Non-linear fatigue propagation of multiple cracks in an aluminium metal matrix composite (AlMMC) with silicon-carbide fibre reinforcement

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Abstract
The fatigue crack growth (FCG) in a mesoscale metal matrix composite (MMC) sample has been simulated by the analyses of a 3D finite elements (FEs) model of a sample volume cell of the composite. Several FCG numerical simulations have been performed on MMC specimens made of aluminium (Al) alloy and silicon carbide (SiC). First, in the microscale, the homogenization of the single MMC unit cell has been performed in order to find the crack initiation sites. Subsequently, in the mesoscale, a tensile remote load with appropriate boundary conditions has been applied on the MMC unit volume. Simulation of FCG has been carried out using the Paris law and two non-linear laws for small-scale yielding (SSY), namely, the modified Kujawski-Ellyin (KE) and UniGrow laws. Finally, the FCG rates provided by numerical simulations have been compared with each other.

KEYWORDS
Fatigue crack growth, Kujawski-Ellyin law, MMC, SSY, UniGrow law

1 | INTRODUCTION

The main purpose of aluminium metal matrix composite (AlMMCs) is to combine the most desirable properties of aluminium with those of reinforcement materials. In this work, the aluminium alloy AA2024 has been used in combination with silicon carbide (SiC) reinforcement fibres. Aluminium has desirable properties such as high strength, ductility, and high thermal conductivity. On the other hand, the AA2024 has a low stiffness, while SiC is much stiffer, even though it is fragile. It also has an excellent resistance to high temperatures.[1] The aluminium alloy AA2024 has good manufacturing characteristics and good fatigue resistance. This alloy has been widely used in aircraft structures to produce wing and fuselage tension members. It can also be used to make car engine components, which are subjected to high temperatures such as pistons and alternating and rotating parts including transmission shafts, rotor brakes, and other structural parts, which require low weight and high strength.[2] Generally, metal matrix composites are used in high temperature applications. The potential advantages of a metal matrix with respect to a polymeric matrix include better resistance to abrasion and erosion, higher strength in shear and transversal loading, greater toughness, larger deformation prior to fracture, and the possibility of using conventional manufacturing processes. Furthermore, the metal matrix can make a significant contribution to the strength and to the elastic moduli in all directions. In applications involving a cyclic loading of structural parts made of MMCs, the material degradation produced by fatigue stress develops inside the metal matrix.[3] Therefore, the knowledge of fatigue behaviour and of the consequent fracture properties of these materials becomes fundamental for the design of structural components. Moreover, the type, the size, and the volume fraction of the reinforcement fibres or particles play a key role in the fatigue life of MMCs. With addition of SiC reinforcements, it is possible to increase toughness, fracture resistance, and the impact resistance of these materials.[4] In this work, a study of the fatigue behaviour of an MMC structural sample, made of AA2024 and SiC at room temperature, was carried out in the mesoscale, exploiting the typical condition of homogeneity and isotropy of the adopted scale. In doing so, three cracks have been introduced into the MMC sample simulating the fatigue cracks propagation by means of both linear, ie, the Paris law, and non-linear, namely, the modified Kujawski-Ellyin (KE) or UniGrow laws. Non-linear models for fracture mechanics can also assess the fatigue damage both at microstructural and macrostructural levels, which are based on the estimate of the energy release rate (ERR) for the prediction of fatigue crack propagation.[5-8]

2 | MATERIALS AND METHODS

In Figure 1A, the dimensions of the MMC specimen have been shown while periodic boundary conditions (PBCS), applied to all surfaces of the unit cell except those on which the load has been imposed, have been shown in Figure 1B. Hence, three cracks have been introduced in a 3D uncracked finite element (FE) model, as shown in Figure 1C, using the Zencrack Graphical User Interface (GUI).[9] Then, several simulations of the crack propagation have been carried out. The same load, of 5 MPa, has been applied on both the upper and lower end of the MMC specimen using the kinematic coupling. Thus, the resulting forces have been applied as a displacement field on two surfaces of the MMC specimen.

