (5), where the (Nf)of 2024-T3 was higher by (94%) than the (Nf) of AA2060 and by (89%) Nf of the 7075-T73 alloy. In addition, 2024-T3 documented the longest crack length; 40% and 23% longer than AA2060 and 7075-T73, respectively.

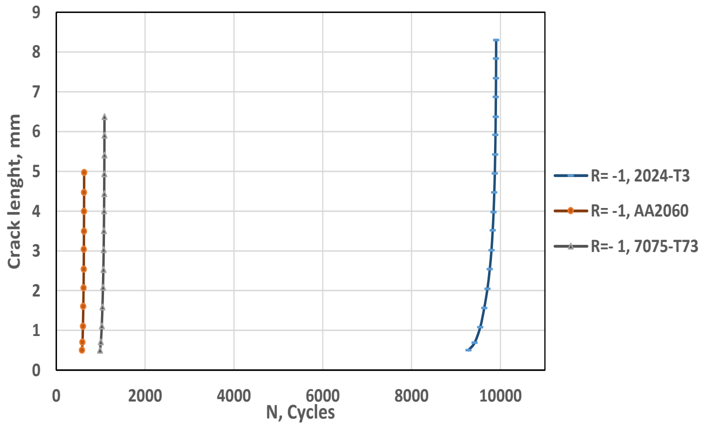

Fig. 5 Fatigue life (Nf) histories of the alloys in load case σ=40 MPa, R= - 1

Simulation images Figs. (6), (7) and (8) accurately describe Figs. (3) and (5). 2024-T3 had the longest number of cycles to failure; it was higher by (94%) from AA2060 (Nf) and by the same percent from its crack length due to the effect of equivalent stress; see images Figs. (6), (7) and (8).

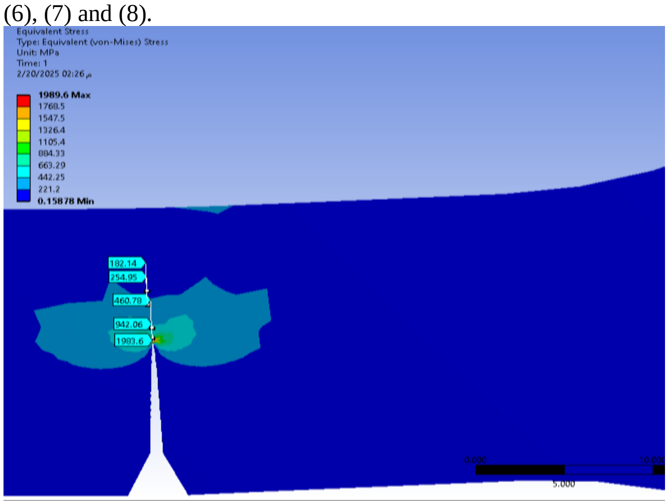

Fig. (6) Stress intensity zones of the 2024-T3 alloy in load case σ= 40 MPa, R= -1, stp.18

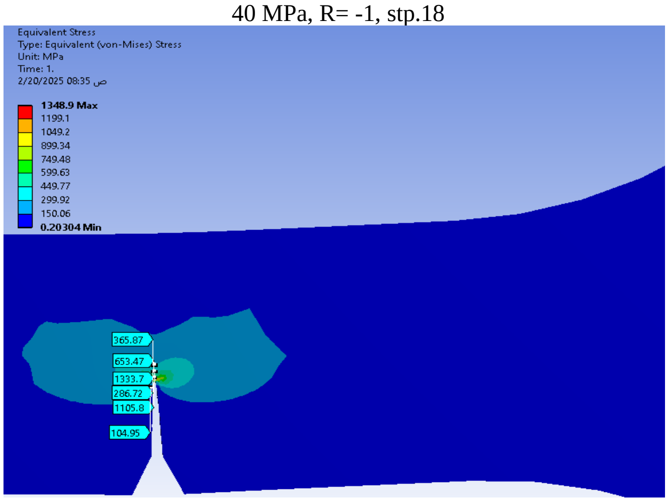

Fig. (7) Stress intensity zones of the 7075-T73 alloy in load case σ= 40 MPa, R= -1, stp.14

