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学 位 論 文 要 旨
Dissertation Summary

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論　文　名：　Monitoring the internal strains in CFRP laminates from processing to machining and temperature cycling.

(Dissertation Title)

This study aims at investigating the internal strain of Carbon Fiber Reinforced (CFRP) laminate from processing to machining and the thermal expansion coefficient of fiber metal laminate FML) during temperature cycling. Chapter 1 is an introduction. CFRP and CFRP-Metal laminate are widely used in aerospace, automotive, wind energy, and machinery construction application due to their high stiffness and high strength to weight ratio. For example, using CFRP instead of metals in automobile vehicles is reported to bring a weight reduction factor, significantly improving fuel efficiency, maneuverability, and payload capacity of the vehicles. Compared with traditional materials (e.g., metals), carbon fibers have greater fatigue resistance, better long-term stability, lower thermal expansion, and excellent corrosion resistance. Such advantages make CFRP a potential candidate for a wide range of applications in various and extreme environmental conditions.

Nonetheless, in the manufacturing of composite, unexpected deformation such as geometrical distortion due to residual stress/strain must be minimized to assure the dimensional accuracy and structural integrity of the component. The presence of internal residual stress/strain due to processing and machining may cause difficulties in assembly or degradation of in-service of composite component or structure. It has been reported that a lot of factors such as chemical (cure) shrinkage, thermal shrinkage, and viscoelastic properties affect the residual stress/strain level during and after a cure process. In the machining-process, the transient and permanent residual strain appear due to cutting force, temperature, and machining-induced damage. Recently, various methods have been developed to measure the residual strain and thermal strains in composite materials such as Electric resistance strain gauge, Raman microspectroscopy, Moiré interferometry, Digital

image correlation (DIC), and Fiber Bragg Grating (FBG) sensors. It is found that the FBG sensors are the best tool not only to measure the internal strain during processing and machining but also to measure the thermal expansion coefficient of laminate precisely.

Chapter 2 is the theoretical background. FBG sensor is the optical fiber sensor with many advantages such as small size, high resolution, and accuracy. The mechanical strain or temperature is known by measuring the change in wavelength and using a thermocouple for temperature compensation. Lamination theory is a classical laminate theory used to calculate and predict the residual strain after a cure process.

Chapter 3 is the seamless monitoring of internal strain during processing and drilling in a CFRP laminate. The material used is a carbon/epoxy prepreg (T700S/2592) to produce cross-ply and quasi-isotropic laminate utilizing an autoclave. FBG sensors were embedded in the laminate to monitor the entire curing process and machining. The strain at the gel point when the laminate starts to vitrify was defined as zero strain in both processing and drilling. Then, the residual strain was calculated from the wavelength shift recorded by the optical sensing interrogator and the temperature change. By using the same specimen and sensor (FBG and Thermocouple), hole machining was conducted near the FBG sensors and thermocouple. The temperature and peak wavelength shift recorded by the data logger and optical interrogator used to calculate the internal strain and strain change during drilling. Various machining conditions were applied to create a specific damage/delamination size. The reflection spectrum is also considered to assure the reliability of strain measurement data. The exact location of the FBG sensor and the size of delamination caused by drilling was then quantitatively measured using soft X-ray radiography. Finally, the specimen was cut in the cross-section to observe the sensor condition after drilling.

The absolute internal strain was consistently monitored through processing (curing) to machining (drilling) by defining the strain at the gel point to zero. As a result, the drilling-induced strain is separated from the process-induced strain. This seamless monitoring makes it possible to distinguish between the process-induced strain and machining-induced strain, and it is impossible to know the sign (tensile or compressive) of the internal strain until the seamless strain monitoring is conducted, just like in this study. It was found that the internal strain detected by the FBG sensor was correlated with not only damage size or a delamination factor but also its relative position and total internal strain.

Chapter 4 is the in-situ monitoring of CFRP-metal laminate with low thermal expansion. A pitch-based CFRP and Stainless Steel (SST) laminate is employed to develop Fiber Metal Laminate (FML) with a near-zero coefficient of thermal expansion. Base on the lamination theory, Young's modulus and CTE of the FML were obtained to confirm the quasi-isotropy of the elastic modulus and thermal expansion. The thickness ratio between SST and CFRP was determined to achieve an exact zero-CTE at room temperature (25°C). The density of the zero-CTE FML was also calculated with the aid of the rule of mixture. The thermal strain of the UD-CFRP, QI-CFRP, and FML was measured using an embedded Fiber Grating (FBG) sensor during a heating or cooling cycle. Then, the CTEs of the CFRPs and FML were obtained to investigate the temperature dependence of the CTEs of the materials and verify the zero-CTE of the FML in the vicinity of room temperature. The last, Finite Element Analysis (FEA) was conducted taking the temperature dependence of the CTEs and elastic moduli of the CFRP into account to compare the CTE of the FML between the experimental lamination theory and FEA result.

It is found from the experiment results that the CTE of a fabricated FML was accurately measured using embedded fiber Bragg grating (FBG) sensors to verify that the CTE had a near-zero value around room temperature. The temperature dependence of the FML CTE from 20 to 120°C was investigated via finite element analysis (FEA), taking the temperature-dependent material properties into account. It was demonstrated from the experiment and FEA that the present FML had a near-zero CTE around room temperature (20-40°C) and higher Young's modulus and specific modulus compared with other relevant materials.

Chapter 5 is the conclusion. The seamless internal strain and strain change during the whole processing and machining was successfully monitored using an embedded FBG sensor and thermocouple. It is found that the internal strain and drilling-induced strain are correlated with the relative FBG sensor position and the delamination factor, which is never reported in any references. Furthermore, the accurate measurement of near-zero CTE has been clarified using embedded FBG sensors. The FML laminate has a high specific modulus compared with other competing materials and conventional FMLs even though quasi-isotropy and zero CTE are maintained simultaneously.