Mechanical Characterization of PEEK/IM7 Fabricated Using an Automated Tape Placement Processing System

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1. Introduction

Composite materials have been widely used in aerospace structures, automotive parts, marine structures, and sporting goods due to their unique properties such as low-weight, low-density, high-strength, high-stiffness, chemical resistance, thermal-shock resistance, and many others[1]. Polyetheretherketone (PEEK) is a thermoplastic polymer, as high performance engineering thermoplastics, with a superior properties including high strength, high stiffness, high impact resistance, high thermal stability, and excellent chemical resistance[2,3]. PEEK can be used with high performance carbon fibers such as IM7 fibers and PEEK/IM7 shows unique mechanical properties which meet the design requirements of many high-performance structural applications especially in aerospace and militaries. In general, very thin tape-type PEEK/IM7 prepreg is used for structural applications. For consolidating multi-layered PEEK/IM7 tapes, very high processing temperature and pressure are required because the melting point of PEEK approaches up to 400^{o}C and PEEK can hardly flow between carbon fibers even at melting temperature. By using a tape placement processing for a thermoplastic resin/carbon fiber tape, tape laying and consolidation process can be simultaneously achieved[4,5]. Furthermore, tape laying pressure and tape tension can be easily controlled during the tape laying process. In this study, unidirectional PEEK/IM7 tape has been placed on to the steel tube by using an automated PEEK/IM7 tape placement process and the cross section of PEEK/IM7 tape placed on steel tube has been examined by X-ray CT scan and SEM. In addition, the mechanical tests including tensile, compressive, short-beam shear, and bending tests were performed to investigate the mechanical characteristics of laminated PEEK/IM7 tapes.

2. Experimental

A unidirectional PEEK/IM7 thermoplastic tape with a 12mm width and 0.1mm thickness was used. PEEK is a semi-crystalline polymer with a glass transition temperature of 143^{o}C. The PEEK/IM7 tape (resin content = 40 vol%) was heated above the melting point of PEEK, 340-350^{o}C. The PEEK/IM7 tape was placed and consolidated on the steel tube (outside diameter is about 200mm) using an automated tape placement processing system, in which a hot gas torch system was introduced to heat the PEEK/IM7 tape up to 400^{o}C and pressing roll was used to apply a high pressure on to the PEEK/IM7 tape, as schematically shown in Fig. 1. The PEEK/IM7 was exposed to torch flame only for few seconds. Typical processing temperature was about 400^{o}C.

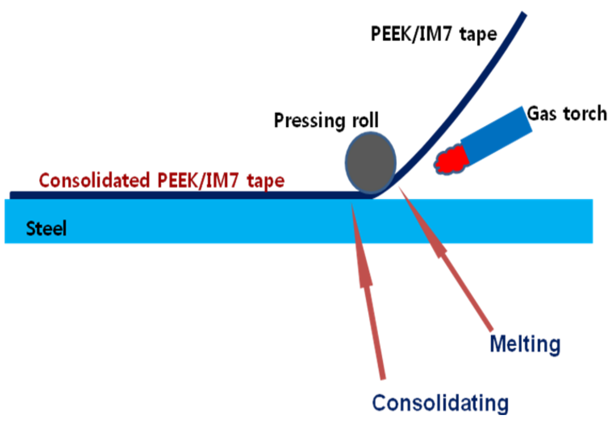


Fig. 1. Schematic diagram of an automated PEEK/IM7 tape placement process.

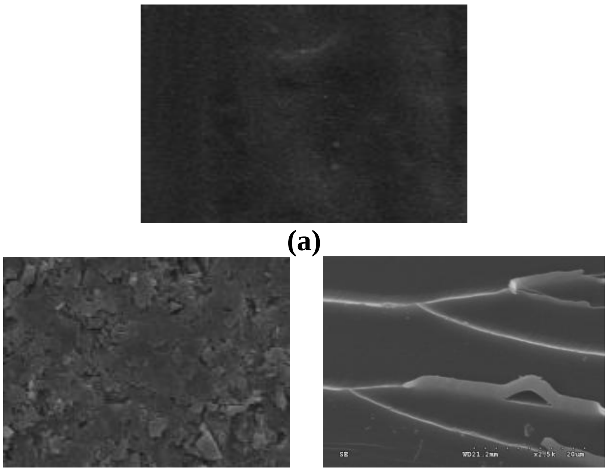
Mechanical tests including tensile (ASTM D 3039), compressive (ASTM D 3410), short-beam shear (ASTM D 2344), and bending (ASTM D 790) tests were performed to measure tensile strength, tensile elastic modulus, Poisson's ratio, compressive strength, and inter-laminar shear strength. Instron mechanical test machine and lead wire-integrated strain gauge (TML(Tokyo Sokki Kenkyujo Company)) were used to characterize the fabricated laminates. X-ray CT scan (X-ray inspection system, Revolution Model, two-dimensional image mode) was performed to examine the interfacial adhesion and voids at the interface of metal tube and PEEK/IM7 composite.