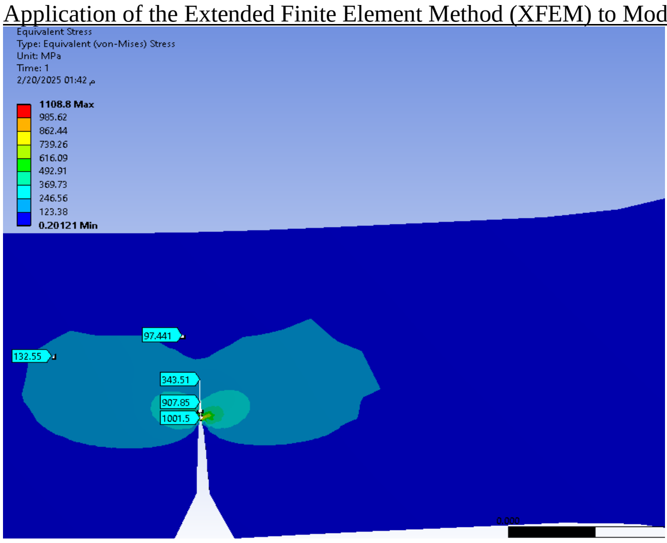

Fig. 8 Stress intensity zones of the AA2060 alloy in load case σ= 40 MPa, R= -1, stp.11.

The graph below is represented on a log-log scale, which is typical for the fatigue crack growth data. This allows for a wider range of data to be displayed and helps identify the Paris region. The graph generally shows an increase in the crack growth rate (da/dN) with increasing (ΔK), which aligns with the fundamental principle of fatigue crack growth.

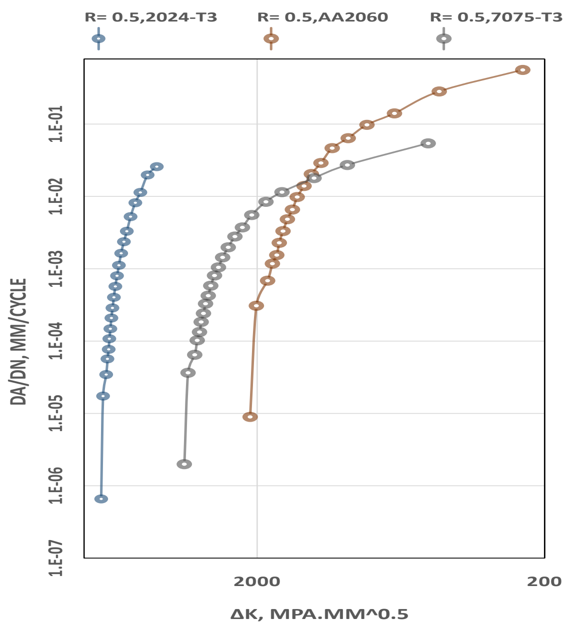

Fig. 9 A typical crack growth rate vs. stress intensity factor range at R= 0.5.

The 2024-T3 alloy shows a relatively flat curve in the lower (ΔK) region, indicating a slow and stable crack growth rate. As (ΔK) increased, the crack growth rate gradually increased, but it remained lower than the other two alloys throughout most of the plotted range. This indicates that 2024-T3 has a higher resistance to fatigue crack growth at lower and moderate (ΔK) values compared to the AA2060 and the 7075-T73.

In contrast, AA2060 exhibits a more rapid crack growth rate as (ΔK) increases, indicating lower fatigue resistance than 2024-T3. Meanwhile, 7075-T73 falls in between, with a crack growth rate that is faster than 2024-T3 but slower than AA2060 at higher (ΔK) values. This highlights the varying fatigue performance characteristics of these alloys under different stress intensity conditions. The AA2060 alloy exhibits a steeper slope in the higher (ΔK) region, indicating a more rapid increase in crack growth rate with increasing (ΔK). AA2060 exhibits rapid crack growth at higher (ΔK) values.

The 7075-T73 alloy shows a behavior that is intermediate between 2024-T3 and AA2060. It exhibits a gradual increase in crack growth rate with increasing (ΔK) , but the slope is steeper than 2024-T3 and less steep than AA2060. This alloy shows a gradual increase until the higher end of the (ΔK)range, where it begins to increase rapidly, much like the AA2060.

