

Influence of stacking angle of carbon fibers on fracture behavior of TiNi fiber impregnated CFRP composites

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Abstract

TiNi/CFRP composites have been fabricated by hot-pressing at a temperature of 180 °C. The CFRP layers were stacked with the carbon fibers at angles of 0°, 30°, 60° or 90° relative to the tensile direction. The fracture behavior was studied using notched specimens, which act as one-dimensional AE sources during tensile testing, to determine the fracture mode of the composites. Detection of strong Lamb waves shows that fracture in TiNi/CFRP composites with a 0° stacking configuration is mostly due to fiber breakage, which accounts for the high tensile strength of this configuration. In contrast, specimens with high stacking angles mainly fail by matrix cracking, with the production of weak Lamb waves, resulting in lower tensile strengths.

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1. Introduction

Over the past decade, much research into incorporation of functional materials in structural materials to form advanced composites has been reported. Shape memory alloys (SMAs), optical fibers and piezoelectric materials have all been used in the fabrication of new functional composites [1–3].

SMAs are one of the best types of functional material to add to composites because they exhibit multiple types of useful behavior, including actuation, super-elastic response and self-recovery. In particular, TiNi SMAs have received a great deal of attention because of their large shape memory effect, high damping capacity and high stiffness in the austenite state. Various kinds of composites with new functional properties have been prepared by incorporating SMAs of various shape, such as fibers, ribbons, particles and thin films [4,5].

TiNi fiber impregnated composites show good damping and actuation behavior because of the shape recovery that takes place at and above the austenitic–martensitic transformation temperature of TiNi [6–9]. To develop TiNi fiber impregnated composites and further improve their actuation behavior, fundamental

evaluation of their fracture behavior is vital. One technique that can provide useful information about the fracture behavior of structural materials, such as fiber reinforced composites, ceramics, lamellar composites and concrete structures, is the AE (acoustic emission) technique [10–13].

Despite the potential of these materials, very little research has been done to examine the effects of processing parameters, such as the stacking angles of the carbon fibers, on fracture behavior of TiNi fiber impregnated carbon fiber reinforced plastics (CFRP) composites. Not surprisingly, few investigations into the fracture behavior of these composites using the AE technique have been reported.

To help understand the complex processes occurring in these materials during synthesis and loading, in this work we examine the effect of the stacking angle of the carbon fibers on the fracture behavior of TiNi fiber impregnated composites. The fracture behavior has been investigated by Lamb wave analysis using notched tensile specimens as one-dimensional AE sources.

2. Experimental procedures

2.1. Fabrication of tensile specimens

CFRP prepregs (0.2 mm thick) (Hexcel Co.) were used as the matrix material. Each CFRP prepreg was cut to a size of 200 mm × 105 mm. TiNi fibers

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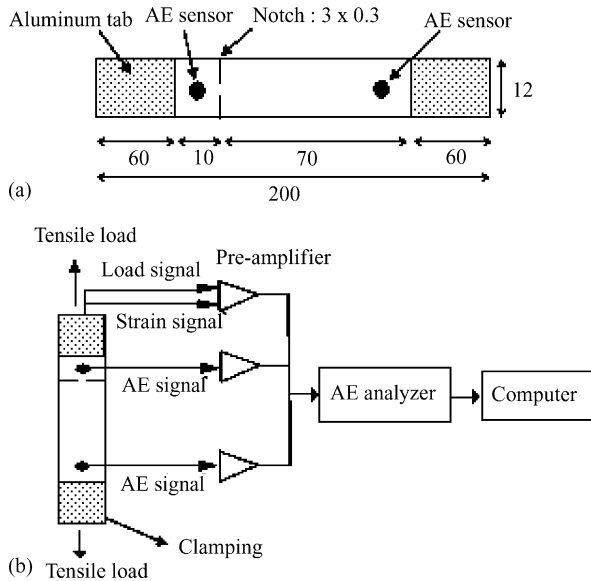


Fig. 1. Schematic drawing showing (a) dimensions of notched tensile specimens (in mm) and (b) setup for tensile testing of notched tensile specimens by AE analysis.

(Daido Steel Co.) 0.4 mm in diameter and with a composition of 55% Ni–45% Ti were used. Each TiNi/CFRP composite was prepared by sandwiching the TiNi fibers between layers of CFRP prepreps. The prepreps were stacked with carbon fibers aligned at angles of either 0°, 30°, 60° or 90° relative to the direction of tensile testing in order to establish the optimal design of TiNi/CFRP composites.

