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# Investigation of fatigue crack propagation mechanisms of branching crack in 2324-T39 aluminum alloy thin plates under cyclic loading spectrum

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ABSTRACT

Significant macroscopic crack branching has been observed in the crack growth paths of 2324-T39 aluminum alloy under spectrum loading, the mechanisms of which was investigated in this paper. The relationships between microscopic fracture surface characteristics and macroscopic fatigue crack growth paths and the relationship between plastic zone size and fracture surface characteristics were revealed. The change in fracture mode, which relates to the changes in the plastic zone in the thickness direction, and the growth of secondary cracks led to the appearance of branched cracks. A high level of $\sigma_x$, $\sigma_z$ leads to mixed-mode growth of the subsurface secondary cracks.



## 1. Introduction

The 2324-T39 aluminum alloy (AA) is one of the Al–Cu–Mg alloys developed by Alcoa for tension-dominated, fatigue and fracture critical plate applications. This alloy has been used in commercial aircrafts, such as the Boeing777 and ARJ21. It is a higher strength version of the 2024-T351 alloy, which shows an approximately 10–30% higher yield strength, tensile strength and fracture toughness [1]. The elemental composition of AA 2324 is given in Table 1 [1]. The tensile and yield strengths are approximately 475 and 370 MPa, respectively. The fracture toughness $K_{IC}$ is approximately 38.5–44 $\text{MPa}\sqrt{\text{m}}$ (for specimen thickness $t$ = 19.05–33.02 mm).

Because AA 2324-T39 plate is ordered according to the in-house specifications of the customer, there are no federal, MIL, or AMS specifications for this alloy. Little fatigue and crack growth data can be found in the literatures. However, knowledge of the fatigue and crack growth properties are the basis for evaluating the fatigue and damage tolerance performance of aircraft structural components made from this alloy. Crack growth tests with 2324-T39 middle crack tension (M(T)) specimens under flight-by-flight spectrum loading were conducted in the authors' research lab, which has been reported in the literature [2–4]. During the tests, significant macro-level crack branching, which is abnormal in the expected Mode I crack growth path in M(T) specimens, was observed.

According to achievements in fatigue theory and fracture mechanics, through thickness middle crack in an isotropic thin plate subjected to remote tension dominated loading should propagate perpendicular to the load direction, i.e., Mode I. This is reasonable from a physical perspective because the tensile stress component, which opens the crack, will certainly promote the conversion of cyclic plastic deformation into crack extension [5]. In the microscopic perspective, there are two different modes for crack propagation morphology: the zig-zag mode and the continuous mode, which are determined by the relationship of crystal orientation with the tension direction of the crack [6]. At the macro level, crack kinking, bifurcation and branching are influenced by microstructural irregularities, load effects (global and local multiaxial stress state, spectrum loading), and environmental factors [7–11]. No references have been found in the literature reporting that the metallurgical properties of the above alloy lead to an improvement in crack growth morphology with respect to those of other Al–Cu–Mg alloys, such as 2024-T351 and 2524-T3, among other. Nevertheless, it must be conceded that the comparatively large grains size of AA 2324-T39 is one factor to take into account for the crack branching, as shown in the tests reported in Refs. [2–4] and should be further studied.

Schijve [12] reported that fatigue cracks grow in a direction perpendicular to the main principle stress (provided the crack growth

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**Nomenclature**

| | |
|---|---|
| $a$, $a_0$ | half crack length, half initial crack length in middle-crack tension, M(T), specimen |
| $W$ | width of the specimen |
| $t$ | thickness of the specimen |
| $K$, $K_{max}$ | stress intensity factor (SIF), maximum SIF |
| $n$ | cycles between two overloads |
| $N$ | load cycle |
| $\sigma$ | remote applied stress, stress in the loading spectrum |
| $\sigma_{max}$ | maximum value of $\sigma$ |
| $\sigma_x$, $\sigma_y$, $\sigma_z$ | stress parallel to the crack plane, Stress in the direction perpendicular to the crack plane, Stress through the thickness |
| $\sigma_{mises}$ | Mises stress |
| $\sigma_e$, $\sigma_{0.2}$, $\sigma_b$ | proportional limit, yield stress, tensile strength |
| $\tau_{max}$ | maximum shear stress |
| $r_p$ | overload plastic zone size |
| $\alpha$ | plastic zone factor |
| $T$ | $T$ stress |
| $E$ | Young's modulus |
| $\nu$ | Poisson's ratio |