Working with contour integral evaluation and the Virtual Crack Extension (VCE) method[10] to propagate the crack, Zencrack[9] only applies a static load up to its maximum value and then calculates the fatigue crack propagation using the user-defined fatigue law or its default law. This is because the Small-Scale Yielding (SSY) condition is an extension of the Linear Elastic Fracture Mechanics (LEFM).[5] Furthermore, all the simulations have been carried out in constant amplitude loading condition to calculate the maximum Stress Intensity Factor (SIF) and then ΔK, using an R-ratio equal to 0.1. The main advantage of the non-linear approaches is related to their intrinsic ability to consider the energy dissipated within a small area surrounding the crack front by means of the Low Cycle Fatigue (LCF) properties.[11] Hence, the material chosen for the composite matrix is modelled with either a linear or a non-linear behaviour according to the Ramberg-Osgood Equation (1),

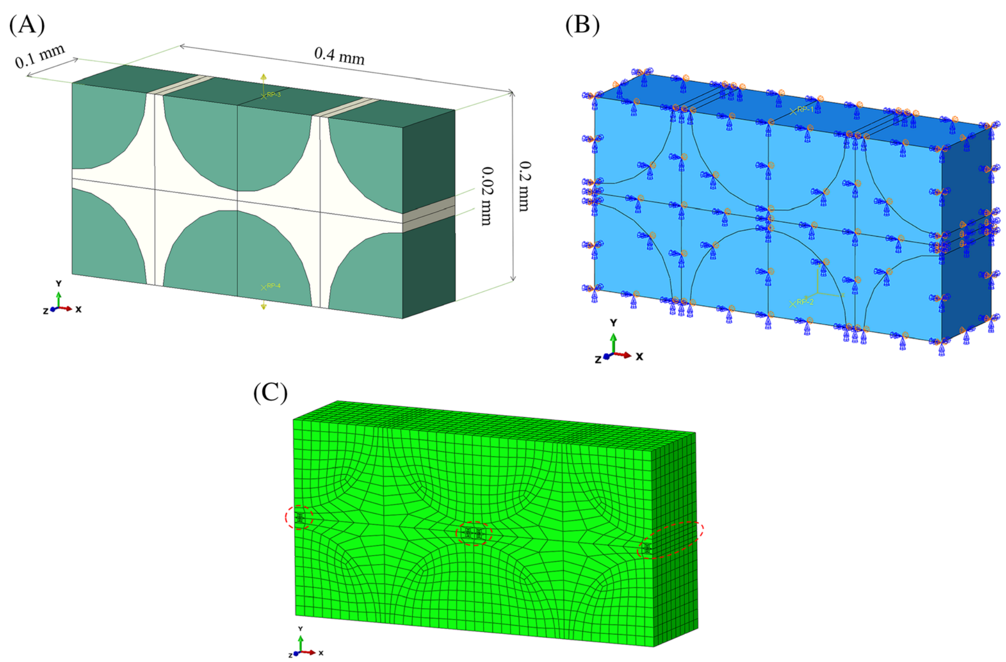


FIGURE 1 A, Uncracked finite element (FE) model of a volume cell of the composite with highlighted dimensions (SiC fibres are in green colour). B, periodic boundary conditions (PBCS) are shown on the surfaces of a volume cell of the composite. PCBS are not applied on surfaces where the load is applied. C, FE meshed model of a volume cell of the composite with highlighted cracks

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_0}\right)^{1/n}, \tag{1}$$

where n = 0.178 is the strain hardening coefficient, E = 74 000 MPa is the Young modulus, σ_0 = 314 MPa is the tensile yielding strength of the material, while the ultimate strength is σ_{ult} = 487 MPa.[12] In Figure 2, the material behaviour of the aluminium has been modelled by means of Ramberg-Osgood equation.

