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On fatigue crack growth mechanisms of MMC: Reflection on analysis of ‘multi surface initiations’

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This work attempts to examine the mechanisms of fatigue when cracks synergetically initiate in more than one site at the specimen surface. The metal matrix composites (MMC) i.e. silicon carbide particles reinforced aluminium matrix composites (Al/SiC$_p$–MMC), seem to be good candidates to accelerate fatigue failures following multi surface initiations (MSI). Closure effects of MSI mechanisms on the variation of fatigue behaviour are explored for various stress states. Experiments were carried out using non pre-treated and pre-treated specimens. Using an Equivalent Ellipse Method (EEM), it is shown that the aspect of surface finish of specimen plays an important role on crack growth. Scanning Electron Microscope (SEM) inspections have lead to distinguishing the initiation regions from propagation regions and final separation regions. It is also revealed that the total lifetime of specimens is sensitive to heat treatment. Moreover, it is found that the appearance of MSI in cycled materials is more probable at high level of fatigue loads.

1. Introduction

Metal matrix composites (MMC) are increasingly used for critical structural applications in advanced sectors. This is essentially due to their excellent stiffness-to-density and strength-to-density ratios [1]. They have the advantage to be reinforced with different type of fibres or particles and different reinforcement percents. Their specific behaviour enlarges their use, provides potential energy savings and gives them the potential to replace conventional metals in some applications. MMC materials are also considered for many high temperature applications in advanced aerospace, vehicles and gas turbine engine components. In spite of their popularity, their elaboration still causes many questions that must be resolved for a better use in manufacturing.

In previous years, many researches have been conducted to improve the properties of composite materials [1–4]. The use of these materials has been shown to increase the lifetime of mechanical parts in some cases [5,6]. The behaviour of such material does not depend only on the microstructure characteristics, matrix and reinforcement type but also on the elaboration mode that might affect the mechanical and thermal characteristics of composites. It is so complicated to explain all phenomena at micro-scale when such material is loaded. Nevertheless, Dermakar [2] has found that the reinforcement volume fraction is among the principal parameters that govern the lifetime of MMC.

Aluminium alloys reinforced with discontinuous ceramic fibres or particles have significant potential for structural applications due to their outstanding combination of high specific strength, stiffness and density. They have the advantage to be processed by conventional means such as forging, rolling, extrusion, and machining [7–10]. They are used successfully for developing applications with low-cost processing methods. These properties allowed to the aluminium matrix composites to be attractive candidate for use in weight-sensitive and stiffness-critical engineering components.

Tjong et al. [11], investigated the properties of aluminium based composites reinforced with large volume content of fined particles of TiB$_2$ and Al$_2$O$_3$ under fully reversed tension–compression loading. They have proved the excellent fatigue endurance limit and life under stress controlled condition. As many applications involve cyclic loading in the service lives of parts, fatigue degradation inevitably takes place within the matrix materials [12]. Thus, the knowledge of fatigue behaviour and resultant fracture properties of such materials becomes crucial for the design of the structural components. In particular, the type, the size and the volume fraction of the reinforcement particles have a main role on the fatigue lifetime of composites materials. The addition of silicon carbide (SiC) reinforcements can increase fracture toughness and thermal shock resistance of that materials [13–15]. In aluminium based composites, the fatigue resistance is directly influenced by two parameters: (i) the increasing volume fraction, and (ii) the decreasing of particles size.

For analysing the fatigue mechanisms, the major investigations have referred to tension–compression tests using metallic speci-

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mens i.e. steel, cast iron and aluminium alloys. Four-points reversed bending tests are used, although not as frequent, thanks to some advantages which can be underlined as [16]: (i) bending loads often occur with in-service loading conditions, (ii) there are no problems with buckling compared to tension–compression tests, and (iii) the required forces are much smaller.

In metallic components, the crack propagates always from a single site of initiation up to failure. The crack life periods are characterised by the aspect of failure area occurring under low or high cycles fatigue regimes. The distinguishing of the initiation from propagation mechanisms is extremely important for correlating the failure with the associated fatigue life regime.

From a long time, metals in which failure follows to “single initiation” have been taking the major interests of researches [17–20]. In connection, Kubicki et al. [21] studied fatigue mechanisms in elastic plastic porous materials. In their contribution, authors proposed an equivalent ellipse concept for characterising pores of varying size and shape from which cracks eventually propagate. They found that circular pores are the most dangerous ones on materials lifetime. Recently, series of researches were conducted by Marines et al. [22,23] in order to examine metals behaviour under very high cycle fatigue regime using sophisticated experiments. The crack initiation was modelled as an initial semi-circular area from which crack propagates. Authors pointed out the decrease of material strength with the number of cycles up to high number of cycles. A remarkable event occurring between 10^6 and 10^8 cycles has been underlined. At that range of cycles number, the crack initiation may switch location from the specimen surface to an interior initiation termed as fish-eye. Particularly, it was showed from experimental findings that fatigue fracture in steels can occur in that range as the consequence of initiation at a certain distance from the surface.

