논 문
한국정밀공학회지 제15권 제3호 (1998년3월)
Journal of the Korean Society of Precision Engineering Vol. 15. No. 3. March. 1998.

유리섬유 강화 열가소성 복합재료 판재의 굽힘성에 관한 연구

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An Investigation of the Bendability of Glass Fiber Reinforced Thermoplastic Composite Sheet

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ABSTRACT

유리섬유 강화 열가소성 복합재료는 고상성형법에 의해 저렴한 가격으로 큰 부피의 제품의 제조에 널리 사용될 수 있어 아주 좋은 전망을 가지고 있다. 그러나 이러한 재료의 성형성이나 재료거동의 특성은 아직 잘 파악되지 않았다. 본 연구의 주안점은 이러한 재료의 단순 굽힘에서의 굽힘성형성을 연구하는데 두었다. 실험에 사용된 재료는 임의의 방향으로 위치한 유리섬유를 중량비로 20 %, 35 %, 40 % 함유한 폴리프로필렌이다. 굽힘시험은 75 ℃에서 150 ℃ 사이의 온도에서 25 ℃ 씩 증가하면서 행했고, 펀치속도는 2.54 ㎜/sec와 0.0254 ㎜/sec에서 행했다. 단순 굽힘시험에서 측정된 굽힘성형성은 해석적 모델로 예측한 결과와 비교하였다. 실험결과와 예측결과가 비교적 잘 일치함을 보였으며, 굽힘성 map으로써 성형온도와 펀치반경의 좌굴에 대한 효과를 가시화 함은 물론 좋은 성형조건을 선정할 수 있는 좋은 도구로써 나타내었다.

Key Words : Buckling(좌굴), Simple Bending Test(단순굽힘시험), Formability(성형성), Bendability(굽힘성형성), Solid-Phase Forming(고상성형), 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. Solid-phase forming is a forming process in which the part is formed at temperatures between the glass transition temperature and the melting

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point of a polymer matrix. The major advantages of solid-phase forming are very short cycle time and good surface finish(7-9).

Bending is the most common type of sheet forming operation. Pure bending produces compressive stress on the inner surface of the bend and tensile stress on the outside surface of the bend. Bending around a small radius can lead to splitting or buckling in the early stages of the forming process because it localizes strain and prevents its distribution throughout the part. Many researchers have investigated the distribution of stresses and strains within the sheet, thinning of the sheet, buckling and/or necking of the sheet, movement of material fibers within the sheet,and springback phenomena in the bending process. Soll and Gutowski(10) studied the problem of fiber buckling and wrinkling which was induced by compressive stresses during the right angle bend forming of thermoplastic composites. Bhattacharyya, et al(11) performed vee-bend tests to understand the formability of the fiber reinforced sheets and the parameters influencing their forming characteristics.

Even though many studies have been done on laminate composite materials, very few have been focused on random directional glass fiber reinforced thermoplastic composites. Therefore, this research has been focused on investigating the bendability of these composites. The bending tests were performed at various temperatures and at various forming speeds to understand the bendability of the composite and to find an optimal forming condition. A simple analytical model was derived to predict the bendability in a bending process of the composite.

2. Experimental Investigation

The materials used for the tests were random glass fiber reinforced polypropylene composites (RTC-C-4000-20, RTC-C-3000-35, and RTC-C-3000-40) supplied by the AHLSTROM company in a consolidated sheet form. The average glass fiber length and diameter were reported by the manufacturer to be 12㎜ and 11 ㎛ respectively. Composite sheets with random glass fiber weight fractions of 20 %, 35 %, and 40 % were used for the tests. The thickness of the sheet was 3.81 ㎜ for the 20 % glass and 2.54 ㎜ for 35 % and 40 % glass sheets.

An MTS tension test machine equipped with a RTP high temperature chamber was used for the bending tests. A linear encoder and a load cell were used to measure the punch displacement and load respectively. 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 of composites. Two different punch speeds of 2.54 ㎜/sec and 0.0254 ㎜/sec have been chosen to study the effects of forming speed on the bendability.

