ORAL/POSTER REFERENCE:

THE EFFECT OF PROCESSING ON TENSILE STRENGTH AND FRACTURE BEHAVIOR OF CFRP SMART COMPOSITES WITH EMBEDDED SHAPE MEMORY ALLOY WIRES

Byung-Koog Jang, Ja-Ho Koo, Ya Xu, Nobuyuki Toyama,
Hitoshi Yoshida, Yoshio Akimune and Teruo Kishi

Smart Structure Research Center
National Institute of Advanced Industrial Science and Technology (AIST)
Tsukuba Central 2, 1-1-1, Umezono, Tsukuba-City, Ibaraki, 305-8568, JAPAN

ABSTRACT

TiNi/CFRP composites were fabricated by hot pressing in the temperature range of 130~180°C, by controlling the applied pressure. The TiNi wires were embedded as an 1mm interval into the center of CFRP layers and CFRP host materials were stacked as 0, 30, 60 and 90 degrees configuration on tensile direction, respectively. The stress-strain curve and tensile strength of composites strongly depends on stacking direction of carbon fibers. The tensile strength of TiNi/CFRP composites with stacking direction of 0 and 90 degrees configuration are about 1.2GPa and 50MPa, respectively. The microstructural properties of TiNi/CFRP composites were observed by SEM. Pore and/or voids were found to congregate near the embedded TiNi wire and they increased in proportion to stacking direction of carbon fibers. Larger pores and interfacial cracks were also observed at interface between TiNi wires and epoxy resin. Furthermore, the fracture behavior was studied by one-dimensional AE source location during tensile test, to analyze the fracture mode. It was confirmed that the extensional mode for 0 degree composites and the flexural mode for 90 degrees composites are predominant, respectively.

KEYWORDS

TiNi shape memory alloy, CFRP (carbon fiber reinforced plastics), tensile strength, microstructure, AE (acoustic emission), Lamb wave, fiber breakage, smart composites.

INTRODUCTION

Recently, many research work regarding smart composites by incorporation of functional materials into structural material were reported. Smart composites have proven to be a promising new material system and many applications have been found like as sensors, actuators, and control processors. Shape memory alloy (SMA), optical fiber, and piezoelectric materials, have been found to be capable for fabrication of smart composites [1, 2]. Among such functional materials, SMA is good candidate material because it exhibits various properties of actuator, super-elastic response, high damping and self-recovery function. Specially, TiNi shape memory alloy is attractive because of the large shape memory effect, high damping capacity and high stiffness at the austenite state. Various kinds of smart composites having new functional properties have been investigated by incorporated materials of SMA with various shape such as fibers, wires, ribbons, particles and thin films [3, 4]. The SMA reinforced smart composites can be manufactured with conventional polymer matrix composite fabrication method, by laying the SMA wires with the reinforcing shape into the CFRP prepreg matrix and then using either hot-pressing or an autoclave and several different types of cure cycles. However, manufacturing by autoclave has several demerits such as high cost, high material loss, and low work efficiency. Very little research has been done regarding processing effects on mechanical properties and fracture behavior in TiNi SMA embedded composites. Therefore, this work focuses on effect of processing regarding mechanical properties of CFRP smart composites incorporating TiNi wires of shape memory alloy by using hot pressing. It was also investigated the fracture mode due to separation of Lamb wave by one-dimensional AE source location using the notched tensile specimens attaching two AE sensors.

