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열가소성 복합재료의 2축 인장성형시 성형성에 관한 연구

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An Investigation of the Formability of Thermoplastic Composite in Biaxial Stretch Forming

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ABSTRACT

열가소성 복합재료는 고상 성형법에 의해 저렴한 가격으로 부피가 큰 제품의 제조에 널리 사용될 수 있어 아주 좋은 전망을 가지고 있다. 그러나, 이러한 재료의 성형성에 대해선 아직 잘 알려지지 않았다. 본 연구의 첫번째 주안점은 2축 인장성형시 성형성에 대한 연구에 두었다. 실험에 사용된 재료는 임의의 방향으로 위치한 유리 섬유를 중량비로 20, 35, 40% 함유한 폴리프로필렌이다. 성형시험은 75℃에서 150℃사이의 온도에서 행했으며, 펀치 속도는 0.01cm/sec, 0.1cm/sec와 1cm/sec에서 행했다. 2축 인장성형에서 측정된 한계 변형률(Limiting Strain)은 Marciniak 불완전성(Imperfection) 이론에 근거한 예견치와 비교되었다. 이론치와 실험치가 잘 일치함을 보였으며, 성형한계선도(Forming Limit Diagram)로써 결과들을 요약하였다. 성형한계 변형률은 성형온도와 성형속도에 의해 크게 영향을 받는다는 것을 보인다. 이러한 결과들은 적절한 성형조건이 선택된다면 열가소성 복합재료의 인장성형은 실제 상업적으로 이용하기에 충분한 성형성을 갖는다는 것을 보인다.

Key Words: Solid-Phase Forming(고상성형), Formability(성형성), Biaxial Stretch Forming(2축 인장성형), Thermoplastic Composite(열가소성 복합재료), Limiting Strain(한계 변형률)

1 INTRODUCTION

Glass-fiber-reinforced polymeric composites provide 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, 2, 3]. As a result, the study of the material behavior and forming techniques of such composites has attracted considerable attention in recent years[4, 5, 6, 7, 8]. One of the most promising of the forming techniques for thermoplastic composites is solid-phase forming. Solid-phase forming is a process in which the part is formed at temperatures between the glass transition temperature and melting

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point of the polymer matrix. The major advantages of solid-phase forming are very short cycle time and good surface finish[9].

Understanding the formability of a material is of paramount importance in predicting the success or failure of a formed part. When a sheet part fails by the loss of stability and fracture during manufacturing, a common practice in sheet metal forming is either to redesign the part or to change the processing method so that the state of strain in the critical region does not exceed the forming limits. Because a trial and error is very expensive and time consuming, the failure of sheet metal during forming has received a large amount of attention from many researchers. Marciniak and Kuczynski[10] introduced imperfection theory to analyze the loss of stability for sheet metal subjected to biaxial tension. They assumed that sheet material has originally non-homogeneity. This theory overcomes the shortcoming of Hill's local necking theory in explaining the local instability in biaxial deformation[11].

Even though many studies have been done on the stretch forming of metallic materials, very few have focused on thermoplastic composites. One of the characteristics of stretch forming is that sheet material is prevented from wrinkling. This is especially important for long glass fiber reinforced composites because of their inherent tendency to buckle in compressive deformation[12, 7, 13]. It is therefore very important to investigate the formability of this composite in biaxial stretch deformation. Dutta and Cakmak[14] studied the thermoforming of thermoplastic composites experimentally and found good forming conditions for unidirectional and co-mingled knitted three-dimensional fabric composites. Martin *et al.*[15] studied the forming characteristics of fiber reinforced thermoplastic sheets at various forming temperatures and forming speeds. They formed plate laminates into a circular cavity with a hemispherical die and explained the role of material properties in making precise failure predictions. If solid phase forming of thermoplastic composite sheet materials is to become a practical reality, however, more work is needed in this area.

The objectives of this research have been to investigate the formability of thermoplastic composite sheet in biaxial stretch forming. Limiting strains in biaxial stretch forming were explored using the hemispherical stretch forming test. Marciniak's imperfection theory is used to predict the instability in biaxial stretching of composites.

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 mm and 11 μm respectively. The glass transition and the melting temperatures of the matrix were -10℃ and 165 ℃. Composite sheets with glass fiber weight fractions of 20%, 35%, and 40% were used for the tests. The thickness of the sheet was 3.81 mm for the 20% glass and 2.54 mm for 35% and 40% glass sheets.

Parts were formed on a modified double-acting PHI hydraulic press using a hemispherical punch. The punch and die geometries are summarized in Table 1. A servo valve and linear encoder were installed to control the punch movement and to measure the punch displacement respectively. The 30.48 cm square blanks were cut and machined. Blanks were prepared by printing a 6.35 mm square grid pattern onto one surface. To investigate the effects of the punch speed on the formability of the composites, the stretch forming tests were performed at three different punch speeds, that is, 0.01 cm/sec, 0.1 cm/sec, and 1 cm/sec. Sample formed parts at these punch speeds are shown in Figure 1 for 20% glass content composite.