Table 1 Pnuch and die geometry for bending tests

Punch Radius (r_p) (㎜)	3.175, 6.35, 9.525
Die Profile Radius (r_d) (㎜)	9.53
Die Gap (d_g) (㎜)	36.58
Punch Depth (㎜)	12.7

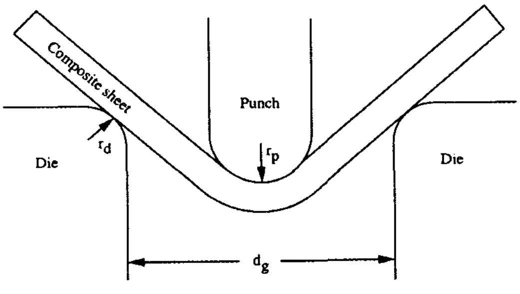

Fig. 1 Pnuch and die geometry used for bending tests

The 50.8 ㎜ × 101.6 ㎜ rectangular shape specimens were cut and machined. Each specimen was kept for 40 minutes in the high temperature chamber to reach the desired temperature before bending. The testing temperature was varied from 75 ℃ to 150 ℃ with 25 ℃ increments to investigate the temperature effects. A gap between the punch bottom and the sheet material was formed above a certain punch depth as shown in Fig. 2. The punch depth without the gap formation depends on the geometry of the punch and die, the thickness of the sheet, and possibly on the material properties. Since no gap was observed for any specimen to the punch depth of 12.7㎜, the specimen were examined for the presence of buckling after being bent to this punch depth. Fig. 3 shows a formed part at this punch depth.

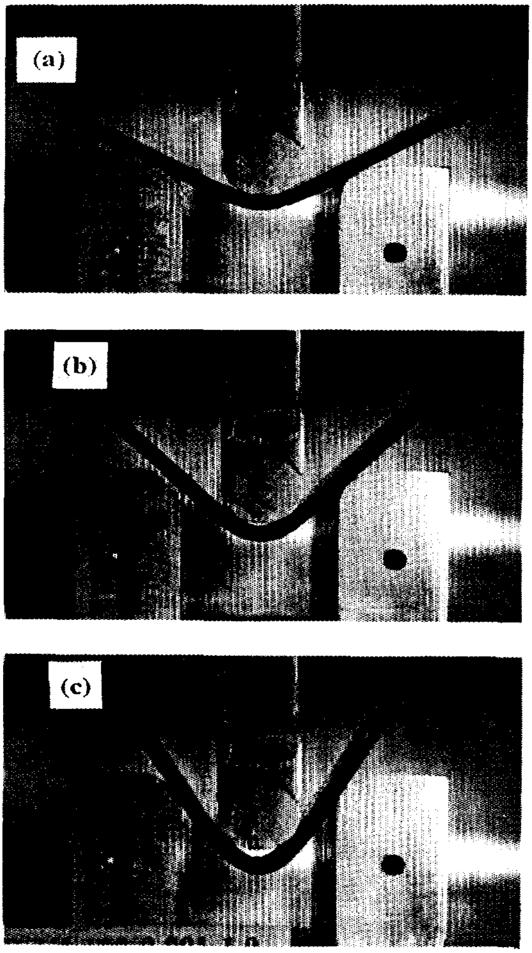

Fig. 2 The gap formation of 20% composite sheet as increasing the punch depth : (a)12.7mm, (b)19.1mm and (c)25.4mm

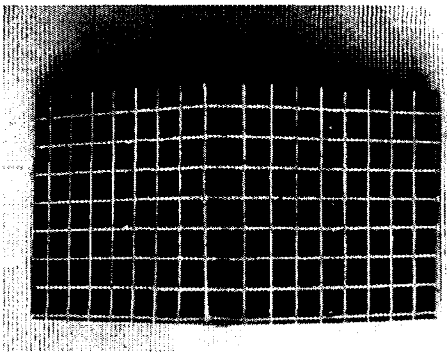

Fig. 3 A photograph of the composite sheet after bending test

3. Method of Analysis

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 at forming temperature, the sheet initially will behave like a homogeneous elastic beam while the shear stresses between the layers start 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 a delamination between layers and a buckling of a layer as shown in Fig. 4(12).