The linear material properties of the reinforcement fibres (SiC) remained unchanged for both the linear and non-linear behaviour of the metal matrix. The material properties of the SiC fibres, as well as the LCF properties of the aluminium alloy, have been taken from the literature.[5,13] The Young modulus of reinforcing fibres has been chosen equal to 380 GPa, while the Poisson ratio is equal to 0.2. The volume fraction of the fibre in the unit cell has been set to 0.63. The unit cell of the MMC has been first homogenized, in order to find the critical area for crack initiation. Afterwards, a stress analysis was carried out on an enlarged volume cell of the composite material, namely, in the mesoscale, where the material had a homogeneous and isotropic behaviour. The unit cell geometry, used for the homogenization of the different material properties of the composite, has been shown in Figure 3.

The von Mises stress distribution of the homogenized unitary cell has been shown in Figure 4. The area with higher stress values is noteworthy for it is where a crack initiation can originate.

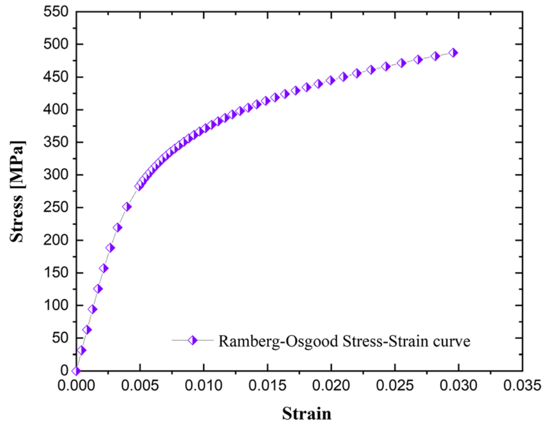


FIGURE 2 The Ramberg-Osgood stress-strain curve for the adopted AA2024

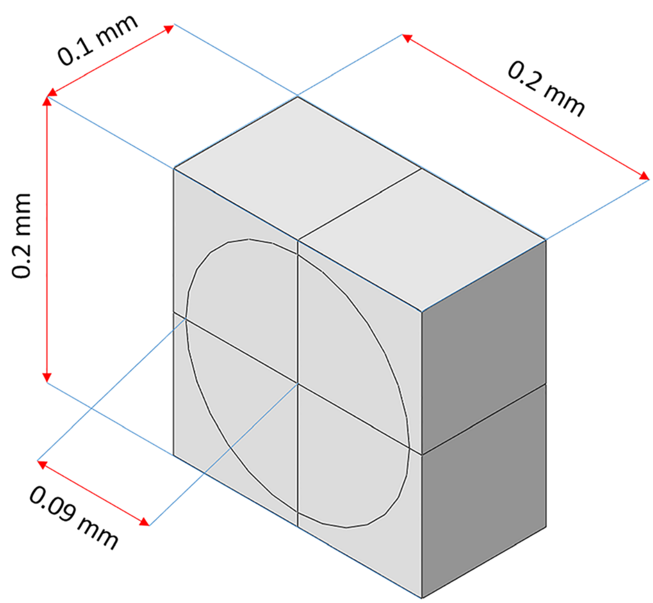


FIGURE 3 Model geometry of the unit composite cell with the highlighted dimensions