Table 1 Punch and die geometry used for stretch forming tests.

Punch Radius (mm)	49.97
Die Radius (mm)	55.56
Die Profile Radius (mm)	12.70
Clearance (mm)	5.59
Punch Depth (mm)	30, 50, 60

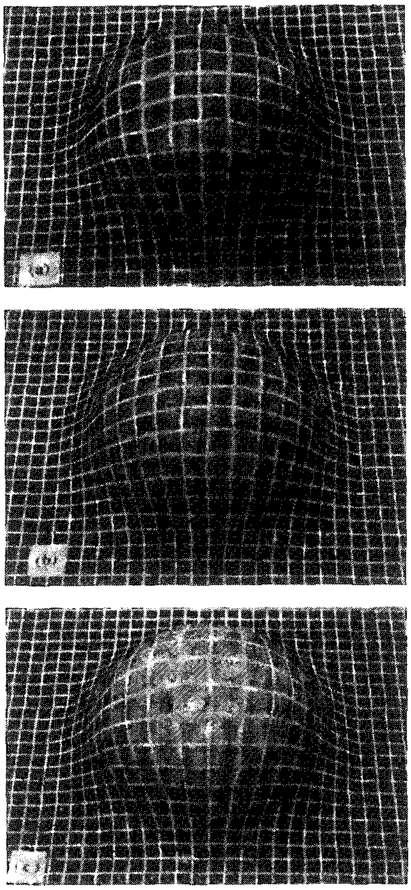

Fig. 1 Sample formed parts of 20% glass material at 100℃ and at punch speeds of (a) 1 cm/sec, (b) 0.1 cm/sec, (c) 0.01 cm/sec.

The blank was held between the die and blank-holder for 30 minutes to reach the desired temperature before testing. To investigate the temperature effect on the forming limit, the stretch forming tests were performed at temperatures ranging from 75 ℃ to 150 ℃ in 25 ℃ increments. The stretch forming tests were performed at three different punch depths, that is, 3 cm, 5 cm, and 6 cm, to investigate the limit strains for each forming condition.

To measure the strains of the formed parts, an automated strain measurement system was used[16]. Figure 2 shows measured major strain contour for a sample part formed from the 20% glass content material.

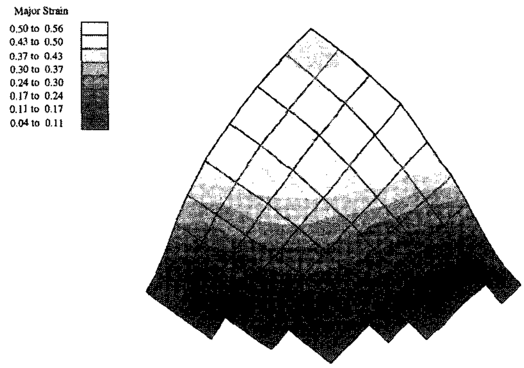

Fig. 2 Measured major strain contour for one quarter of a formed part of 20% glass content material at 100 ℃ and punch speed 0.1 cm/sec.

3 ANALYSIS METHOD

The analytical approach described here is based on Marciniak's imperfection theory[10, 17]. Marciniak and Kuczynski[10] introduced the theory based on the assumptions that the sheet material exhibits normal anisotropy and isotropic hardening. This model is expanded here to take into account both normal anisotropy and strain rate sensitivity for random glass fiber reinforced thermoplastic composites. The basic assumption for plane stress conditions is $\sigma_3 = 0$, with σ_1 and σ_2 are distributed uniformly across the thickness of the sheet. The material used in this analysis is assumed to be incompressible. Incremental plasticity is used in this analysis.

3.1 Formulation

The theoretical analysis of the neck forming process in biaxial stretch forming described here assumes that the composite sheet material shows the same properties in all directions in its plane, but different properties in the perpendicular direction.

Considering a specimen which has an inhomogeneity in the shape of a groove as shown in Figure 3, the following force balance in sections A and B must be satisfied:

$$t_a\sigma_{1a} = t_b\sigma_{1b} \qquad (1)$$

where t_a and t_b are the thicknesses of sheet in sections A and B and the subscript 1 indicates the 1 directional component.

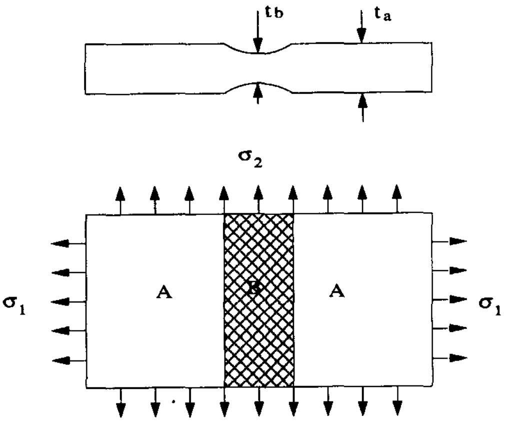

Fig. 3 A description of inhomogeneity of the sheet.

