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Adhesion characteristics of fiber-exposed glass composites

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ABSTRACT

Joining of composite materials has been an issue ever since composites were introduced. Among various joining methods, adhesive joining has been widely adopted because the adhesive joining uniformly distributes stresses over larger area, while the mechanical joining of composites induces stress concentration and fiber breakout. However, adhesive joining requires the surface treatment of composite adherends to increase the bonding strength; this treatment is not only costly but also generates much environmental pollution.

In this study, a composite adherend that does not require any surface treatment to constitute an adhesive joint is developed. The composite adherends are manufactured by a "soft layer method" to expose bare fibers on the surface during composite fabrication. The bonding strength was significantly improved due to the exposed bare fibers, which was comparable to that of the adhesive joint treated by the conventional peel ply method without generating waste materials.

1. Introduction

Composites are widely adopted in lightweight structures, including aircrafts and automobiles, because of their high specific stiffness, specific strength and failure strain. In addition, the properties of composites can be tuned by changing the stacking sequence; such tuning is seldom possible for other materials. Along with the wide applications of composites in various industries, the development of reliable joining methods for composite assemblies has become an important research area [1]. The reliability of a composite structure is largely dependent on the joint rather than on the composite structure itself because the joint is usually the weakest part in the assembled structure [2–4].

Joints can be generally divided in two categories: mechanical joints and adhesive joints. Mechanical joints are usually implemented by fastening the adherends with bolts or rivets. The use of mechanical joints is a simple and relatively well-developed method, having been implemented on traditional metallic materials. However, because the drilling of holes is required for mechanical joints, the mechanical joining method not only precludes uniform distribution of load but also induces high stress concentration near the holes. On the contrary, adhesive joints use an adhesive interlayer between the adherends; such an interlayer can distribute the load over a larger area than the mechanical joints, requires no holes, adds very little weight to the assembly and has superior fatigue resistance. Therefore, adhesive joints are widely adopted for joining composite materials [5].

However, adhesive joints are more complicated than mechanical joints. Adhesive joints are affected by various service environment conditions, including the temperature and humidity of the location where the adhesive joint is used. In addition, surface treatment of the adherend is necessary to obtain reliable bonding. In particular, adhesive joining of large areas or thin composite materials requires even more complicated and careful surface treatments [5]. Currently, many methods are available for the surface treatment of the composite, such as plasma treatment, flame treatment, ultraviolet treatment, coupling agent, and mechanical abrasion. Surface treatments using plasma, flame, or ultraviolet light increase the surface energy of the composite [5–8]. However, such surface treatments are greatly affected by the environment and are prone to contamination. In addition, uniformity and reproducibility is a problem. In the case of plasma treatment, the same flow rate, gas pressure and power input may not produce the same level of surface because of the system dependency of the treatment [9]. Coupling agents, such as silane and sol-gels, act as a bridge between the adherend and the adhesive; however, they are costly and prone to contamination [6,10]. Sandpaper or grit blast are classified as mechanical surface treatments that increase the mechanical interlocking by increasing the surface roughness [11,12]. Mechanical treatment provides a prolonged effect compared to other chemical surface treatments. However, the process is highly

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labor-intensive and generates much waste, especially when the adhesion area is large. In addition, residual contamination can cause detrimental effects on composite adherends. The surface treatment methods listed above require additional post processing after the fabrication of the composite materials; such post processing can result in the increase of the overall manufacturing cost.

In that sense, the peel ply method may appear to be an effective solution because it does not require post processing. This method adopts a release agent coated woven fabric sheet between the molds and the composite laminates. The major role of the peel ply is to form a rough surface after curing of the composite for high bonding strength [13]. Though the peel ply method is widely adopted in industries because of its convenience compared to surface treatment methods, it is not only costly but also generates much waste because the peel ply absorbs resin and therefore is not reusable.

Recently, a fabrication method that exposes bare fibers on the composite surface has been developed. The "soft layer method" uses a thin release film to remove resin on the composite surface, resulting in complete exposure of the fibers [14–19]. Although this method was initially developed to increase the electrical conductivity of the carbon composite, it may also increase the bonding strength via the increased surface roughness generated by the exposed fibers. In this study, the adhesion characteristics of the glass composite adhesive joint prepared by the soft layer method were investigated. Cost-effective and reusable thermoplastic was adopted as a soft layer that effectively exposed glass fibers on the surface and increased the bonding strength without additional surface treatment. The thermal properties of the thermoplastic soft layer were measured to determine the curing condition of the glass composite adherend. The adhesion characteristics of two types of composite adherends, unidirectional glass fiber composite and plain weave glass fiber composite, were investigated and compared. In addition, the adhesion characteristic of the fiber-exposed fabric type glass composite was investigated with respect to the fiber exposure ratio (FER), from which the optimum FER to maximize the bonding strength was suggested.