EXPERIMENTAL PRODECURE

It was designed a TiNi/CFRP composite by sandwiching the TiNi wires between layer of CFRP prepreg. Stacks are composed of CFRP prepreg and embedded TiNi wire and then stacked together. The different stacking direction for carbon fibers such as 0, 30, 60 and 90 degrees configuration on tensile direction are chosen to establish the optimal design for fabrication of TiNi/CFRP composites. CFRP prepreg had been cut in size of 200×105 mm. During the lamination procedure, the TiNi wires were carefully embedded into CFRP prepreg as an 1mm interval into the center of 8 sheets of CFRP layer and those were laid in the 0 degree configuration on tensile direction using the special steel jig. Anti-heat vinyl sheets were used to prevent the flow of epoxy resin of CFRP prepreg during heating. Stacked bodies with CFRP prepreg and TiNi wires were laid up in the steel mold. TiNi/CFRP smart composites could be fabricated by curing at hot-press. Curing was accomplished for 2hr, in range of 130~180°C by controlling the applied pressure in range of 0.03~0.3 MPa. After curing, hot-pressed specimens allowed cooling to room temperature. The hot-pressed TiNi/CFRP composites were cut by diamond blade and prepared as a tensile test specimen according to the standard of JIS-K 7073. It was induced notch having a dimension of 3×0.3 ($L\times t$) at both side of specimens using diamond wheel as shown in Figure 1.

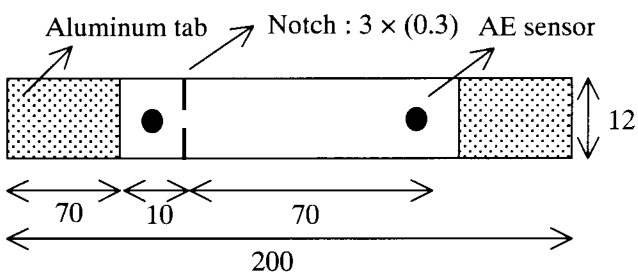

Figure 1: Schematic drawing of notched tensile specimen

The AE (acoustic emission) technique was applied to investigate the fracture mode of TiNi/CFRP composites and was conducted using two channel monitoring system. One AE sensor was attached near notch area and another AE sensor was attached opposite area of notch for classifying the AE signal, easily. Detected AE signals were filtered to avoid the noise and were analyzed by a computer. The microstructural properties of TiNi/CFRP composites such as observation by SEM and optical microscopy were also investigated.

RESULTS

Microstructure

The SEM micrograph of the polished surfaces for TiNi/CFRP composite hot pressed at 180°C, 0.3MPa regarding the different stacking direction of carbon fibers are shown in Figure 2. The brightly big circle materials are an embedded TiNi wire and surrounding materials are CFRP matrix.

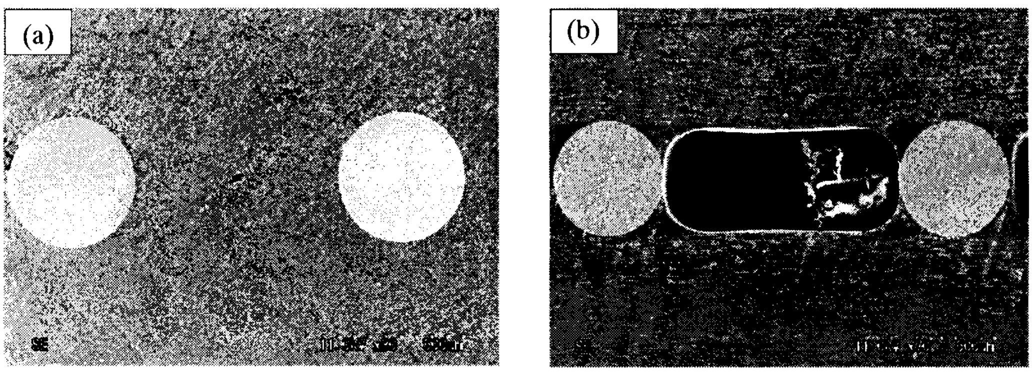

Figure 2: SEM micrographs of TiNi/CFRP composites with different stacking direction of carbon fibers : (a) 0 and (b) 90 degrees configuration on tensile test direction

