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Low cycle fatigue of SiCp reinforced AA2009 composites

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ABSTRACT

Strain-controlled low cycle fatigue (LCF) characteristics of an extruded Al–Cu–Mg aluminum alloy reinforced with SiC particles (SiCp/AA2009 composite) in the T4 and T6 heat treatment conditions were investigated. In comparison with the T6 condition with Al_2CuMg precipitates, the composite in the T4 condition had a higher ductility and equivalent ultimate tensile strength despite a lower yield strength, leading to a higher strain hardening exponent and hardening capacity. Unlike the extruded magnesium alloys, the SiCp/AA2009 composite exhibited symmetrical hysteresis loops in tension and compression due to the dislocation slip-dominated deformation in the aluminum matrix. Cyclic hardening occurred at higher strain amplitudes with a more pronounced hardening in the T4 condition, and cyclic stabilization remained at lower strain amplitudes (0.1–0.3%). Fatigue life in both conditions was equivalent, which can be well described by the Coffin–Manson law and Basquin's equation. Strain ratio significantly affected cyclic deformation characteristics of the composites in both conditions, with a large amount of plastic deformation observed in the tensile phase of the first cycle of hysteresis loops at zero or positive strain ratios. A mean stress relaxation was observed. Fatigue crack was observed to initiate from the specimen surface and crack propagation was characterized predominantly by particle cracking along with debonding.

1. Introduction

Due to the tremendous environmental concerns and rising global energy demand in recent years, lightweighting of vehicles is being deemed as a prime design tool for improving the fuel economy and reducing anthropogenic environment-damaging, climate-changing, costly and human death-causing[1] emissions [1–5]. It has also been reported that the fuel efficiency of passenger vehicles can be improved by 6–8% for each 10% reduction in weight [6–9]. This has drawn a considerable interest in the application of lightweight metals and alloys in the automotive and aerospace industry [10]. Metal-matrix composites (MMCs) are one of the attractive lightweight materials since they can offer significant weight reduction and improve fuel efficiency due to their excellent combination of physical and mechanical properties, such as low density, high tensile strength, enhanced stiffness, superior wear and creep properties, as well as improved fatigue resistance compared with their counterpart monolithic alloys [11–17]. MMCs, such as aluminum matrix composites (AMCs) reinforced with ceramic particles, often silicon carbide (SiCp), have found a lot of applications in the automotive industry for the production of pistons, cylinder liners, cam shafts, connecting rods, main bearings, brake rotors and calipers, and in the aerospace industry for the production of structural components [18]. AMCs can be reinforced with continuous fiber or discontinuous particles or whiskers. Compared with the long fiber reinforced AMCs, particle-reinforced AMCs are rapidly developed because of their lower costs, isotropic properties, and desirable deformability [19,20]. The structural application of the AMCs involves inevitably fatigue and cyclic deformation characteristics due to the fact that structural components experience dynamic loading, which results in the occurrence of fatigue failure [14,15,21–26]. Hence, an understanding of fatigue and cyclic deformation behavior of AMCs is critical for the design, durability evaluation and life prediction of engineering components.

Studies have been conducted to understand the influence of particulate reinforcements on high cycle fatigue (HCF) behavior [27,28] and tensile fracture behavior [12,29] of AMCs. Several studies also

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[1] According to Science News entitled "Air pollution kills 7 million people a year" on March 25, 2014 at http://news.sciencemag.org/signal-noise/2014/03/air-pollution-kills-7-million-people-year: "Air pollution is not just harming Earth; it is hurting us, too. Startling new numbers released by the World Health Organization today reveal that one in eight deaths are a result of exposure to air pollution. The data reveal a strong link between the tiny particles that we breathe into our lungs and the illnesses they can lead to, including stroke, heart attack, lung cancer, and chronic obstructive pulmonary disease."

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reported the effect of particulate reinforcements on LCF behavior of AMCs [11,13–15,30,31], e.g., cyclic plastic strain response and fracture behavior of AMCs reinforced with Al_2O_3p [15,31] and SiCp [11,13,14,30], respectively. Uyger and Külekcì [14] reported the influence of volume fraction, particulate size and strain ratio on the LCF behavior of SiCp/AA2124-T4 composites. Srivatsan et al. [11] also reported the effects of temperature on the LCF properties and fracture characteristics of an AMCs reinforced composite with SiCp. In addition, high cycle fatigue resistance and tensile properties of friction stir welded SiCp/AA2009 composites were also reported by Ni et al. [32,33]. To the authors' knowledge, no systematic studies have been conducted to understand the effect of heat treatment conditions on the LCF behavior of AMCs reinforced with SiCp. It is unclear whether these composites exhibit cyclic hardening or softening and how the heat treatment and strain ratio affect the tensile-compressive yield symmetry and fatigue life. The present study was, therefore, aimed at exploring the cyclic deformation behavior of an extruded Al–Cu–Mg aluminum alloy reinforced with SiCp (SiCp/AA2009) in T4 and T6 temper at varying strain amplitudes and strain ratios.

2. Material and experimental procedure

The material used in the present investigation was an aluminum alloy (designated by the Aluminum Association as AA2009) based composite reinforced with 17 vol.% SiCp. The chemical composition of the AA2009 alloy was: 4.0 Cu-1.5 Mg (wt.%). SiCp with an average particle size of ~7 μm were adopted. The composite material was produced by powder metallurgy and the hot pressed ingot was extruded into plates of 30 mm × 200 mm. The extruded material was then subjected to (a) T4 heat-treatment: solutionized at 515 °C for 1 h, water quenched, and then aged at room temperature, and (b) T6 heat-treatment: solutionized at 515 °C for 1 h, water quenched, and then aged at 175 °C for 6 h, respectively.