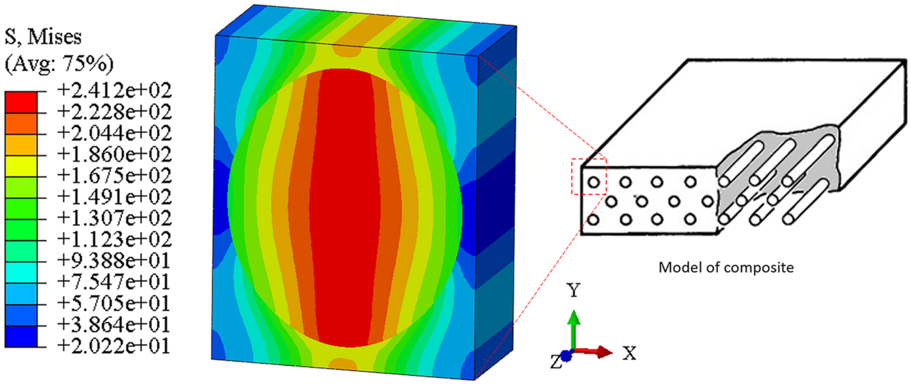


FIGURE 4 The von Mises stress distribution (MPa) on the unitary homogenized cell

2.1 | The modified non-linear KE law

In this work, the modified version of the KE law for fatigue crack propagation has been adopted for the simulation of FCG.[14] This law can be written as follows:

$$\frac{da}{dN} = 2\delta^* \left\{ \frac{\left(\Delta K^2 - \Delta K_{th}^2\right)}{4(1+n')\left(\sigma_f' - \sigma_m\right)\pi E \varepsilon_f' \delta^*} \right\}^{1/\beta}, \tag{2}$$

where E is the Young modulus, σ_f' is the fatigue strength coefficient, ε_f' is the fatigue ductility coefficient, $\beta = -(b + c)$ (b and c are the fatigue strength exponent and the fatigue ductility exponent, respectively). Furthermore, σ_m is the local mean stress,[15] n' is the cyclic hardening exponent, and δ^*, as proposed by Li et al,[16] is a length in the crack extension direction called the "fracture process zone" (FPZ) in which the majority of the damage is experienced by the material,[14] and ΔK_{th} is the threshold value of the SIF. Values for all the material and LCF properties have been reported in Table 1.[5]

2.2 | The modified non-linear UNIGROW law

The modified version of unified two-parameter fatigue crack growth driving force model (UNIGROW) has been used in this work for a comparison with results provided by using the modified KE law for fatigue crack propagation.[5,8,14,17] In the Equation (8), the fatigue law for growing the crack has been described starting from the Equation (3) (Paris law),

$$da/dN = C\,(\Delta\kappa)^{\gamma}, \tag{3}$$

$$\text{where } C = 2\,\rho^* \left[1 \Big/ 2\left(\sigma_f'\right)^2 \left[\left(\psi_{y,1} \Big/ \sqrt{2\pi\rho^*} \right)^{3n'+1} \left(K' \Big/ E^{n'} \right) \right]^{1/n'+1} \right]^{-1/2b} \tag{4}$$

$$\text{and } \Delta\kappa = \left(K_{max,tot}^{p}\, \Delta K_{tot}^{0.5} \right). \tag{5}$$

TABLE 1 Material and LCF parameters of the matrix aluminium alloy (AA2024)

ΔK_{th} (N/mm$^{3/2}$)	E (N/mm^2)	υ	σ_y' (N/mm^2)	σ_f' (N/mm^2)	ϵ_f'	n'	b	c
52	74 000	0.33	330	835	0.174	0.109	−0.096	−0.644

Abbreviation: LCF, Low-cycle fatigue.

Moreover, $p = \frac{n'}{(n'+1)}$ (n' is the cyclic hardening exponent), and $K' = {}^{\sigma'_f}/_{\epsilon'^{n'}_f}$ is the cyclic strength coefficient,

$$\gamma = -{}^{1}/_{b}, \tag{6}$$

$$\text{and } \rho^* = {}^{\pi}/_{24} \left({}^{\Delta K_{tot}}/_{\sigma_{ys}} \right)^2, \tag{7}$$

$$ {}^{da}/_{dN} = 2\,\rho^* \left[{}^{1}\Big/_{2} \left(\sigma'_f\right)^2 \left[\left({}^{\psi_{y,1}}/_{\sqrt{2\pi\rho^*}} \right)^{3n'+1} \left({}^{K'}\Big/_{E^{n'}} \right) \right]^{{}^{1}/_{n'}+1} \right]^{-1/2b} \left(K^p_{max,tot}\ \Delta K^{0.5}_{tot} \right)^{\gamma}, \tag{8}$$