Pore and/or voids could not almost detected in composites stacked as 0 degree configuration of carbon fibers, whereas big voids existed at around TiNi wire and matrix in composites stacked as 30 degrees configuration of carbon fibers. For composites stacked as 60 and 90 degrees configuration of carbon fibers respectively, bigger void existed at interfacial matrix between TiNi wires. The averaged pore and/or void size of composites stacked as 0 degree configuration were smaller than those of composites stacked as 30~90 degrees configuration. Combining the data from all cross-sections, the average void size for specimen stacked as 0 degree configuration was found to be below 20 μm, whereas that for specimen stacked as 90 degrees configuration was found to be up to 600 μm, respectively. It seems that the mass transport of epoxy resin for composite with various stacking direction may be inhomogeneous during curing, resulting in defect formation. These results indicate that a more uniform microstructure can be obtained for stacked bodies as 0 degree configuration. Based on result of pore and/or voids distribution, it could be understood that the microstructure of TiNi/CFRP composites strongly depend on stacking direction of carbon fibers. These results suggest that stacking design for manufacturing of composites should be carefully carried out in order to obtain the TiNi/CFRP composites with defect free. Also, it may be that the embedded TiNi wires act as an impurity sites for the formation of pore and/or voids. Pore and/or voids fraction also increased in proportion to volume of the embedded TiNi wire location. Based on this work, By properly designing a stacking configuration of carbon fibers, internal defects may be reduced or controlled.

Mechanical Properties
The detected various defects induced during processing can significantly degrade the mechanical properties of SMA composites. So, the tensile strength was experimentally investigated as shown in Figure 3. It was found that the tensile strength of composites stacked as 0 degree was higher than those for various 30~90 degrees configuration. The reason of the degradation in tensile strength resulted from increase of internal defects such as pore or voids fraction as well as a little fiber breaking. These results mean that the tensile strength of TiNi/CFRP composites has strongly depended on the stacking direction of carbon fibers and tensile strength precisely showed the remarkable decrease with increasing stacking direction of carbon fibers for TiNi/CFRP composites. In addition, CFRP monolithic without TiNi embedding is 1.3 GPa, whereas TiNi embedded composites is below 1.1 GPa. The reason for the degradation in tensile strength of TiNi/CFRP composites is attributed to the fact that the material defects are generated in the matrix by incorporation of TiNi into the CFRP matrix. It is considered if volume fraction of TiNi embedded into CFRP matrix is increased, it may be more decreased the tensile strength.

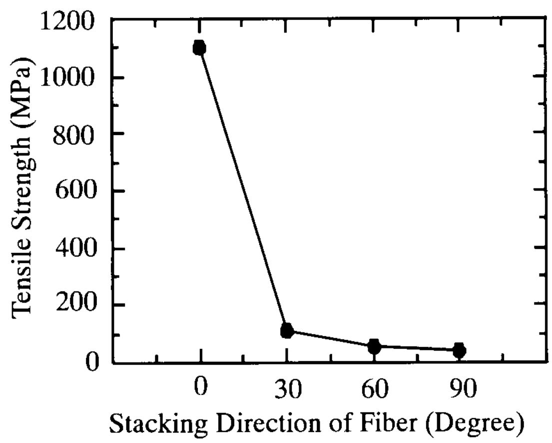

Figure 3: Tensile strength of TiNi/CFRP composites with different stacking direction of carbon fibers

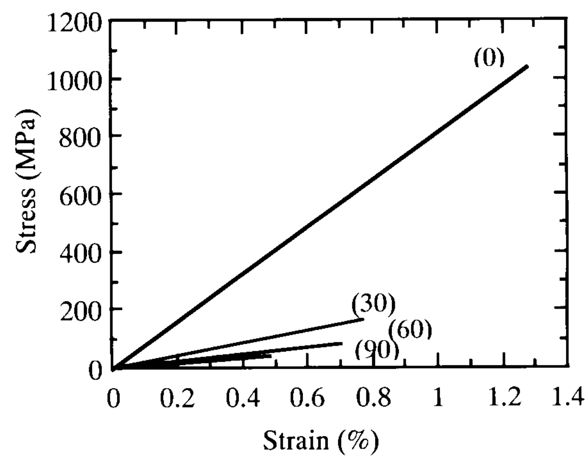

Figure4: Stress-strain curves of TiNi/CFRP composites with different stacking direction of carbon fibers

