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Tensile and fatigue behavior of carbon fiber reinforced magnesium composite fabricated by liquid-solid extrusion following vacuum pressure infiltration

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ABSTRACT

Liquid-solid extrusion following vacuum pressure infiltration (LSEVI) technique is a new technology, which is suitable for the fabrication of carbon fiber reinforced magnesium composite (C_f/Mg composite). This work details an experimental investigation on understanding the fatigue performance of C_f/Mg composite fabricated by LSEVI technique. The *S-N* curve of the composite was determined and the fatigue behavior considering different loading levels and cycles was studied. Moreover, the fracture surfaces and microstructures of test samples were examined to understand the fatigue damage mechanism. The investigation finds that the residual tensile strength of specimens that survived during fatigue test was enhanced with the increase in fatigue cycles and applied stress. In addition, fatigue loading could change the tensile behavior of the composite, and a yielding point was observed at stress-strain curves of specimens which survived during fatigue test. Observations of the fracture surfaces revealed that more fibers were pulled out with the increase in fatigue cycles and applied stress.

1. Introduction

Magnesium alloy is a distinctive lightweight metal due to its extraordinary low density [1,2]. Unfortunately, its utilization is often restricted since Mg alloy suffers from several material inherent deficiencies like low stiffness, low fatigue resistance, high thermal expansion coefficient, etc. These shortcomings can be overcome by incorporating carbon fiber to fabricate carbon fiber reinforced magnesium composite (C_f/Mg composite) which has the advantages of both carbon fiber and Mg matrix [3,4]. Thus, C_f/Mg composite has great potential as replacement for traditional structural materials, and has bright and broad application prospects in weight saving applications notably in aerospace, automotive, and military industries owing to the high strength-to-weight ratio (i.e. specific strength) [5–7].

Among various methods available for manufacturing C_f/Mg composite, liquid-solid extrusion following vacuum infiltration (LSEVI) technique is a special forming technique that combines the principles of vacuum infiltration, squeeze casting and liquid-solid extrusion. C_f/Mg composite fabricated by LSEVI is very cost-effective and promising due to the advantages such as simplicity, adaptability, low processing cost, and high production rate. A number of investigations also have been carried out to improve the microstructure and properties of C_f/Mg composite. It is generally accepted that the magnesium and carbon fiber are treated as non-reactive, and the interface bonding between carbon fiber and magnesium alloy is one of the most dominant factors for improving the composite properties. Some scholars have paid efforts to modify the fiber with suitable coating for improving the adhesion between the fundamental constituents. In addition, some coatings such as silicon dioxide coating [8], PyC coating [9], yttria stabilized zirconia coating [10], γ-Al_2O_3 and anatase-TiO_2 coatings [11] were also used to modify the interface bonding. While the others have paid efforts to add an additional alloying element into the matrix material to form an interface layer between the fiber and the matrix. Al [3,12], Gd and Y [13,14] were selected as alloying element to improve the interface bonding of C_f/Mg composite, and mechanical properties of the composites were investigated.

As stated above, although lots of progress has been made in the study of the composite mechanical properties in the last few years, the fatigue behavior of C_f/Mg composite is still not well understood.

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It is well known that fatigue is one of the main critical design issues in structural components and is dominant for the majority of structure final failures [15–17]. Various industrial applications have to bear constant or variable amplitude fatigue loads during use. Typical examples include the crankshaft, connecting rod, gears, bridges, etc. The estimated life of those structures subjected to fatigue loads is highly dependent upon damage accumulation caused by fatigue loads. Stiffness reduction and energy dissipated per cycle were found to be complementary measurements of fatigue damage accumulation, occurring in three stages: a first stage characterised by rapid changes, a more quiescent second stage, followed by a third stage where the (decreasing) stiffness and (increasing) energy dissipation change irregularly and then rapidly, to failure [18]. Moreover, the fatigue behavior of composite has been recognized as a complex phenomenon compared to that of monolithic materials [19]. Thus, numerous studies have been conducted to investigate the fatigue performance of various composite, including glass/epoxy [20,21], carbon/epoxy [22,23], carbon/carbon [24,25] and their hybrid composites. These reports indicated that the fatigue behavior of fiber reinforced composite highly associated with interface cracking between the matrix and matrix-fiber. Furthermore, those studies also revealed that it would be possible to have a better understand of the composite constitutive behavior and improve the mechanical property, safety, and durability of the composite materials through experimental investigation. Therefore, considering the importance of fatigue study, a clear understanding of the behavior of C_f/Mg composite under fatigue loading is necessary.