$$\text{with,}\quad \Delta K_{tot} = \Delta K_{apll} \left\{ 1 - \left[\frac{(\sigma_{0.05} - \sigma_0)}{\sigma_{0.05}} \right] (1-R) \right\}, \tag{9}$$

where, $\sigma_{0.05}$ is the stress value corresponding to, $\varepsilon = 0.05$, on the true stress-strain curve shown in Figure 1, σ_0 is the material yield strength, while ΔK_{appl} is the current ΔK obtained from the J-integral calculation.

2.3 | The Paris law

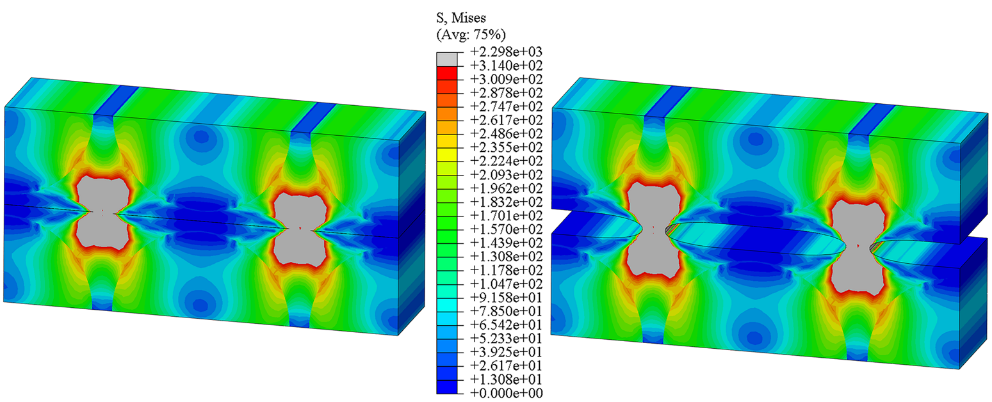
The Paris law is the most common law for fatigue crack propagation in linear elastic analyses. It can be described as reported in Equation (10),

$$ {}^{da}/_{dN} = \mathrm{C}\,(\Delta \mathrm{K})^m, \tag{10}$$

where C = 7.64458e-10 and m = 3.23 are the constant values provided by the literature.[12]

3 | RESULTS AND DISCUSSION

In Figure 5A,B, the von Mises stress field related to the final configuration of both undeformed and deformed cracked volume cell, respectively, has been shown. The use of PBCS has permitted to simulate the propagation of perfectly in-plane cracks. The geometrical model of the MMC specimen has been meshed with 11 460 quadratic elements corresponding to 52 288 nodes, and it has been established as convergence configuration. Then, three cracks have been introduced and propagated simultaneously through the aluminium matrix, and thus, three simulations of fatigue crack



(A) (B)

FIGURE 5 (A,B) Undeformed and deformed shape of the metal matrix composite (MMC) specimen corresponding to the final configuration of the cracked specimen before the plastic collapse (MPa) obtained by means of the modified UniGrow law

