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Effect of Mode-Mixity on Fatigue Crack Growth

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Abstract

In an attempt to understand the effect of mode-mixity on the growth of a nominal defect under repetitive sub-critical loads, fatigue experiments are conducted on an Aluminium alloy at different mode-mixities. Three-dimensional finite element simulations akin to experiments are performed at different crack lengths and mode-mixities to study their effect on the opening stress, stress-state characterised by triaxiality parameter and equivalent plastic strain, at the mid-section of the model specimen.

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Keywords: Fatigue, Mode-Mixity, Triaxiality, Equivalent Plastic Strain, Aluminium.

1. Introduction

Fatigue is a progressive, localised and permanent damage that occurs in materials subjected to cyclic stresses, at a value that is well below the static yield strength of the material. The significance of cyclic loadings in causing failure was recognised much before Linear Elastic Fracture Mechanics was developed [14]. The service loads are seldom monotonic. They are variable amplitude loads with combination of various load sequences. Thus, it is of great importance in design to study the behaviour of material subjected to cyclic loads to avoid any catastrophic failure.

The complex mechanism of fatigue involves, crack initiation, followed by crack propagation and eventually, fatigue failure. Most of the fatigue studies that happened over last few decades concentrate on mode-I type of loading condition and the experiments are also conducted for the same [4]. On the contrary, in real time, the structures experience mixed-mode nature of loadings where stress-states are very complex in nature. Also, under mixed-mode conditions, cracks don't grow in a self-similar manner, but digress from the original direction [1]. Hence, it is of immense significance to comprehend the fatigue crack growth under mixed-mode, as it resembles the real time service conditions and also, has a potent influence on features, viz., microstructure, strain-distribution, crack growth rate, crack path.

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Most ductile materials deform plastically prior to fracture. The crack tip is attended by a plastic deformation through which the crack extends [5]. These deformations are measure of ductility of the component. The difference between an uncracked component and a component with a notch or a crack is the triaxial state of stress in front of the crack tip [9]. The triaxiality affects the material's ductility [11, 16], as they are potent factors for voids initiation, nucleation and coalescence, which eventually affects the component's structural integrity. Also, mode-mixity has a major influence on the triaxiality [15].

Furthermore, as the mixity increases, the mode-II component comes into play, leading to extensive plastic zone formation and thus, localisation of plastic strains, which is yet another potential factor influencing fatigue failure. Thus, both equivalent plastic strain and triaxiality have a dominating influence on the fatigue crack growth mechanism, independently as well as interdependently. As the crack grows perpendicular to the direction of maximum normal stress direction [8], it is important to understand the effect of normal opening stress under mode-mixity as well.

Recent mixed-mode fatigue studies include- fatigue crack growth analyses of functionally graded materials with multiple discontinuities were performed using XFEM under mixed-mode loading and plane-strain conditions and the effect of the volume fraction of discontinuities on the fatigue life was studied [3]. Experimental and numerical study on fatigue crack growth behaviour of aluminium alloy under mixed-mode loading were carried out to understand the influence on crack growth rate at different stress ratios and the effect on crack closure[6]. Effect of overloading on the fatigue crack growth behaviour under mixed-mode condition was studied through FE modeling of Compact Tension specimens[13]. XFEM and cyclic cohesive zone model were combined and implemented into commercial finite element software to study the fatigue crack propagation under mixed-mode loading conditions [16]. Also, XFEM was integrated with standard FEA code to study the effect of particle size and volume fraction on crack propagation behaviour of particle-reinforced metal-matrix composite [7].

On the account from literature, most of the mixed-mode fatigue studies never take into consideration the dominating influence of stress-states under mode-mixity while understanding the crack propagation behaviour or estimating fatigue life of a material. Therefore, in order to understand the fatigue crack growth behaviour of materials subjected to mixed-mode loading conditions and make a realistic assessment of components structural integrity, it is important to study the influence of mode-mixity on the stress-states, characterised by Triaxiality, $\sigma_{mean} / \sigma_{mises}$, Opening Stress and Equivalent plastic strains.