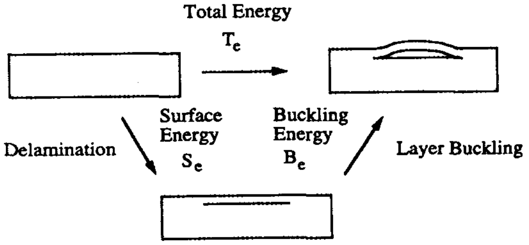

Fig. 4 Two steps of buckling and total energy causing a buckling

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. 5 for 20 % and 40 % composites. Unlike other buckling models in solid mechanics, no predelamination assumption is required in the proposed model. The layers are assumed to be initially perfect, which means that they are free from cracks, delaminations, and any other defects.

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. 4. 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 the forming.

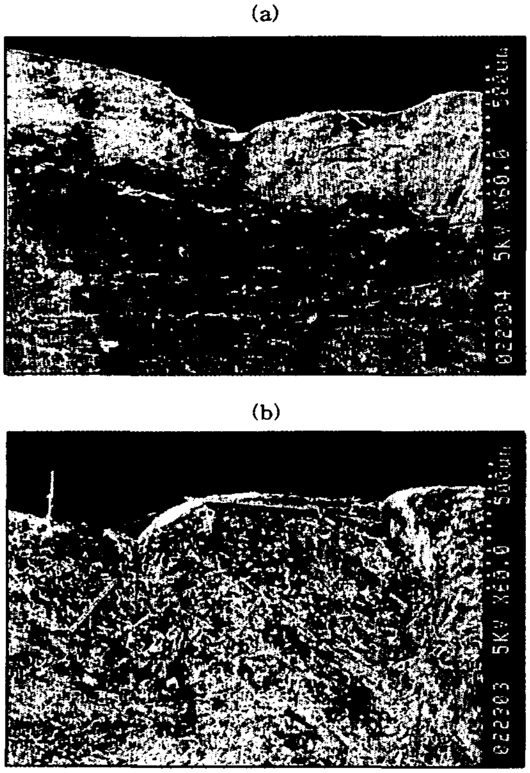

Fig. 5 SEM micrographs of the buckling of the bent part of (a) 20% and (b) 40% glass contents composites

3.1 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:

$$S_e = 2lw\gamma_s \tag{1}$$

where γ_s is the surface tension between the layers. This model assumes that the delamination occurs only in the matrix rich region and goes across the width of the sheet. The surface tension of the polypropylene can be calculated based on the surface tension measured at room temperature. The surface tension of a polymer at temperature T is given by Van Krevelen(13):

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

where γ_{so} and T_{cr} are the imaginary surface tension at 0 °K and the critical temperature of the polymer. The values of these parameters are reported for polypropylene as 47.2 mN/m and 914 °K by Wu(14). The computed surface tensions at the different forming temperatures are summarized in Table 2.

Table 2 computed surface tension at various forming temperature

Temperature (℃)	75	100	125	150
Surface Tension (γ_s)(mN/m)	26.28	24.86	23.47	22.09

3.2 Mechanical strain energy due to layer buckling

In the case of a layer fixed at both ends, the critical load for buckling can be written as(15):

$$P_{cr} = \frac{4\pi^2 E_f I}{l^2} = \frac{\pi^2 E_f h^3 w}{3l^2} \tag{3}$$

where w is the width of the sheet, h is the thickness of the layer, E_f is $E/(1-\nu^2)$ because of plane strain, and I is the 2nd area moment of inertia of a layer. Then the critical buckling stress can be expressed as:

$$\sigma_{cr} = \frac{\pi^2 E_f h^2}{3l^2} \tag{4}$$

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

$$B_e = \frac{V\sigma_{cr}\varepsilon}{2} = \frac{\pi^4 E_f h^5 w}{18l^3} \tag{5}$$

where V is the volume of the section considered.