3. Results and discussion

SEM image of PEEK/IM7 tape is shown in Fig. 2. At the surface of PEEK/IM7 tape (resin content = 40 vol%), resin-impregnated unidirectional carbon fibers are clearly shown. For determining tape placement processing parameters, unidirectional PEEK/IM7 laminates were fabricated using hot press. The PEEK/IM7 tape was pre-heated to about 400 ^{o}C above the melting point of PEEK, 340-350^{o}C, in the oven for a short time period, and then consolidated under high pressure in the pre-heated hot press. Consolidation process under high pressure is needed because PEEK possesses non-flowing nature even at high temperatures.

Fig. 2. SEM image of PEEK/IM7 tape surface.

SEM images of PEEK/IM7 laminate surface and the fractured surface of PEEK/IM7 laminate and epoxy resin are shown in Fig. 3. Under high pressure at about 400^{o}C, melt flow occurs between carbon fibers, leading to forming a surface-smoothened PEEK/IM7 laminate as shown in Fig. 3(a). The fractured surface of PEEK/IM7 shows that there are no voids at the interface of PEEK/IM7 tapes and even in the PEEK/IM7 tape after a pressurized tape consolidation process as shown in Fig. 3(b). At least 20kgf of pressing force (roll width = 20mm) and pre-heating temperature of 400^{o}C are needed for tightening tapes together. Furthermore, the fractured surfaces of PEEK/IM7 laminate and epoxy resin, as shown in Fig 3(b) and 3(c), indicates that PEEK/IM7 possesses higher toughness compared to epoxy resin even PEEK shows a high glass transition temperature. For epoxy resin, fractured surface is clean because there are no blocking mechanisms of crack propagation in epoxy matrix. For PEEK, crack propagation is very random and diverse because crack propagation is effectively blocked in PEEK matrix.



(a)

(b) **(c)**

Fig. 3. SEM images of PEEK/IM7 laminate surface(a), and fractured surfaces of PEEK/IM7 laminate(b) and epoxy resin (c).

An automated tape placement processing system with a pressing roll and hot gas torch system was designed and manufactured for winding PEEK/IM7 tape on the steel tube (outside diameter = about 200mm), as shown in Fig. 4. High pressure of up to 40kgf was applied on to the tape by pressing roll. The temperature near a hot gas torch flame was adjusted to about 600^{o}C. The PEEK/IM7 tape was exposed to a hot gas torch flame for a short time period (typically 1 to 2 seconds) to heat up the PEEK/IM7 tape up to 400^{o}C. At this moment, pressing roll was immediately applied to pressurize the surface-heated PEEK/IM7 tape. At the initial stage of tape winding process, metal tube was cooled down to subzero temperature by using dry ice, resulting in reducing the outside diameter of metal tube, and the PEEK/IM7 tape was tensioned (up to 20kgf) to achieve the enhanced tightness at the interface of metal tube and PEEK/IM7. By introducing this tape placement process, PEEK/IM7 should be pre-stressed at room temperature after tape consolidation. Condensed moisture or ice was formed on the surface of metal tube, and effectively vaporized and removed by a hot gas torch flame, as shown in Fig. 4 (a). In Fig. 4(a), the surface of metal tube and the first layer of PEEK/IM7 were whitened or cloudy due to the condensed moisture. This condensed moisture should be thoroughly removed before PEEK consolidation. Tape laying pressure and tape tension can be easily controlled during the tape laying process. Manufactured PEEK/IM7[0/90 degree]/metal composite is shown in Fig. 4(b) and about 70 layers of PEEK/IM7 tape were stacked on to the metal tube. The total thickness of PEEK/IM7 is about 10mm. The temperature of hot gas torch was precisely controlled by adjusting gas flow rate. PEEK/IM7 tape position and laying angles are automatically determined by PC-assisted program during whole fabrication process. The tension of PEEK/IM7 tape was pre-set manually. The cross-sectional view of PEEK/IM7/metal tube (10cm length) is shown in Fig. 5. PEEK/IM7 was tightly stacked on to the metal tube due to the introduction of pre-stress in PEEK/IM7 layers by both tensioning PEEK/IM7 tape and sub-cooling metal tube.