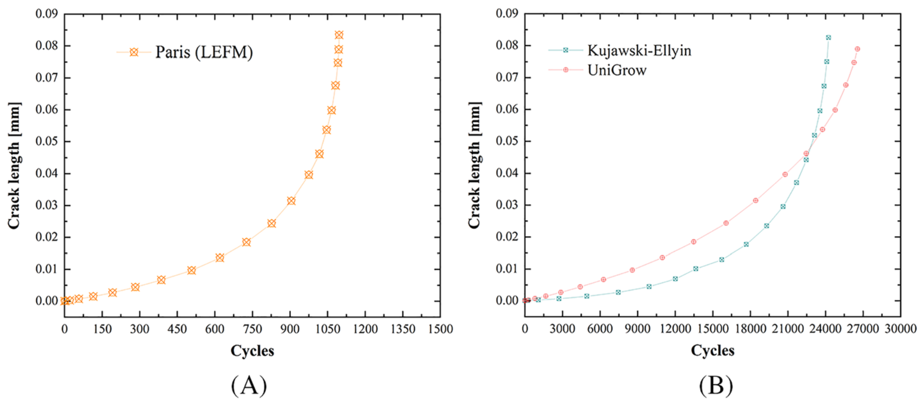


FIGURE 6 (A,B) Comparison between the crack growth rates provided by linear (6A) and non-linear (6B) laws

propagation have been carried out using both LEFM and SSY approaches. Furthermore, when the LEFM has been adopted, the crack front has been modelled as sharp, and the plasticity developed along the crack front has not been considered on the fatigue life of the MMC. On the other hand, when the SSY has been adopted, the plasticity developed along the crack front has been found to have an influence on the fatigue life of the MMC. In all cases, after about 0.0074 mm of the crack propagation, the MMC specimen reached the configuration of plastic collapse. The hypothesis of perfect adhesion between the metal matrix and the SiC reinforcement fibres surfaces has always been adopted; ie, matrix and fibres have been modelled as a unique volume with different material properties.

Comparing the results provided by two non-linear laws, it can be observed that the difference of respective final number of fatigue cycles has been (see Figure 6B). The modified KE law has produced 24 246 cycles of fatigue crack propagation up to the plastic collapse, while at the same conditions, the modified UniGrow model has produced 26 551 fatigue cycles. It is interesting to note that the number of fatigue cycles obtained using the Paris law, which corresponds to about 1100 cycles, has been less than one order of magnitude of those provided by the non-linear models (see Figure 6 A). This happens because, when the Paris law has been used, an "effective" crack length has not been considered because the plasticity along the crack front has been neglected. On the contrary, when the non-linear laws have been adopted, an "effective" crack length has been considered. The first effect of plasticity developed along the crack front has been produced at the root of the crack. Namely, the crack front radius has passed from sharp to blunt and then HRR singularity has been considered. In this case, to model the crack front, "retained" elements with midside point in unchanged position have been used instead of the "collapsed" elements.[5,6]

The use of non-linear models has permitted to consider the damaging produced by plasticity along the crack front to enhance the fatigue life of the MMC cell. These non-linear models can act both at microstructural and macrostructural level but considering two different types of "process zones." The modified KE model uses a FPZ smaller than the cyclic or monotonic plastic zone, while the modified Unigrow law describes a process zone comparable with the monotonic plastic zone. In SSY conditions, the size of the plastic zone has been found small enough to produce a similar prediction of fatigue life for both non-linear models. Furthermore, plasticity developed along the crack front can be effectively considered as the main actor in the fatigue crack propagation life while the SiC fibres do not influence the fatigue behaviour of the growing crack.

4 | CONCLUSIONS

In this work, three cracks have been introduced in an MMC volume cell in the mesoscale. The AA2024 aluminium alloy has been adopted as matrix material. Fibres of SiC have been chosen as reinforcement. All the simulations have been carried out by the Abaqus software package.

The results can be summarized as follows:

- The non-linear material behaviour has been modelled by means of the Ramberg-Osgood equation;
- The crack fronts have been modelled to account for the blunting effect;
- The Paris law has been adopted for fatigue crack propagation in linear elastic conditions;

- The modified versions of the KE and Unigrow laws for fatigue crack propagation have been considered in SSY conditions;
- A comparison between the crack growth rates of the crack front points at free surface of the volume cell, obtained by using different laws for FCG, has been carried out;
- The results related to the non-linear cases have shown a very close prediction of fatigue life;
- The use of Paris law has produced a significant reduction in the fatigue life of the MMC specimen.

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