3.3 Total buckling energy and deformation energy

From Equations (1) and (5), the total energy for buckling a layer, T_e, can be obtained as follows:

$$T_e = S_e + B_e = 2lw\gamma_s + \frac{\pi^4 E_f h^5 w}{18l^3} \tag{6}$$

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

$$D_e = whl\int_0^{\varepsilon}\sigma_{cr}d\varepsilon \tag{7}$$

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

4. Results and Discussion

A buckling theory was applied to predict buckling of the glass fiber reinforced polypropylene. Measured and computed buckling limit diagrams are shown in Fig. 6 and Fig. 7 for 20 %, Fig. 8 for 35 %, and Fig. 9 for 40 % materials. Good agreement was observed between the analytical

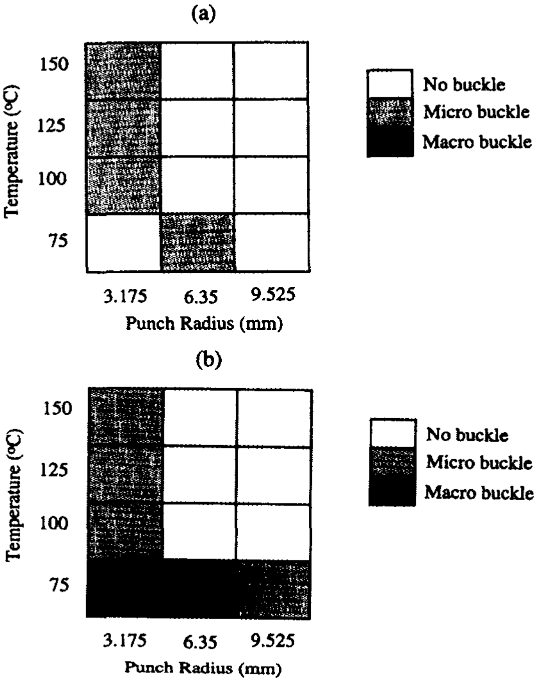

Fig. 6 Comparison of bendability for the 20% glass composite at punch speed 2.54 mm/sec: (a)measured buckling and (b)predicted buckling

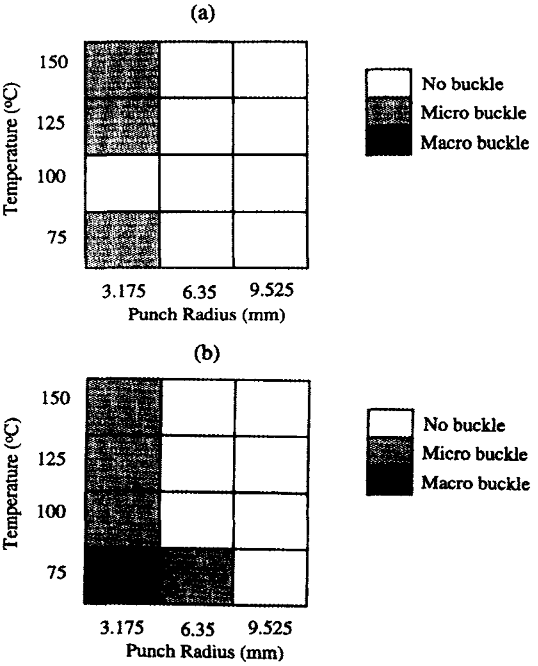

Fig. 7 Comparison of bendability for the 20 % glass composite at punch speed 0.0254 mm/sec: (a)measured buckling and (b)predicted buckling

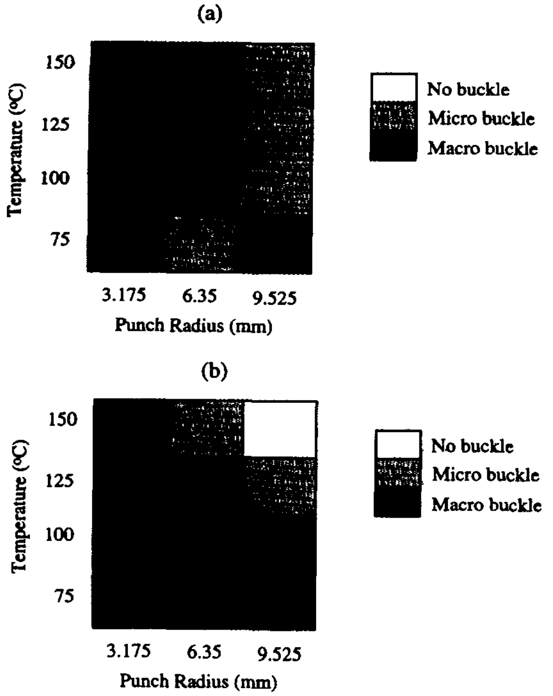

Fig. 8 Comparison of bendability for the 35 % glass composite at punch speed 2.54 mm/sec: (a)measured buckling and (b)predicted buckling

