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유리섬유 강화 열가소성 복합재료의 굽힘성에 대한 연구
A study on the bending process of glass fiber reinforced thermoplastic composite

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Abstract

Glass fiber reinforced thermoplastic composite materials have considerable promise for increased use in low cost high volume applications because of the potential for processing by solid phase forming. However, the forming characteristics of these materials have not been well known. The primary focus of this research is the investigation of the bendability of these composites and spring-back phenomena in pure bending. The materials tested contained 20, 35, and 40 percent by weight of randomly oriented glass fiber in a polypropylene matrix. The bending tests were performed at temperatures ranging from 75 ℃ to 150 ℃ and at punch speeds of 2.54 ㎜/sec and 0.0254 ㎜/sec. The measured bendability and spring back angle in pure bending were compared with the predictions based on the simple analytical models. Good agreement between experimental and analytical results was observed.

Key words: Solid phase forming(고상성형), bendability(굽힘성형성), thermoplastic composite(열가소성 복합재료)

1. Introduction

Glass-fiber-reinforced polymeric composite provides the desirable properties of high stiffness and strength as well as low specific weight. Hence, they have become some of the most important materials in several industries, most notably the automotive and aerospace industries[1-3]. As a result, the study of the material behavior and forming techniques of such composites has attracted considerable attention in recent years[4-6]. One of the most promising forming techniques for thermoplastic composites is solid-phase forming[7,8]. Solid-phase forming is a forming process in which the part is formed at temperatures between the glass transition temperature and the melting temperature of a polymer matrix. The major advantages of solid-phase forming are very short cycle time and good surface finish[9].

Bending is the most common type of sheet forming operation. Pure bending produces compressive stress on the inner surface and tensile stress on the outside of the bend. Bending around the a small radius can lead splitting or buckling in the early stages of a forming process because it localizes strain and prevents its distribution throughout the part. Many researchers have investigated the distribution of stresses and strains within sheet, thinning of the sheet, buckling and/or necking of the sheet, movement of material fibers within the sheet, and spring-back phenomena in the bending process.

Even though many studies have been done on laminate composite materials, very few have focused on random directional glass fiber reinforced thermoplastic composites. Therefore, this research has been focused on investigating the bendability and spring-back phenomena of these composites.

2. Experimental Investigation

The materials used for the tests were random glass fiber reinforced polypropylene composites. The average glass fiber length and diameter were reported by the manufacturer to be 12 mm and 11 ㎛ respectively. Composite sheets with glass fiber weight fractions of 20%, 35%, and 40% were used for the tests. The

(a)

(b)

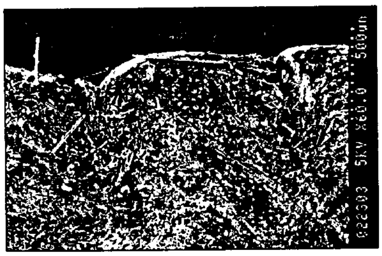

Fig. 3: SEM micrographs of the buckling of the bent (a) 20% and (b) 40% glass contents.

given by Van Krevelen[11]:

$$\gamma_s = \gamma_{so}(1 - T/T_{cr})^{11/9} \qquad (2)$$

where γ_{so} and T_{cr} are the imaginary surface tension at 0 °K and critical temperature of the polymer. The values of these parameters are reported for polypropylene as 47.2 mN/m and 914 °K by Wu[12].

3-1-2. Mechanical strain energy due to layer buckling

In the case of a layer fixed at both ends, the critical buckling stress can be expressed as[13]:

$$\sigma_{cr} = \frac{\pi^2 E_f h^2}{2l^2} \qquad (3)$$

Therefore, the strain energy to buckle a delaminated layer, B_ϵ, is then obtained by assuming that the layer is elastically deformed:

$$B_e = \frac{V\sigma_{cr}\varepsilon}{2} = \frac{\pi^4 E_f h^2}{3l^2} \qquad (4)$$

where V is the volume of the section considered.