2. Experimental Procedure

Compact-Tension-Shear (CTS) specimens of width, thickness, notch radius and depth are 44 mm, 22 mm, 0.3 mm and 1 mm, respectively, are machined from Aluminium plate (AA2219-T87), along the rolling direction to avoid any change in behaviour due to grain orientation as shown in Fig. 1. Its young's modulus and yield strength are 70 GPa and 281 MPa, respectively. The initial notch-to-width ratio is 0.6. To generate different mode-mixities, modified and hardened arcan test fixtures are manufactured from steel plate (IS 2062) [9]. The fixtures facilitate the application of superimposed shear and normal loads.

The fatigue tests are performed under laboratory conditions at room temperature in a 100 kN closed-loop servo hydraulic DMG machine. The specimens are subjected to tension - tension loads in a sinusoidal waveform at a frequency of 3 Hz. The load amplitude is kept constant throughout the fatigue test. The loading configurations are 0^o and 45^o. Each experiment is repeated thrice to ensure the accuracy of the data extracted. The crack lengths in each test are measured for every 1000 cycles till failure by observing the specimens under the microscope and with the help of vernier scales attached to it. The experimental setups are shown in Fig 2.

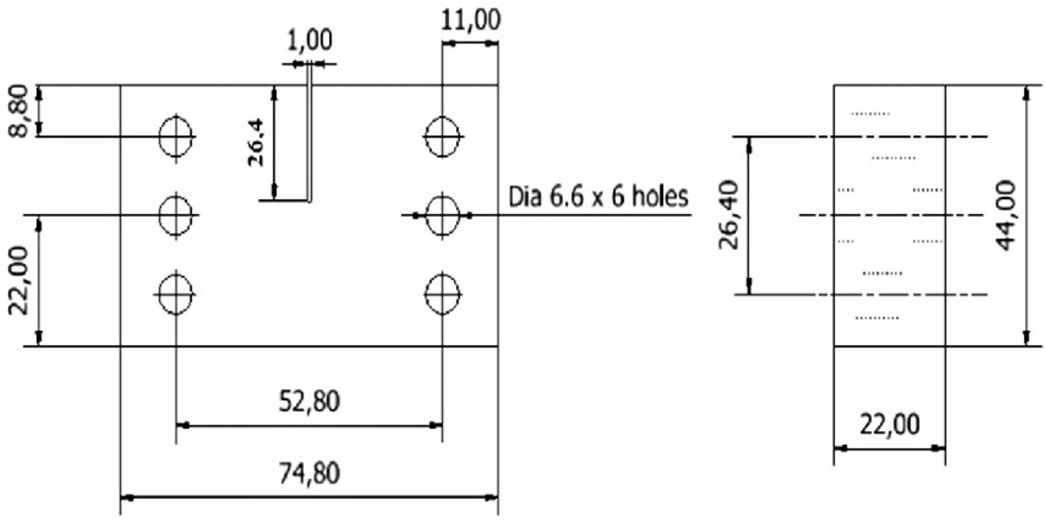

Fig. 1: Measurement of CTS Specimen

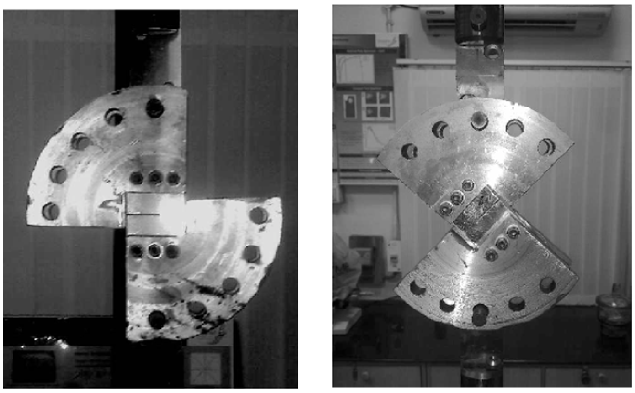

Fig. 2: Experimental Setup for mode-I (0^o) and Mixed-Mode (45^o)