During the lamination procedure, the TiNi fibers were carefully embedded at 1 mm intervals at the center of eight sheets of CFRP parallel (i.e., at 0°) to the tensile direction using a special steel jig. Anti-heat vinyl sheets were used to prevent the flow of epoxy resin from the CFRP prepreps during heating. Stacked layers of the CFRP prepreps and TiNi fibers were laid up in the steel mold. The TiNi/CFRP composites were formed by curing in a hot press. Curing was accomplished at 180 °C for 2 h at a pressure of 0.3 MPa. After curing, hot-pressed specimens were allowed to cool to room temperature.

These hot-pressed TiNi/CFRP composites were then cut with a diamond blade and prepared as notched tensile test specimens of 200 mm (length) $\times$ 12 mm (width) $\times$ 1.2 mm (thickness) as shown in Fig. 1(a). Notches 3 mm long and 0.3 mm deep were cut from two sides of each specimen using a diamond wheel to leave a thin section at the center of the bar at which fracture would commence.

2.2. Tensile testing

Tensile testing was performed in conjunction with the AE technique to investigate the fracture mode of TiNi/CFRP composites. A two-channel monitoring system consisting of an AE analyzer (DCM140, JTT) and two AE (piezoelectric) sensors (Fuji Ceramics, M304A) were used in the manner illustrated in Fig. 1(b). One AE sensor was attached near the notched area and the other AE sensor was attached away from the notches in order to interpret the AE signal easily. A threshold of 50 μ V and a dead time of 1 ms were selected. Strains in each specimen were measured using an extensometer. Tensile tests were performed using an MTS 810 test machine with a constant crosshead speed of 0.1 mm/min.

The AE signals generated during tensile testing were detected with an AE sensor and recorded in digital wave form. This was then analyzed by computer to obtain the AE wave form. The AE signal was located in one dimension on the basis of the difference between the arrival times of the AE signals to the two channels. The microstructural properties of the TiNi/CFRP composites were investigated by SEM observation and optical microscopy.

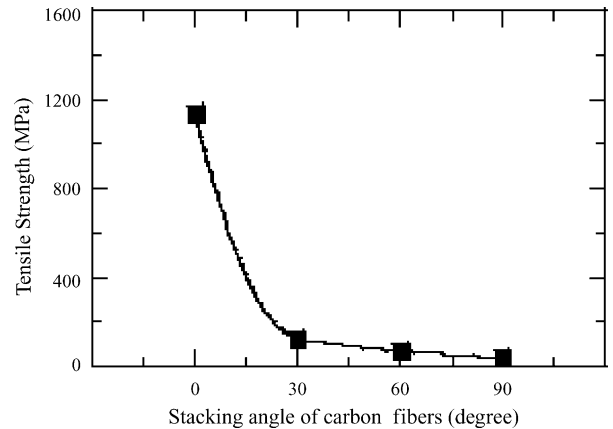


Fig. 2. Influence of stacking angle of carbon fibers on the tensile strength of TiNi/CFRP composites.

3. Results and discussion

3.1. Tensile strength

Fig. 2 shows the results of tensile strength for specimens without the notches. The tensile strength decreased markedly with increasing carbon fiber stacking angle. These results mean that the tensile strength of TiNi/CFRP composites strongly depends on the stacking angle of the carbon fibers. The decrease in tensile strength as the stacking angle was increased resulted from insufficient strengthening of the composite by the carbon fibers (the higher the angle, the further the carbon fiber long axes face away from the tensile direction, thereby effecting less stiffening in this direction), as well as the increase in the number of internal defects, such as pores and/or voids on introduction of TiNi fibers.

3.2. Fracture of notched specimens

In order to investigate the fracture behavior in the composites, AE measurements were taken for notched tensile specimens to provide a one-dimensional (point) AE source. Fig. 3 shows representative optical micrographs of the fracture surfaces of notched specimens after tensile testing. The fracture of the 0° stacked specimen reveals critical breakage of the carbon fibers at the notch. In contrast, for the 30–90° stacked specimens, fracture propagation occurred along the direction of stacking of the carbon fibers after the initial cracks had originated in the notched area.

Longitudinal surface cracks in the 0° stacked specimen were generated along the fibers on the surface of the specimen before final fracture, whereas such cracks could not be detected for the 30–90° stacked specimens. For these specimens, fracture occurred within the epoxy resin without critical breakage of the fibers. It can be concluded that the fracture pathways in the specimens are strongly influenced by the stacking angle of the carbon fibers.

3.3. Fracture behavior of notched specimens

Fig. 4 shows typical results of Lamb wave measurements obtained from the one-dimensional (point) AE source of the

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