3-1-3. Total buckling energy and deformation energy

From Equations (1) and (4), the total energy for buckling a layer, T_e, can be obtained as follows:

$$T_e = S_e + B_e = 2lw\gamma_s + \frac{\pi^4 E_f h^5 w}{18 l^3} \qquad (5)$$

The deformation energy of this layer can be obtained from the integration the stress-strain curve:

$$D_e = whl\int_0^{\varepsilon} \sigma_{cr} d\varepsilon \qquad (6)$$

In this analysis, l and h values are chosen to be 1 mm and 0.16 mm for 20% and 1 mm and 0.105 mm for 35% and 40% glass materials. These values are average values of thickness and length of the buckles measured in tested specimens. If the total buckling energy T_e due to bending of the sheet is in some percent range of deformation energy D_ϵ, then the layer will be considered to be buckled.

3-2. Spring-back angle

The analysis model described here to predict spring-back angle is based on plane strain analysis. The coordinate system used for the analysis is shown in Fig. 4. In this figure, r and z are the radius of curvature to the mid-plane and the distance of an element from the mid-plane and d_z is an increment in distance of an element.

From the yield criterion for a rotationally symmetric material and the flow rule associated with the incompressibility, the flow stress in plane strain will be:

$$\sigma_x = \sqrt{\frac{(1+R)}{(2R+1)}}\, X \qquad (7)$$

where the parameter R represents the ration of the width strain to thickness strain and X is the yield stress in a uniaxial tension test. The total bending moment of the sheet is found from the assumption of a net external force of zero.

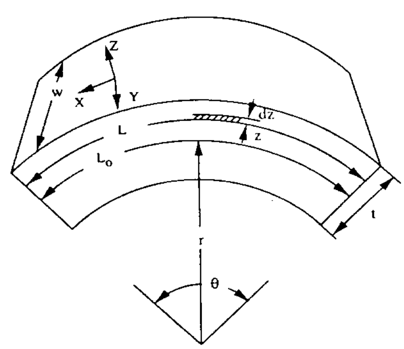

Fig. 4: Coordinate system used for bending analysis.

Table 1: Dimensions of Puch and die.

Punch radius(r_p)(mm)	3.18, 6.35, 9.53
Die profile radius(r_d)(mm)	9.53
Die gap(d_g)(mm)	36.58
Punch depth(mm)	12.7

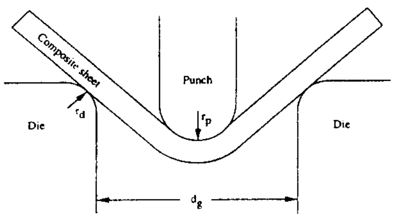

Fig. 1: Punch and die geometry used for bending test.

thickness of the sheet was 3.81 mm for the 20% glass and 2.54 mm for 35% and 40% glass contents.

The punch and die geometries are shown in Fig. 1. The dimensions of the punch and die are summarized in Table 1. The bending tests were performed with 3 different punch radii to investigate the bendability and the spring-back phenomena of the composites. Two different punch speeds, 2.54 mm/sec and 0.0254 mm/sec, have been chosen to study the effects of forming speed on the bendability and spring-back phenomena. The testing temperature was varied from 75 ℃ to 150 ℃ with 25 ℃ increments to investigate the temperature effects. The specimens were examined for the presence of buckling after being bent to a punch depth of 1.27 cm, since no gap was observed at this punch depth for any specimen. The spring-back angle was measured from the difference in the bent angles of a part before and after unloading.

3. Method of Analysis

The buckling and spring-back phenomena are very important issues in the bending process. The analytical works have been done to predict the buckling and the spring-back angle of the composites.

