Finite element fatigue analysis of cracks in metal matrix composites

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Abstract—The fatigue behavior of metal matrix composite (MMCs) depends on the characteristics of the reinforcements, size of the particle and the volume fraction of reinforced particles. The objective of the present work is to simulate the stress distribution within the cyclic plastic zone near the crack tip for MMC under the cyclic loading. The finite element analysis has been implemented to evaluate the stress distribution within the vicinity of crack tip under the cyclic load using plane stress condition. This work depicts the variation of equivalent stresses, crack deformation and stress intensity near the crack tip.

Keywords — Metal matrix composite; Finite element analysis; Fatigue crack growth; Crack deformation; Cyclic plastic zone.

I. INTRODUCTION

The metal matrix composite (MMC), is extensively used in many engineering applications (avian industries, automotive industries etc.), due to its mechanical characteristics such as higher strength, superior wear resistance and improved stiffness etc. The performance of the MMCs are much improved as compared to its base matrix material [1], [2]. To assure the safety and durability of MMCs under working conditions is of prime importance. Fatigue is one of the important property of material which causes catastrophic failure and needs to be studied. The fatigue crack growth in MMCs are influenced by the microstructural parameters such as particle size [4–7], volume fraction and the distribution of reinforced particles [8–12].

Some experimental studies were conducted to cater the effects of each microstructural parameter on the fatigue behaviour of the MMCs [12]–[14] . These experimental studies are expensive and time consuming. To overcome such difficulties, finite element fatigue analysis (FEFA) are used to examine the path of the crack, to evaluate the crack initiation and to predict the fatigue life of material [15]. Some studies were conducted to analyse the fatigue-fracture based 2D and 3D problems in metals [16], [17]. Very limited work has been reported in literature that could administer the FEFA of crack growth in MMCs under cyclic loading [15], [18], [19].

The objective of present work, is carry out the FEFA of crack growth in MMCs. The numerical investigation is carried out on the compact tension (CT) specimen using extended finite element method (XFEM) technique. The stress distributions, displacement and stress intensity near the crack tip has evaluated under cyclic loading condition using the he assumption of linear elastic fracture mechanics (LEFM). The stress distribution and fatigue crack growth (FCG) in the MMCs has been and is compared with the analytical work that has been presented in the literatures.

II. THEORETICAL ASPECT

The MMCs structure is subjected to multiaxial stress acting at the same time. The Von Mises criterion is used to most commonly in the engineering application to transform the stress tensor into single equivalent stress. The equivalent stress component (σ_v) is treated as a tensile stress acting on the MMC structure and then it is easily compared with the strength of the material. The yielding occurs in the component when second invariant deviotric stresses (J_2) reaches to a critical value [20]. The relationship between the deviotric stress.

$$\sigma_v = \sqrt{3J_2} \qquad (1)$$

General equation, with no boundary conditions are shown in Eq (2)

$$\sigma_v = \sqrt{\frac{1}{2}\left[(\sigma_{11}-\sigma_{22})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2\right]+3({\sigma_{12}}^2+{\sigma_{23}}^2+{\sigma_{31}}^2)} \qquad (2)$$

The physical clarification of the above criterions was suggested by Hencky [21] that yielding occurs when maximum distortion energy (E_g) is reaches to a critical

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value [22]. The relationship between the elastic energy of distortion and the second variant of deviotric stress is given by the Eq (3)

$$E_g = \frac{J_2}{2G} \tag{3}$$

III. XFEM MODELLING AND SIMULATION USING ANSYS SMART CRACK

The stress distribution and the fatigue crack growth is predicted at the vicinity of crack tip subjected to cyclic loading for MMCs by using the stress intensity factor (SIFs). SIFs are one of the essential parameters that helps in evaluating the critical crack displacement in CT specimen. Various properties of aluminium based MMCs are depicted in Table 1a and 1b [23]. The fatigue crack initiation and the stress distribution within the crack tip is modelled and simulated for the MMCs under various cyclic loads.