3. Finite Element Studies

The present finite-element studies are performed in ABAQUS. A series of load – controlled analysis is performed on a three-dimensional model akin to the experiments for crack lengths, 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm, respectively. The analyses are performed for mode-1(0^o) and mixed-mode (45^o) loading configurations, respectively. A typical 3-D model is shown in Fig. 3. Full specimen geometry is considered due to the lack of symmetry. The bolts used in the analyses are modeled as rigid bodies and the boundary conditions are applied at reference points. The loads are cyclic in nature and the amplitude remains constant throughout the analyses. The load cycle is as shown in Fig.4. The geometry is meshed using eight-node linear elements with hour-glass control. To capture the crack tip singularity, quarter point elements are used with the first element being as small as 0.0008 mm. The mesh around the crack tip is as shown in Fig. 3.

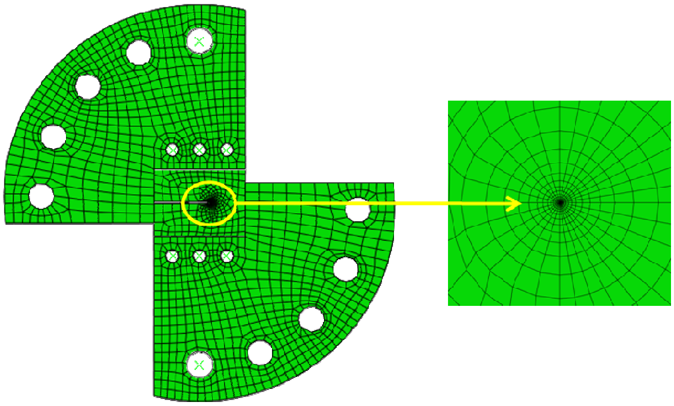

Fig. 3: 3-D Finite Element model and Mesh around the crack tip

4. Results and Discussion

From the experiments, the number of cycles to fracture and corresponding loading angles are as shown in Table 1.

Table 1: Number of Cycles to fracture for different mode angles

Mode angle (degrees)	No. of cycles
0	58000
45	97000

The increase in the crack lengths with increasing number of cycles for different loading angles is shown in Fig 5. As the applied load levels were kept constant throughout the tests for all the loading angles, more number of cycles is required to achieve crack initiation and the corresponding propagation. The crack growth curves have non-linear slopes as is evident from the trend, which intuitively may be due to the influence of state of stress. The crack initiation angles at different loading conditions are measured with the help of optical images of the fractured specimens as shown in Fig. 4(a) and Fig. 4(b). The angles at which crack initiates and propagates closely match with that of the loading configurations.

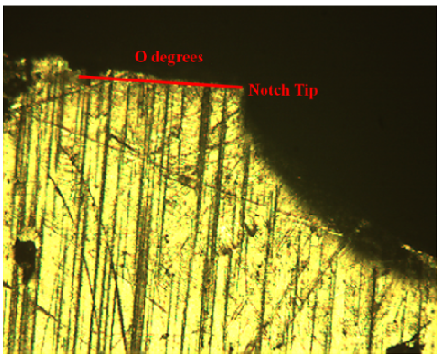

Fig. 4(a): Optical images- mode-I (0°)

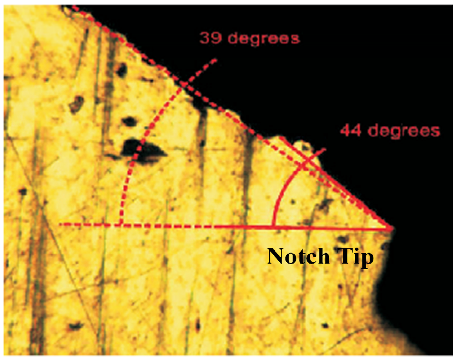

Fig.4(b):Optical images- mixed-mode (45°)