3-1. Buckling of the inside layer

Buckling of the inside surface layer is one of the most common defects occurring in the bending process. It reduces the mechanical strength of composites and also makes a rough surface on the formed part. Therefore, buckling of the inside layer should be avoided. When a composite sheet is bent, the sheet initially will behave like a homogeneous elastic beam while the shear stresses between the layers to build up. The model used here assumes that there are some layers in the sheet which are composed of a fiber rich region and a matrix rich region due to the manufacturing process of the sheet and/or inhomogeneities of the composite materials. This model also assumes that buckling results from both surface tension between layers and a buckling of a layer[10]. Fig. 2 shows these two steps. Buckling will occur on the inside of the bent sheet as a result of increasing compressive stress. Buckling of a layer found in the bending experiment is shown in Fig. 3 for 20% and 40% glass contents composites. Unlike other buckling models in solid mechanics, no predelamination assumption is required in this model.

The total energy causing inside layer buckling is the sum of the surface energy required to delaminate into two surfaces, and the mechanical strain energy required to buckle a delaminated layer, as shown in Fig. 2. These two energies can be obtained separately based on simple models and superposed together to calculate the total energy required to initiate buckling of a layer during forming.

3-1-1. Surface energy required for delamination

When a portion of a layer delaminates, two new surface areas are created with each surface having an area of length(l)×width(w). Then, the surface energy S_e can be written as:

$$S_e = 2lw\gamma_s \quad (1)$$

where γ_s is the surface tension between the layers. The surface tension of a polymer at temperature T is

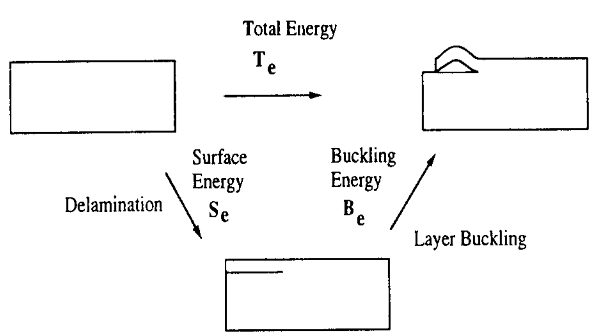

Fig. 2: Two steps of buckling and total energy causing a buckling

$$M=\int_{-t/2}^{t/2} w\sigma_x z dz = 2\int_{0}^{t/2} w\sigma_x z dz \quad (8)$$

where t is the thickness of the sheet.

As described by Gardiner[14], when the external moment is released, the internal moment will vanish. For the elastic unloading stage, the change in stress is proportional to the change in strain. The changes in strain cause a change in bending moment:

$$\Delta M = 2w\int_{0}^{t/2} \Delta\sigma_x z dz = 2w\int_{0}^{t/2} E_f\left(\frac{1}{r_b}-\frac{1}{r_a}\right)z^2 dz$$

$$= \frac{wE_f t^3}{12}\left(\frac{1}{r_b}-\frac{1}{r_a}\right) \quad (9)$$

where r_b and r_a are the radius of curvature before and after spring-back respectively. Since $M-\Delta M=0$ after spring-back, the radius of curvature after spring-back can be obtained from Equations (8) and (9). From the relation of the radius and the flank angle of wrapped region before and after unloading, the spring-back angle can be calculated.

4. Numerical Analysis

The finite element method(FEM) is used to model the bending process. For this purpose, the FEM package ABAQUS has been used[15]. Only half of the bent part need to be modeled due to symmetry. The 4 node plane strain element CPE4 is used to model the composite sheet. The IRS21 interface element with Coulomb friction is used to model the contact region between the tool and workpiece.

5. Results and Discussion

Measured and computed buckling limit maps are shown in Fig. 5. Good agreement was observed between the analytical results and experimental results. These composite materials are very susceptible to failure in the compressive deformation, as micro buckling of thin layer occurs easily during compressive deformation. This micro buckling leads to macro buckling as the compressive deformation increases. Tested specimens are separated into three groups; they are not-buckled, micro buckled, and macro buckled specimens.