In this study, the tensile and fatigue behavior of C_f/Mg composite was investigated experimentally. Attention was focused on the tensile behavior and damage mechanism of C_f/Mg composite after fatigue loading. Tension-tension cyclic fatigue tests were conducted under load control at a sinusoidal frequency of 15 Hz to obtain stress-fracture cycles (S-N) relationship. The residual strength and elastic modulus after fatigue loading at various numbers of cycles and loads were investigated. In order to study the damage mechanism during fatigue loading, the fracture surfaces and cross-sections of the fatigued C_f/Mg composite were observed by SEM or TEM. Finally, the mechanism of strength enhancement by fatigue loading was discussed based on the experimental test.

2. Experimental

The composite material under investigation is an Mg matrix reinforced with carbon fabric which is fabricated by LSEVI technique. Preforms were made of Toray T700 non-woven fabrics orthogonally which was made of T700 carbon fibers, and the specification of T700 carbon fibers are presented in Table 1. Carbon fibers might react with Al in AZ91D alloy and convert to Al_4C_3 [26], which enhanced the toughness of interface greatly and had negative influences on the performance of C_f/Mg composite. Furthermore, the presence of Al_4C_3 crystals caused large scatter in the mechanical properties [27]. In addition, Orbulov and his co-workers found that temperature and wetting are extremely important and have great influence on the required infiltration pressure [28–30]. To improve the wettability and control the interfacial reactions, preforms were placed in CVD furnace to deposit pyrolytic carbon coating (PyC coating) on the surface of the fibers [12]. The deposition was performed with following parameters: deposition temperature 1000–1200 °C, flow rate of C_3H_8 0.2–0.4 m^3/h, flow rate of CH_4 0.5–0.8 m^3/h, and deposition time 1–3 h.

Table 1
Specification of T700 carbon fibers.

Fiber diameter of monofilament (μm)	Ultimate tensile strength (MPa))	Elastic modulus (GPa)	Elongation (%)	Density (g/cm^3)
6–8	3669	242	1.71	1.8

Table 2
Chemical composition of AZ91D alloy (mass fraction, wt%).

Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
9.02	0.69	0.22	0.07	0.001	0.004	0.0006	Bal

AZ91D magnesium alloy was selected as matrix alloy, due to its excellent casting performance. Its density is 1.82 g/cm^3, and its solidus and liquidus temperatures are 470 and 595 °C, respectively. The chemical composition of AZ91D can be found in Table 2.

LSEVI technique combined the principles of vacuum infiltration and squeeze casting [9,31,32]. The whole system consisted of four subsystems, including extrusion mould system, gas circuit system, vacuum smelting equipment, and data collection and monitor system. The schematic diagram of this technique was shown in Fig. 1. The specific fabrication process of C_f/Mg composite was given as follows: prior to infiltration, the preform deposited with PyC coating was put into the extrusion recipient, then a vacuum pump was turned on to keep the vacuum level of the whole system between 0.02 and 0.03 MPa. Then the mould and preform were preheated to 580–590 °C, to improve the liquidity of liquid alloy and reduce the infiltration pressure. At the same time the alloy was melted in the vacuum smelting equipment at 740–760 °C, and the temperature was held for 1 h to ensure the alloy melt completely. Liquid alloy was fed into the extrusion mould under gas pressure (Ar) of 0.2–0.4 MPa. When the molten alloy and the container cooled to 580–590 °C, liquid and solid phases coexisted in molten alloy. At this point a hydraulic machine was used to press the liquid-solid alloy to infiltrate into the preform, and the infiltration pressure was maintained at 30–60 MPa until the liquid-solid alloy completely solidified.

Single quasi-static tensile tests and tension-tension fatigue tests were carried out to test the mechanical properties of C_f/Mg composite. The Single quasi-static tensile test was carried out on a universal tensile testing machine (CMT5304-30KN) which was based on the displacement loading method, and the loading rate was 0.5 mm/min. The fatigue tests were carried out on a servo hydraulic universal testing machine (Instron8871). The tests were performed in load control with the ratio R (minimum to maximum stress) of 0.1 to avoid the introduction of compressive stresses. All fatigue experiments were conducted using a sinusoidal wave load at frequency of 15 Hz. The applied maximum stresses were in the range of 85–385 MPa according to the results from single quasi-static tensile tests. Fatigue run-out limits were defined as 10^5 cycles. Cycles to failure or up to 10^5 were documented for fatigue life (*S-N*) curve. To investigate the residual strength and elastic modulus of C_f/Mg composite after fatigue test, different specimens were first used for fatigue test at various numbers of cycles and applied stresses and then the specimens were used for single quasi-static tensile tests to get residual strength and elastic modulus if the specimens were not failed. The details of the experimental program are given in Table 3.

Microstructural analysis was performed on samples after different cycles of fatigue using a scanning electron microscope (SEM) and transmission electron microscope (TEM).

3. Results and discussions

3.1. Characterization and fatigue limit of C_f/Mg composite

A typical cross-sectional view of the C_f/Mg composite is depicted