rate is not very high). For a cyclic tension load, the crack growth will be perpendicular to the loading direction. A noteworthy exception to the perpendicular crack growth is observed in Al-alloys. The growing fatigue crack at the material surface exhibits so-called shear lips at an angle of approximately 45° with the central part of the crack front. The shear lip width increases during faster crack growth until they cover the full thickness. The shear lips start at the material surface, and in fact it should be considered to be a free surface phenomenon. The possibilities for plastic deformation at the location where the crack front meets the free surface are less restrained than at mid-thickness. It apparently allows plastic shear deformations which promote the formation of shear lips. These shear lips are similar to the shear lips observed on the fracture surface of static failures along the free surface edges.

Pook [11,13] reported that there are two fundamentally distinct classes of crack propagation under both fatigue loading and rising load static loading: principal stress dominated crack propagation and shear dominated crack propagation. Flat (Mode I) crack propagation in sheets is principal stress dominated, associated with low stresses in the vicinity of a crack tip, and slant crack propagation that is sometimes observed in thin sheets is shear dominated, associated with high stresses. The transition from flat to slant crack propagation in thin sheets begins with the development of shear lips. These lips increase in width until they meet in the center of the sheet, thereby completing the transition. Until recently, only qualitative explanations of the transition have been available.

Other researchers [14] have accurately reported experimentally observed features of the transition from flat to slant crack propagation, under a rising static load, numerically by a series of finite element calculations using a newly developed theory of plasticity. Factors taken into account include the Lode angle, which is a function of the third invariant of the stress tensor, the strain hardening properties of the material and its pressure sensitivity, and the specimen thickness. More than 100,000 elements were used; thus, the calculations would not have been possible without a modern computer. Similarly, numerical studies can be used in crack tip shielding [15], 3D effects/thickness effects [16], plastic zone size near the crack tip [17,18] and crack surface roughness effects on the crack path [19].

Load effects, including the stress intensity factor range level, stress ratio, overloads and underloads, on the macroscopic fatigue crack growth behavior of AA 2324-T39 thin plates were experimental investigated in a previous study in Ref. [4]. For the specimens tested under constant amplitude loading condition, crack path deviation appeared at a high $\Delta K$-level, and the stress ratio $R$ exhibited little effect on the change in crack growth path. For the specimens tested under simple variable-amplitude loading conditions, significant crack branching was observed irrespective of the interval between the two peaks of the load.

The purpose of this paper is paid attention to the macro and microscopic fracture behaviour, including the relationship between microscopic fracture surface characteristics, macroscopic fatigue crack growth paths and the relationship between plastic zone size and fracture surface characteristics.

## 2. Experimental research and FE model

### 2.1. Experimental research

To better understand how the crack path changes with respect to different loading condition and the following on discussions on fracture surfaces characteristics and crack-tip stress fields corresponding to different crack morphologies, the crack growth tests and the corresponding loading cases are presented here in brief, the details can refer to Refs. [2–4].

M(T) specimens in L–T orientation with a thickness of 4.5 mm were used in the crack growth tests and were machined from AA 2324-T39 plates with a thickness of 19 mm. L is the longitudinal direction, and this is the direction in which the external load is applied. T is the transverse direction. All the tests were accomplished using Instron8803 servo hydraulic fatigue test system in laboratory air, and an observation system consisting of a digital microscope, a servo motor, and a raster ruler is used to register the position of crack tip. All the tests were run at 5 Hz.

The loading cases contain flight-by-flight spectrum loading and simple variable amplitude loading. For the flight-by-flight spectra:

(1) The baseline flight-by-flight spectrum block, marked as S0 consists of five flight types and simulates 4200 flights, as illustrated in Fig. 1a. The loading cycles were arranged randomly in each flight type, and then the five flight types were

**Table 1**
Chemical composition limits of AA 2324.

| Alloy | Alloy elements | | | | Impurity substance (%) | | | | | Others (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cu | Mg | Mn | Al | Fe | Si | Zn | Ti | Cr | Each | Total |
| 2324 | 3.8–4.4 | 1.2–1.8 | 0.3–0.9 | Remainder | 0.12 | 0.10 | 0.25 | 0.15 | 0.10 | 0.05 | 0.15 |

Value maximum if range not shown.