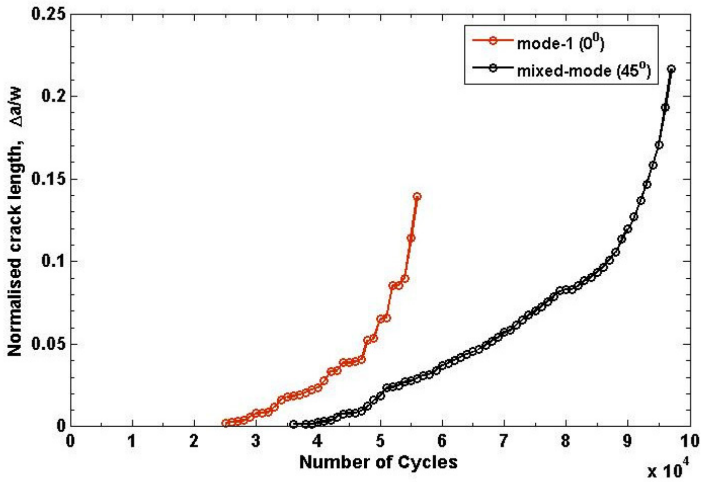

Fig. 5: Variation of crack lengths with number of cycles for different loading angles

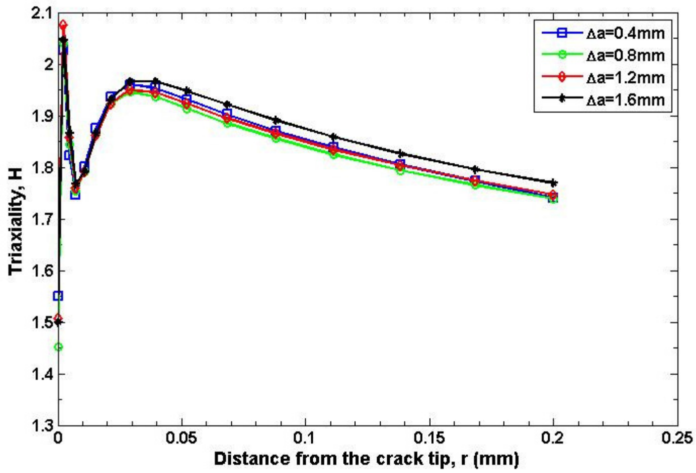

Fig.6 (a): Variation of Triaxiality for different crack lengths under mode-I (0^o)

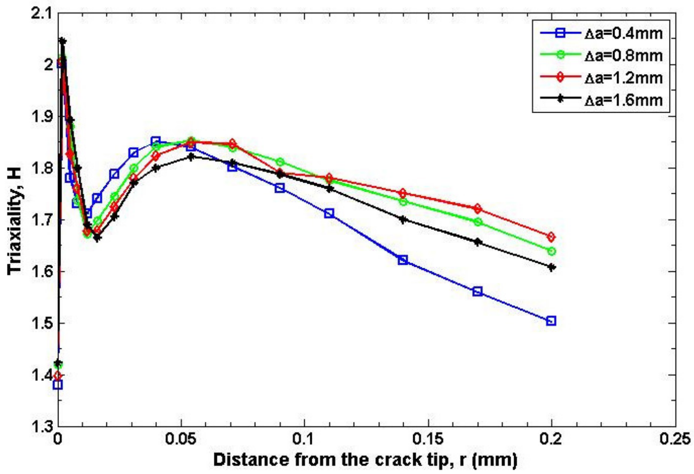

Fig.6 (b): Variation of Triaxiality for different crack lengths under mixed-mode (45^o)