(a)

(b)

Fig. 4. An automated tape placement processing system with a pressing roll and hot gas torch system; initial stage (a) and middle stage (b) of tape winding process.

Fig. 5. Cross-sectional view of PEEK/IM7/metal tube.

The image of X-ray CT scan is shown in Fig. 6. For X-ray inspection, scanned in two-dimensional image scan mode, was performed and inspection specimen of PEEK/IM7/metal tube of 10cm length was prepared. Scanning time was set to 6 minutes. Inspection was performed at room temperature to investigate the effect of pre-stress in PEEK/IM7 layer on the interfacial adhesion at the interface of metal tube and PEEK/IM7 composite. As marked in Fig. 6, white-colored thick circle refers to metal tube and gray-colored thick circle refers to PEEK/IM7. There were no voids and gaps in PEEK/IM7 layer and at the interface of metal tube and PEEK/IM7 composite, as well.

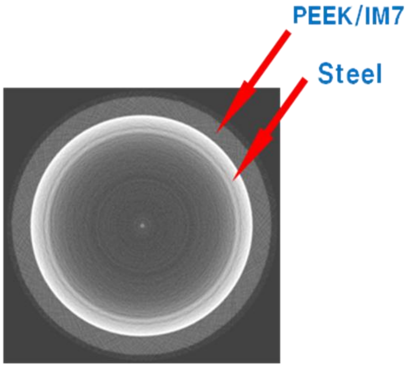


Fig. 6. Image of X-ray CT scan (cross-sectional view of PEEK/IM7/metal tube).

For measurements of mechanical properties of PEEK/IM7 composite, mechanical test specimens were prepared according to the appropriate test standards and fabricated using an tape placement process. The photo image of short-beam test zig and specimen is shown in Fig. 7. The PEEK/IM7 composite used in this study exhibited high strength and high elastic modulus, as shown in Table 1. Tensile strength, tensile elastic modulus, compressive elastic modulus, Poisson's ratio, and bending strength were evaluated. In particular, by inter-laminar shear strength measurements, interfacial adhesion strength between PEEK/IM7 tape layers could be determined. After performing a short-beam test to measure an inter-laminar shear strength, micro-cracks were observed at the both sides of a specimen since uniform consolidation between each layer of PEEK/IM7 has been achieved. High inter-laminar shear strength was measured in this study, indicating that pre-heating and pressing conditions have been optimized.

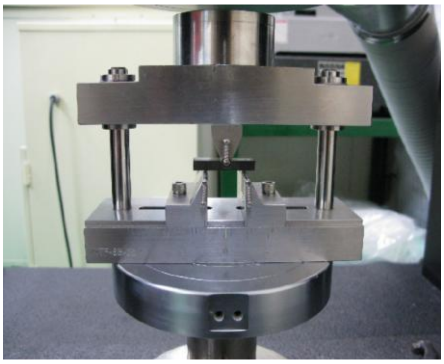


Fig. 7. Photo image of short-beam test zig and specimen.

Table 1. Mechanical properties of unidirectional PEEK/IM7 composites.

Test Item	Test Meth-od	Mechanical Property.	Value
Tensile Test	ASTM D3039	Tensile strength, X_t	2203.60 [MPa]
		Tensile elastic modulus, E_{11}	153.10 [GPa]
		Poisson's ratio, υ_{12}	0.21
Compressive Test	ASTM D3410	Compressive strength X_c	610.72 [MPa]
		Compressive elastic modulus, E_{11}	125.6 [GPa]
Short-beam Test	ASTM D2344	Inter-laminar shear strength, S_{23}	30.90 [MPa]
Bending Test	ASTM D790	Bending strength, F_{23}	1601.05 [MPa]

4. Conclusions

A unidirectional PEEK/IM7 tape has been placed on to the steel tube by using an automated PEEK/IM7 tape placement processing system, in which a hot gas torch system and pressing roll are installed. The temperature near hot gas torch flame was adjusted to about 600^{o}C, compaction pressure of the roll to about 20kgf, and tape tension to about 20kgf. The tape placement process was automatically operated using a PC-assisted program. In this study, PEEK/IM7 composite exhibits high mechanical properties and this automated PEEK/IM7 tape placement processing system will be applied to manufacture gun tubes to reduce weights as well as to achieve better balance of gun tubes in the ongoing works.

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