A. Physical Model

The fatigue crack growth and stress distribution near the crack tip is investigated on the model of Compact Tension (CT) specimen. The metal matrix composite based CT specimen is symmetrical with respect the dimensions (length = 62.5mm, breadth = 60mm and thickness = 3mm) having initial crack $a_i = 2\ \mu m$ and crack tip opening angle of 30^{O} as shown in the Fig 1.

The flow chart in Fig 1. depicts the modelling approach to solve the problem of fatigue behavior on MMCs reinforced with the dispersed particles of Al_2O_3.

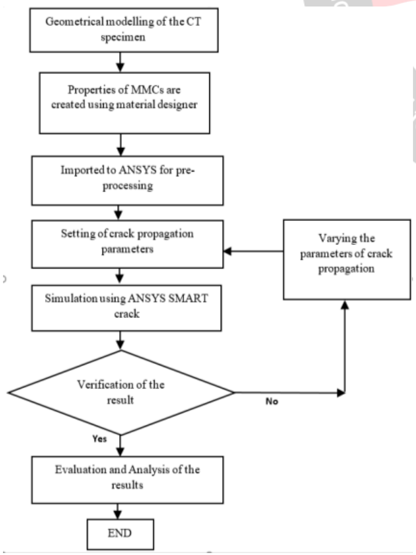

Fig 1. Schematic Flowchart of Simulation

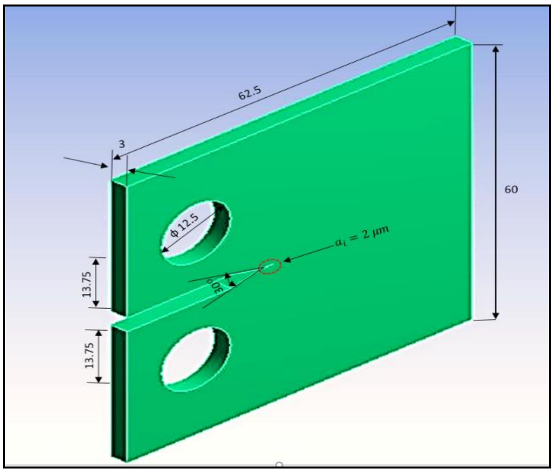

Fig 2: Dimensions of Compact Tension specimen geometry [24]

The size of the Al_2O_3 reinforced particle is 10 μm and the volume fraction in the matrix is 30%. The geometry is imported to the ANSYS ICEM for the mesh generation. The results are obtained near the vicinity of crack which is confined to six number of contour.

B. Material Properties

The cast aluminium alloy (JIS-AC4CH) reinforced with Al_2O_3 [23] is consider in the present fatigue crack growth analysis. The mechanical properties are calculated by incorporating the individual properties of matrix and the reinforced particles, having particle size of 10 microns. The effective orthotropic material properties of MMCs are designed on ANSYS material designer module, as depicted in Fig 3. The orthotropic properties are determined as depicted in the Table 2.

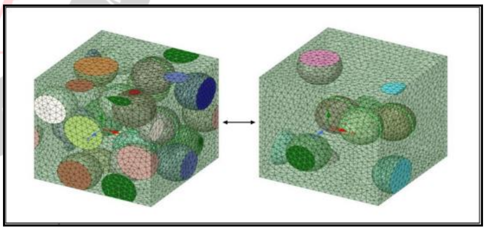

Fig 3: Random Distribution of Al_2O_3 reinforced particles.

Table: 1(a) Monotonic mechanical properties of the reinforced particles in MMCs

Mechanical Properties	Material Constraints	
	Elastic Modulus (GPa)	*Possions ratio*
Al Alloy AC4CH	70	0.33
Al_2O_3	380	0.27

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Table 1(b): Cyclic properties of the matrix materials

Cyclic Mechanical Properties	*Threshold SIFs (MPa-$m^{1/2}$)*	*Paris Constant (C)*	*Paris Law Exponent (m)*
Al Alloy AC4CH	4.2	7.8×10^{-13}	4.5

Table 2: Effective material constraints for The Al based MMC reinforced with Al_2O_3

Mechanical Compositions	*Material Constraints*					
	Elastic Modulus (GPa)		*Possions ratio*		*Modulus of Rigidity (GPa)*	
The Al based MMC reinforced with Al_2O_3	E_{11}	111	v_{12}	0.307	G_{12}	42.3
	E_{22}	110	v_{23}	0.307	G_{23}	42.9
	E_{33}	111	v_{31}	0.310	G_{31}	42.7