The relationship of the stress-strain (S-S) curves during tensile test is plotted in Figure 4. All stress-strain curves have tendency to be steadily linear until fracture at maximum load. As expected, stress-strain curves decrease with increasing the stacking direction of carbon fibers. For TiNi/CFRP composites stacked as 0 degree configuration, a strain increases gradually with increasing stress. The tendency of largely linear stress-strain curve for 0 degree configuration, also means the existence of carbon fiber breakages arising at carbon fibers, because embedded carbon fiber direction is 0 degree against tensile direction. S-S curve results indicate the low inclination for specimens stacked as 30~60 degrees configuration and it shows the extremely lower inclination for 90 degrees configuration. The Young's modulus can be measured from the S-S curve. It is expected that composites of 0 degree configuration having the higher inclination in results of S-S curve show the higher Young's modulus, whereas composites of 30~90 degree configuration with lower inclination correspond to the lower Young's modulus. The average Young's modulus of specimens stacked as 0 and 90 degrees configuration, were estimated as 75 GPa and 8 GPa, respectively.

Analysis of Fracture Behavior by One Dimensional AE Source Location
The fracture mode of a fiber reinforced composites depends on its embedded direction in the specimen. Different fracture mode, such as matrix crack, debonding, fiber breakage and buckling,

may complicatedly occur due to tensile, compressive, shear or a combination of these stresses. Generally, the AE technique proved to be effective for investigating the fracture process of fiber reinforced plastic composite materials. The generated AE events resulted from the generation of micro-fracture such as carbon fiber breaking, debonding and matrix micro cracking during tensile test. However, AE characteristics of these fracture modes associated with embedded direction are rarely investigated. In order to investigate the fracture mode in TiNi/CFRP composites, AE measurements have been coupled using notched tensile specimens applying the AE source location. Figure 5 shows the representative results of Lamb wave generated by one-dimensional AE source location from detected AE signals. Generally, AE signals propagate as the extensional and flexural plate modes in thin composite plates and plate-like geometries such as shells, pipes and tubes. The relative amplitude of the two modes depends on the directionality of the source motion [5, 6]. Therefore, if specimen is plate with thin thickness like in the present specimen, detected AE signal correspond to Lamb wave. Lamb wave can be also divided to two kinds, that is, the extensional mode and flexural mode as shown in Figure 5.