A good bent part can be obtained by choosing optimal forming conditions for 20% glass fiber reinforced composite. In general, analytical and experimental results indicate that the optimal forming condition for 20% material is above the temperature of 75 ℃ and a punch radius of 6.35 mm for this material. However, poor bendability is observed for 35% and 40% materials.

A simple bending theory was also applied to

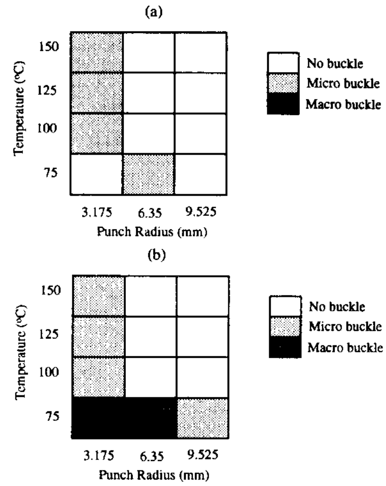

Fig. 5: Comparison of bendability of (a) measured and (b) predicted buckling for 20% glass content.

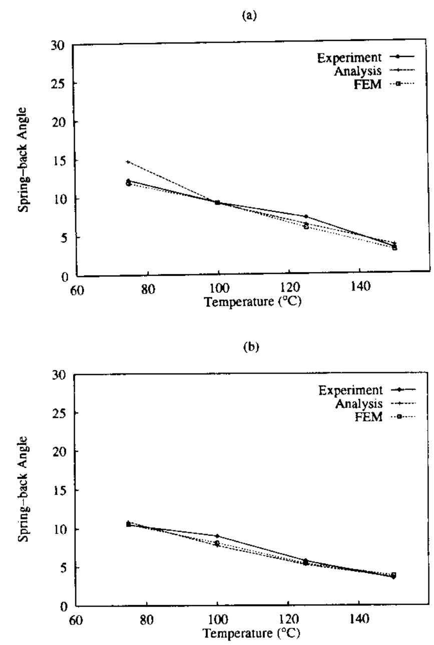

Fig. 6: Comparison of computed and experimental spring-back angles for the 35% glass composite at punch radius 9.53mm and punch speed (a) 2.54 mm/sec and (b) 0.0254 mm/sec.

predict the spring-back angle of glass fiber reinforced polypropylene at elevated temperatures. This model is capable of approximately simulating the spring-back angle over a wide range of punch radii and temperatures. Comparisons of the computed and experimental spring-back angles of 35% glass fiber reinforced polypropylene composite sheet at four different temperatures are shown in Fig. 6. This figure show that the analytical and FEM models capture the main trends of the spring-back angle.

6. Conclusion

A buckling theory and a simple bending theory were applied to predict buckling and spring-back angle of the glass fiber reinforced polypropylene. Good agreement between experimental and analytical results was observed.

The bendability map is presented as a tool for identifying good forming conditions as well as visualizing the effect of forming temperature and punch radius on buckling. Based on the experimental and analytical results, for 20% glass content material, when the ratio of the punch radius to sheet thickness R/t is larger than 1.67 and forming temperature is above 75 ℃, the sheet can be successfully bent at any punch speed tested. Further when the ratio R/t is larger than 2.5, this sheet material can be successfully bent at any temperature and punch speed tested. For 35% and 40% glass content composites, the only conditions under which the material was consistently bent without large buckles was with the ratio R/t larger than 3.75 and forming temperature between 100 ℃ and 125 ℃. In general, 35% and 40% glass reinforced composite materials may not be suitable for simple bending at any temperature for the range of punch radii tested. Stretch bending would be needed to avoid buckling with these materials.

Experimental and analytical results show that the spring-back angle strongly depends on the forming temperature. As the forming temperature increases, the spring-back angle decreases and spring-back angle also increases with increasing punch radius and glass content.

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