C. Modelling Technique for fatigue analysis

The geometry of CT specimen is imported into the static structural module and given finer meshing at the crack tip by defining a coordinate system at the front of crack tip. The fracture tool is considered and pre mesh crack is obtained by selecting the crack tip front. Fixed support is provided at the lower hole in the specimen by face selection and the force of values 50 kN, 100 kN, 150 kN are applied at the upper hole in the specimen by face selection for both the materials. The different values of equivalent Von-mises stress are obtained for MMCs under different loading application.

IV. RESULTS AND DISCUSSION

The analysis has been carried out using SMART crack growth module. The CT specimen is subjected to the fully reversed loading to analyze the range of deformation for the all three cases. As per the analysis, it is observed that the component has undergone maximum deformation of 0.011 mm when subjected to the 150 kN completely reversed load of magnitude as shown in Fig 4. The maximum equivalent stress of 749.6 GPa and 249.9 GPa has been observed at the edge of the crack tip, when the component is subjected to completely reverse loading of 150 kN and 50 kN respectively. The minimum equivalent stress of 6.133 MPa is observed when the component is subjected to the completely reversed load of 50 kN as shown in Fig. 5. Further, the fatigue analysis depicts the stress intensity at the line of the crack tip. It is evident from the Fig.6 that the maximum stress intensity of 766.2 GPa is observed under 150 kN cyclic load.

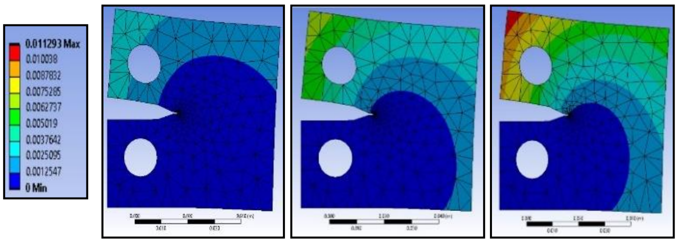

Fig 4. Deformation in crack tip of MMCs reinforced with Al_2O_3 particle

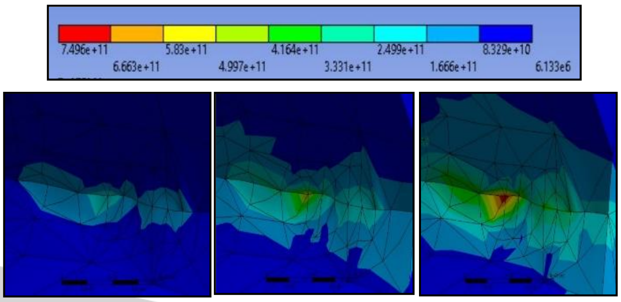

Fig 5. Equivalent stress at the crack tip of MMCs reinforced with Al_2O_3 particle

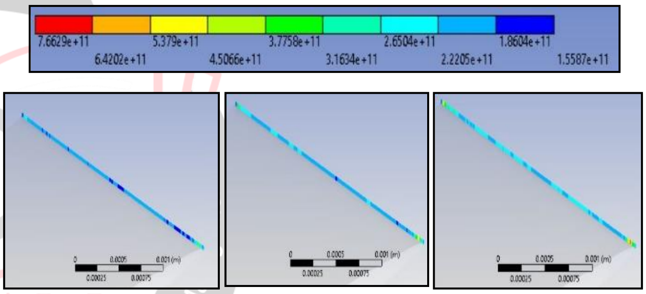

Fig 6. Stress intensity at the crack tip of MMCs reinforced with Al_2O_3 particle

V. CONCLUSION

The finite element fatigue analysis has been carried out to evaluate the stress distribution within the vicinity of crack tip under the cyclic load using plane stress condition. This work depicts the variation of equivalent stresses, crack deformation and stress intensity near the crack tip. The FEFA depicts that overall fatigue behaviour of aluminum alloy are improved by reinforcing the Al_2O_3 particles when dispersed in random order.

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