In this framework, we pose the question: how materials react when the fatigue behaviour is governed by ‘multi surface initiations’ mechanisms? To answer this question, the failure area of Al/SiC$_p$ composites obtained under four-points reversed bending tests were analysed using SEM. Combination of observations with the EEM showed the validity of the approach in examining the failure mechanisms.

2. Experimental procedure

The material studied is an extruded composite. It is a 2009 aluminium matrix reinforced with discontinuous silicon carbide particles (Al/SiC$_p$–MMC). The average dimension of the SiC$_p$ particles is about 5–8 μm (typical microstructure is shown in Fig. 1). The reinforcement is arbitrary distributed into the longitudinal cross-section of the material. Contrary to long fibres reinforced materials, where orientation is easily detected, the considered reinforcement does not exhibit preferred orientation.

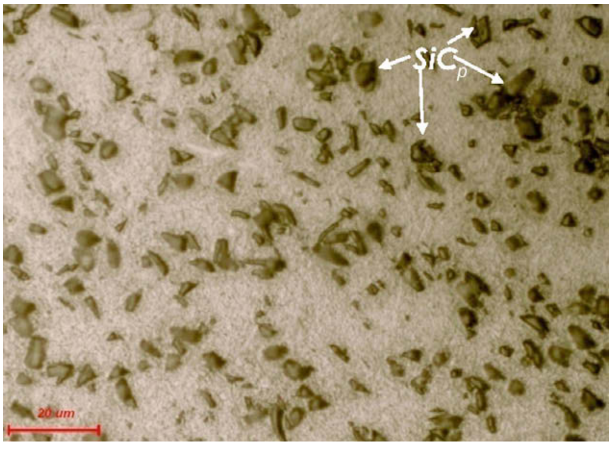

Fig. 1. Microstructure of Al/SiC$_p$ composite: as-received state.

The manufacturing parameters used are cutting speeds of 90 m min^{-1} and feed rates of 0.15 and 0.3 mm rev^{-1}. The pre-treated specimens were manufactured after the heat treatment; the surface of specimen was not polished. The depth of cut is kept constant at 1.25 mm. For ensuring good comparison between the results of fatigue, the finishing operation uses a new tool for each specimen. As recommended in the literature [24,25], an uncoated tungsten carbide tool (WC) with clearance angle of 5°, cutting edge angle of 35°, length edge of 9.525 mm and nose radius of 0.4 mm was used. Lubrication was kept active during machining. The specimen used for fatigue test has the standard geometry of Fig. 2.

The fatigue tests were performed using SIMPLEX bending machine equipped with four-point fixtures devices. The rotation speed of the machine was fixed to ~3500 rev min^{-1}. All experimental tests were carried out at the same load ratio, $R = -1$ and room temperature conditions. Two states of material have been used: non pre-treated state and pre-treated state. Material was heated to 498 °C in a furnace and held at temperature for 240 min before quenching by water to room temperature. The heat treatment has the advantage to enhance the mechanical homogeneity within the matrix material by relaxing the residual stresses introduced at the particle–matrix interface from prior elaboration process of the composites [1]. Thermal properties of ceramic are known to be significantly different from metal phases of compos-

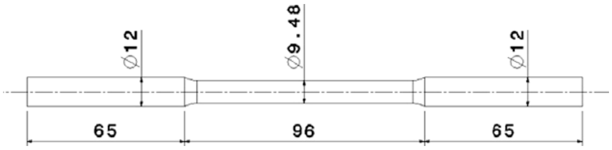

Fig. 2. Geometry and dimensions of specimen used for fatigue test.

Table 1
Chemical composition, mechanical properties and heat treatment conditions used.

	Chemical composition	Mechanical properties
Al/SiCp composites		Yield stress $\alpha_{y\text{-MMC}}$: 300 MPa Ultimate tensile strength (UTS): 500 MPa
Matrix (Al-2009)	Silicon (wt%): 0.25max Iron (wt%): 0.2max Copper (wt%): 3.2–4.4 Chromium (wt%): 1.0–1.60 Oxygen (wt%): 0.1max Titanium (wt%): 0.6max	Young's modulus E: 70×10^3 MPa Yield stress: 260 MPa < $\alpha_{y\text{-Al}}$ < 300 MPa Ultimate tensile strength: 390 MPa < (UTS) < 440 MPa
Reinforcement (SiC$_p$)	Volume fraction (%): 15	Young's modulus E: 425.10^3 MPa Yield stress $\alpha_{y\text{-SiCp}}$: 1172 MPa Ultimate tensile strength (UTS): 3900 MPa
Heat treatment	Treatment at 498 °C – 4 h Rapid cooling (water: 20 °C)	