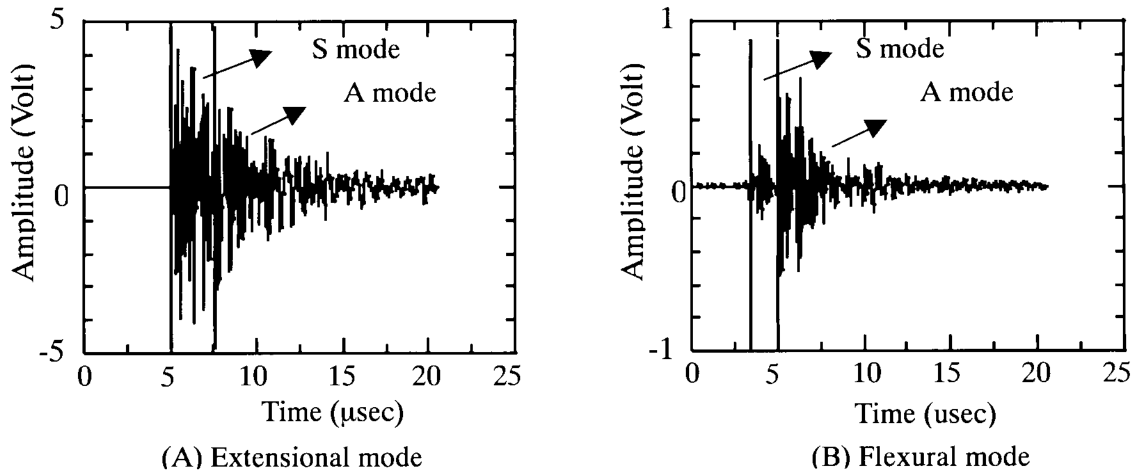

Figure 5: Lamb wave of AE signal generated by tensile test using notched tensile specimens of TiNi/CFRP composites: (A) Extensional mode and (B) Flexural mode

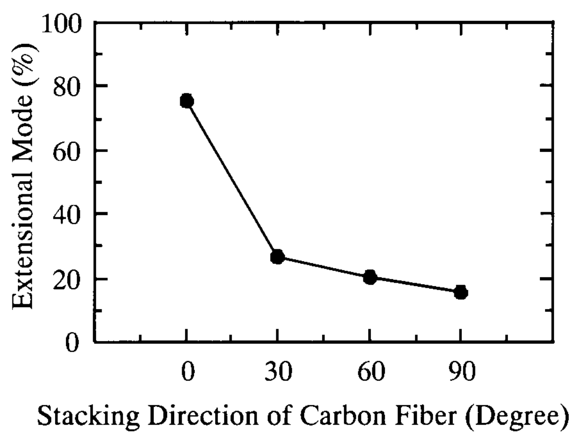

Figure 6: Extensional mode ratio by separation of Lamb wave for notched tensile specimens of TiNi/CFRP composites

From analyzing results of AE wave, the extensional mode shows that S mode of wave is relatively large amplitude and A mode shows small amplitude. However, the flexural mode shows that S mode of wave is low-level amplitude and A mode relatively shows large amplitude. Furthermore, the extensional mode corresponds to generation of mainly fiber breakings, whereas the flexural mode correspond to generation of mainly debonding and micro cracking. Figure 6 compares an extensional mode ratios based on one-dimensional AE source location using notched tensile specimens. The detected AE signals were collected total 10mm range area including notch center, because this notch area generated many AE events during tensile test. The extensional mode ratio is derived from value that extensional mode is divided by sum of extensional mode and flexural mode. Extensional mode ratio of 0 degree specimen is about 80%. However, various 30~90 degrees composites shows very low extensional mode. This demonstrates that the generation of fiber breakings for specimen with 0 degree is predominant during tensile test. However, in case of 30~90 degrees composites, the generation of flexural mode is predominant rather than extensional mode. Consequently, this means that the generation of fiber breakings is very few. These results demonstrate that fracture mode in TiNi/CFRP composites can classify by one-dimensional AE source location using notched tensile specimen.

CONCLUSIONS

TiNi SMA wires embedded CFRP smart composites with free of pores or voids, were successfully fabricated. Stacking direction of carbon fibers is more important processing parameter for obtaining the dense composite. Pore and/or voids rarely existed in composites stacked as 0 degree configuration of carbon fibers, whereas bigger voids mainly existed near TiNi wires with increasing the stacking direction. With increasing the stacking direction of carbon fibers, the tensile strength and Young's modulus of composites decrease. The fracture mode of TiNi/CFRP composites depends on its stacking direction of fibers from the results of one-dimensional AE source location using two AE sensors. TiNi/CFRP composites with 0 degree predominantly show the extensional mode, corresponding to fiber breakages.

ACKNOWLEDGEMENTS

First author wishes to acknowledge NEDO (New Energy and Industrial Technology Development Organization) and RIMCOF (R&D Institute of Metals and Composites for Future Industries) which offer the opportunity of NEDO fellowship for this research.

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