From finite-element studies, the stress-state characterised by Triaxiality, Opening stress and Equivalent Plastic Strain are extracted at the mid-section of the material for different crack lengths under two different loading configurations. They are plotted with respect to the distance from the crack tip. Fig. 6(a) shows the Triaxiality variation for mode-I loading for different crack lengths, which shows a rise near to the crack tip followed by a gradual decrease. Also, further away from the crack tip, the triaxiality seems to increase with increase in crack lengths, keeping the crack tip distance constant. Fig 6(b) shows Triaxiality trends for mixed-mode (45^0) loading configuration, which shows a very confusing trend. Comparing Fig. 6 (a)-(b), the effect of mode-mixity on triaxiality can be understood. It shows that, as the mode – mixity increases, the triaxiality decreases. Mixed-mode loading configuration shows a slightly lesser Triaxiality values than mode-I configuration.

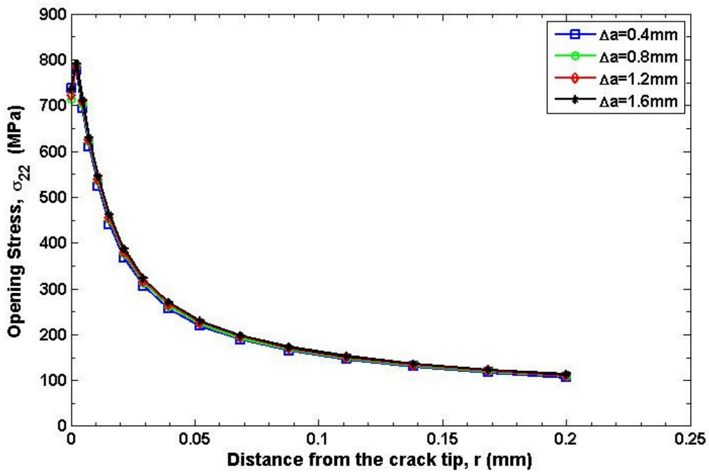

Fig. 7(a): Variation of opening Stress for different crack lengths under mode-I (0^o)

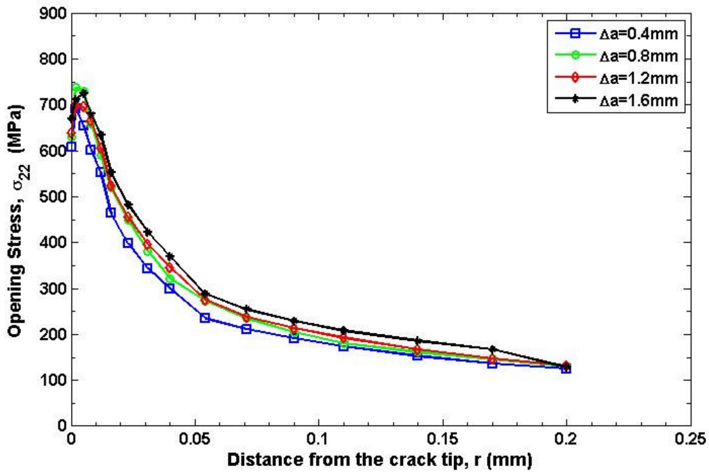

Fig. 7(b): Variation of opening stress for different crack lengths under mixed-mode (45^o)

Fig. 7(a) shows the opening stress variation under mode-I configuration for different crack lengths. It shows an increase in the value of stress with increase in crack length, keeping the crack tip distance constant. Fig. 7(b) shows Opening Stress trends under mixed-mode (45^0) loading configuration. The trends are quite similar to mode-I, with increase in the stress values for increasing crack lengths for any particular value of crack tip distance. But, Analysing Fig. 7 (a) – (b), it can be stated that, as the mode – mixity increases, the opening stress decreases. This could be attributed to the effect of shear which comes into play due to the contribution of K_{II} component.