2. Experimental

2.1. Fabrication of the fiber-exposed composite adherend

High Density Polyethylene (HDPE, Namil Enpla, Korea) sheet of 2 mm-thick was selected to expose glass fibers on the composite surface whose properties are shown in Table 1. HDPE is inexpensive and easy to recycle compared to the Fluorinated Ethylene Propylene (FEP) release film, which was adopted in the previous studies. The soft layer method with FEP release film requires high curing pressure to expose fibers because the release film should yield in order to be squeezed between two fibers. On the contrary, HDPE sheet can function as the soft layer at lower curing pressure by heating up to softening temperature, which is below the damage temperature of epoxy matix. Therefore, the thermal properties of the HDPE were investigated using a differential scanning calorimetry (DSC, DSC 204 F1, Netzsch, Germany) instrument and a thermomechanical analyzer (TMA, Thermo Plus Evo II, Rigaku, Japan) to investigate the melting temperature and the softening temperature. The heating rate of DSC measurement was 10 °C/min, while air and nitrogen gas were used as purge gases at flow rate of 20 ml/min. Softening temperature was measured by TMA using the penetration probe method at a heating rate of 5 °C/min under 0.5 N load. As shown in Fig. 1, the melting point and the softening temperature of HDPE were measured to be 133 °C and 129 °C, respectively. Therefore, under the temperature range of 120–130 °C, HDPE can be adopted as a soft layer because the range ensures HDPE to be soft enough to squeeze out resins while not reaching the melting point.

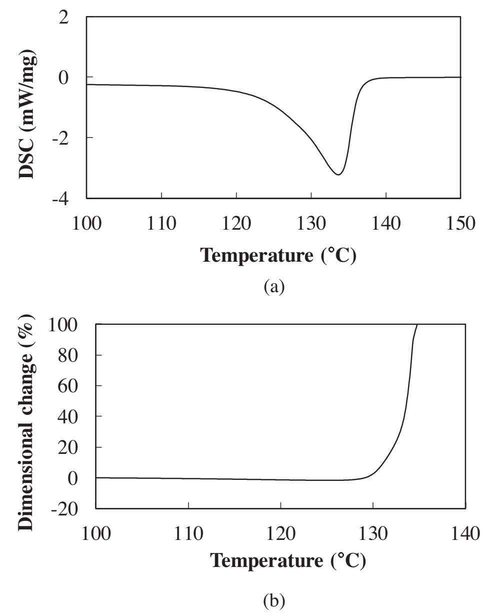

Fig. 1. Thermal properties of the HDPE soft layer: (a) DSC; (b) TMA.

Glass/epoxy composite adherends were used to investigate the adhesion characteristics of the fiber-exposed adhesive joint. Two types of glass composites, unidirectional glass fiber/epoxy composite prepregs (UGN 150, SK Chemicals, Korea) with stacking sequence $[0]_{14}$ and plain weave glass fabric/epoxy composite prepregs (GEP 118, SK Chemicals, Korea) with stacking sequence $[0]_{12}$, were adopted, whose mechanical properties are shown in Table 2. The same epoxy resin (K51, SK Chemicals, Korea) was used as matrices in both prepregs. The DSC curve of the epoxy resin is shown in Fig. 2. The onset temperature is 132 °C, and an exothermic peak appears at 147 °C.

Based on the thermal properties of the HDPE soft layer and curing condition of the epoxy resin, the fabrication temperature was determined to be 125 °C. The glass composite adherends were fabricated via the soft layer method using a hot press, as shown in Fig. 3. The unidirectional glass fiber composites were cured at 0.6 MPa for 1 h while curing pressure was varied for glass fabric composites. In addition, composites were fabricated via the conventional peel ply method for comparison, where non-coated

Table 1
Mechanical properties of the HDPE (25 °C).

Young's modulus (GPa)	3.8
Tensile strength (MPa)	30.8
Failure strain (%)	900
Density (kg/m^3)	961

Table 2
Mechanical properties of the glass/epoxy composite.

	Unidirectional glass fiber composite (UGN 150)	Plain weave glass fabric composite (GEP 118)
E_1 (GPa)	43	21
E_2 (GPa)	14	21
G_{12} (GPa)	4.4	3.5
ν_{12}	0.3	0.15
Thickness (mm)	0.12	0.14