Fig. (9) provides valuable insights into the fatigue crack growth behavior of these aluminum alloys under a stress ratio of 0.5. It highlights the importance of material selection and the influence of Delta K on the crack propagation rates.

Fig. (10) shows that changing in the stress ratio from 0.5 to -1 has a significant impact on the fatigue crack growth behavior of these alloys; The results of the three alloys are much closer together than in the previous graph, when the R value was 0.5.2024-T3 alloy showed the highest (ΔK) values throughout the graph. Moreover, it showed a relatively flat curve in the lower (ΔK) region, similar to the previous graph, indicating a slow initial crack growth rate. The AA2060 alloy showed a very rapid increase in crack growth rate at the high end of the (ΔK) values.

7075-T73 alloy exhibits a very similar behavior to AA2060, This alloy also shows a very rapid increase in the crack growth rate at the high end of the (ΔK) values.

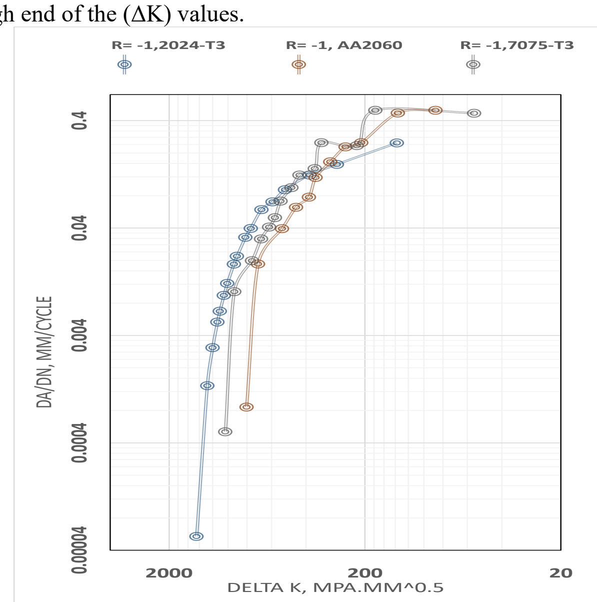

Fig. 10 Fatigue crack growth rate (da/dN) versus (ΔK) at R= -1.

The fatigue crack growth curves for the three alloys are much closer together at R = -1 compared to R = 0.5. This suggests that the severe nature of the fully reversed loading condition diminishes the differences in the intrinsic fatigue resistance of the alloys. The slopes of the curves, particularly at higher Delta K values, appear to be steeper at R = -1, indicating a more rapid increase in crack growth rate with increasing (ΔK).

The graph clearly demonstrates the significant impact of the stress ratio on the fatigue crack growth. At R = -1, the fatigue crack growth behavior of the three aluminum alloys is much more similar, and the crack growth rates are generally higher compared to R = 0.5. The fully reversed loading condition at R = -1 is a much more severe test, and it reduces the differences between the alloys.

Conclusion:

This study successfully applied the Extended Finite Element Method (XFEM) to model the fatigue crack growth in notched aluminum alloys, specifically 2024-T3, AA2060, and 7075-T73, under cyclic loading condition. The results highlight the potential of XFEM in accurately predicting crack propagation trajectories, stress intensity factors (SIF), and fatigue life (Nf), offering significant improvements in The fatigue crack growth behavior varied significantly between the alloys studied, with 2024-T3 exhibiting superior fatigue life compared to AA2060 and 7075-T73.

Among the three alloys, AA2060 showed the shortest crack length and the lowest K_I value, attributed to its superior mechanical properties, making it a potential candidate for high-performance applications such as aerospace. However, 2024-T3 demonstrated the highest fatigue life, which was 94% longer than AA2060 and 54% longer than 7075-T73 under the same loading conditions.

The stress intensity factor (K_I) distribution around the crack tip was analysed at various simulation steps. It was observed that stress concentration near the crack tip intensified with crack propagation, significantly influencing the crack growth rate. XFEM's ability to model the crack tip behavior without mesh refinement was a key advantage in capturing these critical phenomena efficiently. Also, The analysis of the fatigue crack growth rate (da/dN) versus the stress intensity factor range (ΔK) at R = -1 revealed several critical insights. The data, presented on a log-log scale, clearly demonstrates a direct relationship between ΔK and da/dN, aligning with established fatigue crack growth principles.

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