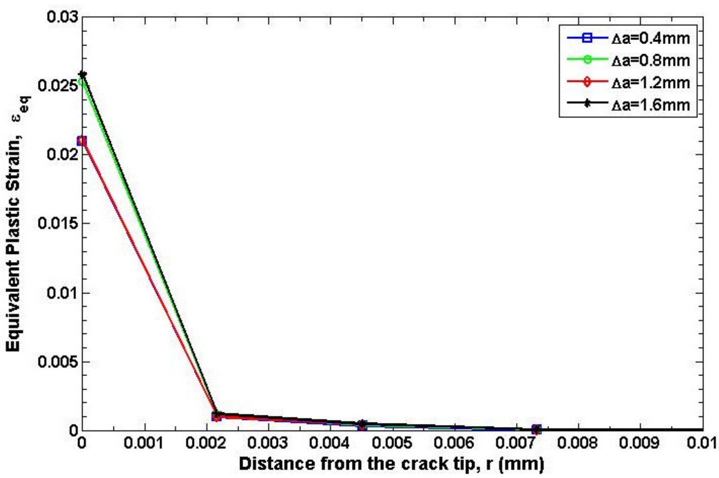

Fig. 8(a): Variation of Eq. plastic strain for different crack lengths under mode-I (0^o)

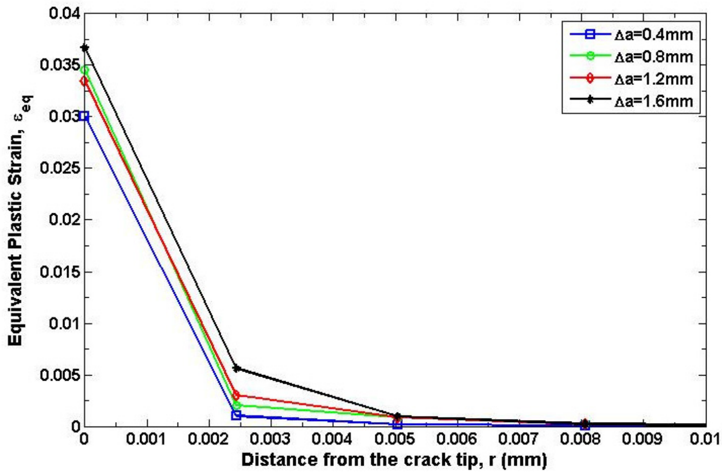

Fig. 8(b): Variation of Eq. plastic strain for different crack lengths -mixed-mode (45^o)

Fig. 8 (a) shows the variation of equivalent plastic strain under mode-I configuration for different crack lengths. The trend looks quite complicated. Fig 8(b) shows equivalent strain variation for mixed-mode (45^0) loading configuration. It shows that, keeping the crack tip distance constant, plastic strain almost has an increasing trend with increase in crack length. Comparing Fig 8 (a) – (b), it can be understood that, as the mode – mixity increases, the plastic strain increases. Thus mixed-mode loading show higher values of plastic strains than mode-I loading configuration.

5. Conclusion

Stress-state characterised by Triaxiality parameter, H and Equivalent Plastic Strain, ε_{eq} are factors that have a significant impact on the fatigue failure mechanisms. A combined experimental and computational study is carried out to understand the effect of mode-mixity on Triaxiality, Opening stress and Plastic strains, at different stages of fatigue crack growth. To summarise, from fatigue experiments of an Aluminium alloy on modified CTS specimens, it is found that the crack growth rate decreases with increase in mode-mixity. Also, the crack growth curves show occasional acceleration and deceleration in the rate of crack growth.

From the corresponding FE simulations, increase in mode-mixity results in overall decrease in opening stresses as well as triaxiality but a slight increase in the equivalent plastic strain. Correlating these trends with experiments it can be argued that higher triaxiality is conducive to faster growth of a fatigue crack.

6. Acknowledgements

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