Microstructural examinations were performed using an optical microscope (OM) equipped with Clemex quantitative image analysis software and a scanning electron microscope (SEM) JSM-6380LV equipped with an Oxford energy dispersive X-ray spectroscopy (EDS) system. Standard metallographic sample preparation techniques were used with an etchant based on Keller's reagent containing 10 ml hydrofluoric acid, 30 ml nitric acid, and 50 ml H_2O. X-ray diffraction tests for phase identification were conducted with Cu K_α radiation source at an accelerating voltage of 45 kV and a current of 40 mA.

Sub-sized fatigue samples, which had a gauge length of 25 mm (or a parallel length of 32 mm) and a cross section of 6 mm × 6 mm in the gauge area, were machined with the length of the samples parallel to the extrusion direction (ED). The gage section of fatigue samples was ground along the loading direction with emery papers up to a grit number of 600 to remove the machining marks and to achieve a consistent surface.

Strain-controlled, pull–push type fatigue tests were conducted using a computerized Instron 8801 fatigue testing system via the Fast Track Low Cycle Fatigue (LCF) program at a constant strain rate of $1 \times 10^{-2}\ s^{-1}$, zero mean strain ($R_\varepsilon = -1$) and room temperature of 25 °C. Triangular loading waveform was applied during all tests. The low-cycle fatigue tests were conducted at total strain amplitudes of 0.1%, 0.2%, 0.3%, 0.4%, 0.5% and 0.6%, with at least two samples tested at each level. Additionally, to study the effect of strain ratio on the LCF behavior of the composite, tests were also carried out at five different strain ratios of R_ε = +0.5, 0, −1, −3, and −∞. All the strain ratio tests were performed using a total strain amplitude of 0.5% and at a constant strain rate of $1 \times 10^{-2}\ s^{-1}$. The fracture surfaces of fatigued specimens were examined via SEM to identify fatigue crack initiation sites and propagation characteristics.

3. Results and discussion

3.1. Microstructure and tensile properties

Fig. 1 shows the microstructures of the extruded SiCp/AA2009 composites in different heat treatment conditions in the longitudinal (L), transverse (T), and short transverse (ST) directions. It is seen that uniform-sized SiCp were dispersed almost evenly in the AA2009 matrix. At regular intervals, some clustering and agglomeration of the reinforcing SiCp could be observed along the longitudinal orientation of the composites. It is seen that those agglomerated sites consisted of a few larger SiCp intermingled with smaller, more uniform, and regular shaped SiCp. Similar types of microstructures were also reported in extruded SiCp/AA2009/15p composites by Srivatsan et al. [11,12], 2xxx series aluminum alloy (Alcoa MB85) reinforced with 15 vol.% SiCp by Bonnen et al. [27], extruded SiC/AA2009/15p-T42 composites by Manigandana et al. [29], and extruded SiC/X2080/20p composites by Srivatsan and Prakash [13]. Though the matrix of the composites revealed grains following deep etching of the polished surfaces, the size and shape of the grains was not easily discernible at low magnifications.

X-ray diffraction patterns obtained from the T4 and T6 heat-treated samples are shown in Fig. 2. In addition to Al and SiCp peaks in both samples, Al_2CuMg peaks were also detected in the T6 heat-treated sample. This indicates that precipitates were formed when heat-treatment extended to aging treatment at 175 °C for 6 h. The presence of Al_2CuMg has been also reported in similar AMCs [34,35]. Other common precipitates, including Al_2Cu and Mg_2Si, reported in the extruded SiCp/AA2009 composites [36,37] were

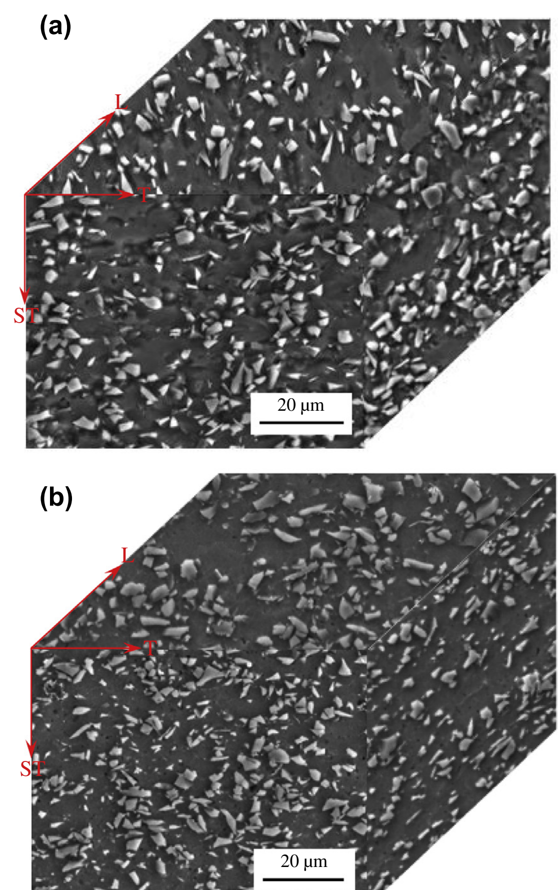

Fig. 1. Microstructures of the extruded SiCp/AA2009 composites in the longitudinal (L), transverse (T), and short transverse (ST) directions in the (a) T4, and (b) T6 conditions.