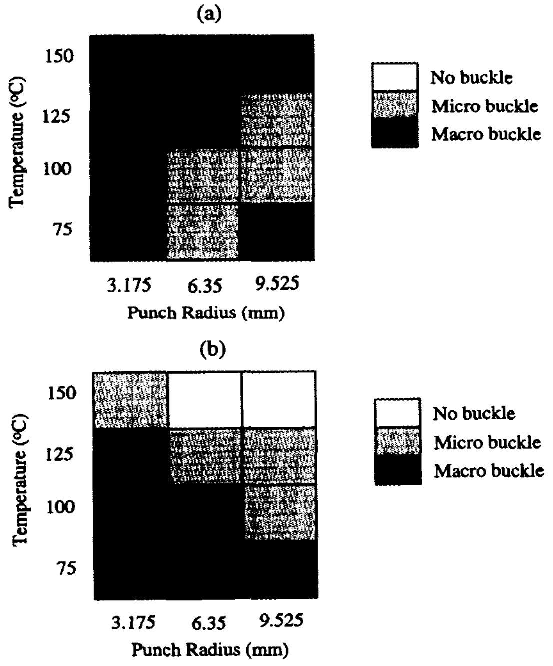

Fig. 9 Comparison of bendability for the 40 % glass composite at punch speed 2.54 mm/sec: (a)measured buckling and (b)predicted buckling

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 (buckled only in a surface region with very small wrinkles), and macro buckled specimens. Since the materials used in this research vary somewhat in their properties(16), it will be more reasonable to define the condition for buckling in ranges. In the cited paper, the variation of measured elastic modulus values reported for random directional glass reinforced polypropylene was approximately ±25 % from the average value(9). For the comparison of analytical results with experimental results, a specimen is considered to be micro buckled when deformation energy is in the range of 75 %~125 % of the total buckling energy. When the deformation energy is below 75 % of the total buckling energy, a specimen is considered to be not buckled. When the deformation energy is above 125 % of the total buckling energy, the specimen is considered to be macro buckled. An example of the computed values for total buckling energy and deformation energy are shown in Fig. 10. This figure shows that the micro buckling will occur only at 75 ℃ because the deformation energy is in the range of ± 25 % of the buckling energy.

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 ㎜ for this material. 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 ℃. It is interesting to note that in none of the bending conditions tested here, it was possible to avoid the micro buckling for 35 % and 40 % glass content materials. However, the analytical approach incorrectly predicted that better bends could be obtained for these materials at 150 ℃. This incorrect prediction may have been due to the overestimation of the buckling energy in the analysis. This overestimation was caused by assuming that the tensile modulus is the same as the compressive modulus. Even though this assumption is not exactly true for these materials, the theoretical and experimental results indicate that the error is larger in the higher glass content materials. Even more error is observed for these materials at higher temperatures.

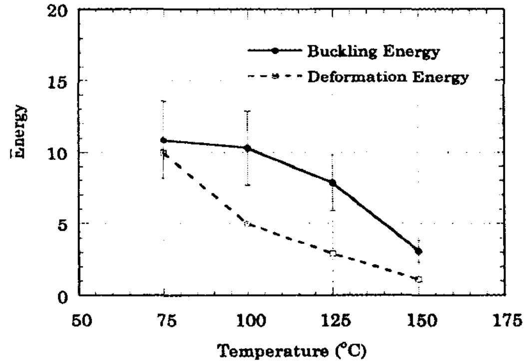

Fig. 10 **Computed buckling and deformation energy at punch speed 2.54 mm/sec and punch radius 9.525 mm for the 20% glass composite.**

5. Conclusion

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. While this model captures the main trends of buckling of these composites, more study is needed to develop a model which can include a delamination rate effect and account for imperfect bonding between fiber and matrix. Because of the variability in material properties, additional data would be required to obtain the bendability maps with confidence.

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. Moreover, when the ratio R/t is larger than 2.5, this sheet material can be successfully bent at any temperature and at any punch speed tested.

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.

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