This equation can be rewritten in terms of initial inhomogeneity f and strain rate sensitivity q as:

$$\frac{(\sigma_{1a}/\sigma_{ya})}{(\sigma_{1b}/\sigma_{yb})}\left(\frac{d\varepsilon_a}{d\varepsilon_b}\right)^{q+1} = f\ \exp\left(\varepsilon_{3b} - \varepsilon_{3a}\right) \qquad (2)$$

where σ_{ya} and σ_{yb} are yield stresses in sections A and B, ε_a and ε_b are the representative strains in these sections, and ε_{3a} and ε_{3b} are strains in thickness direction.

The von Mises yield condition with rotationally symmetric anisotropic yield for plane stress state can be represented as follows[18, 19]:

$$\sigma_y^2 = \sigma_1^2 - \frac{2R}{R+1}\sigma_1\sigma_2 + \sigma_2^2 \qquad (3)$$

where R is the rotationally symmetric anisotropic parameter. The flow rule associated with Equation(3) takes the form

$$\frac{d\varepsilon_1}{(R+1)\sigma_1 - R\sigma_2} = \frac{d\varepsilon_2}{(R+1)\sigma_2 - R\sigma_1} = \frac{d\varepsilon_3}{-\sigma_1 - \sigma_2} = \frac{d\varepsilon}{(R+1)\sigma_y} \qquad (4)$$

where the increment of representative strain $d\varepsilon$ can be written in terms of strain components $d\varepsilon_1$ and $d\varepsilon_2$ as:

$$d\varepsilon = \frac{R+1}{\sqrt{2R+1}}\sqrt{d\varepsilon_1^2 + \frac{2R}{R+1}d\varepsilon_1 d\varepsilon_2 + d\varepsilon_2^2} \qquad (5)$$

The incompressibility condition can be written as follows:

$$d\varepsilon_1 + d\varepsilon_2 + d\varepsilon_3 = 0 \qquad (6)$$

From Equations (3), (4), (5), and (6), the Equation(2) can be represented as the following final differential equations.

$$\frac{\sqrt{1-A}}{\sqrt{1-A(d\varepsilon/d\varepsilon_b)^2}}\left(\frac{d\varepsilon}{d\varepsilon_b}\right)^{q+1} = f\ \exp(B\varepsilon - \varepsilon_{3b}) \qquad (7)$$

where

$$\varepsilon_{3b} = \int_0^{\varepsilon_b}\left\{C\sqrt{1 - A\left(\frac{d\varepsilon}{d\varepsilon_b}\right)^2} + D\left(\frac{d\varepsilon}{d\varepsilon_b}\right)\right\}d\varepsilon_b$$

$$A = \frac{2R+1}{(R+1)^2}\frac{\alpha^2}{\alpha^{2}+\frac{2R}{R+1}\alpha + 1}$$

$$B = \frac{\sqrt{2R+1}}{R+1}\frac{\alpha+1}{\sqrt{\alpha^2 + \frac{2R}{R+1}\alpha + 1}}$$

$$C = \frac{\sqrt{2R+1}}{R+1}$$
$$D = \frac{\sqrt{2R+1}}{(R+1)^2} \frac{\alpha}{\sqrt{\alpha^2 + \frac{2R}{R+1}\alpha + 1}}$$

where α is the ratio of strains in the 1 and 2 directions defined as $\alpha = \varepsilon_2 / \varepsilon_1 = d\varepsilon_2 / d\varepsilon_1$. In this analysis, the ratio of stresses, $\sigma_{1a} / \sigma_{ya}$, in section A is assumed to be constant during the entire forming process, and the transverse strains at sections A and B are assumed to be equal, that is, $\varepsilon_{2a} = \varepsilon_{2b}$ or $d\varepsilon_{2a} = d\varepsilon_{2b}$. To solve this differential equation, Newton's iteration method is used[20]. The strain rate sensitivity q in Equation(7) that corresponds to the forming temperature was computed from the material test results reported in the previous work[8]. For a given strain increment in the neck $d\varepsilon_b$, the difference in the strains between the previous step and the current step was monitored to determine the effective limiting strain ε outside the neck. When the difference of the strains is less than 1% of the strain increment in the neck, then the effective strain at the current step is defined as a limiting strain outside the neck.

4 RESULTS AND DISCUSSION

4.1 Necking

Necking is undesirable in stretch forming because it makes the final product very weak and may lead directly to tearing. Necking in stretch forming will occur when the major strain becomes larger than a limit value. The measured strain values in regions with and without necking are plotted in Figures 4-6 with theoretical results at different punch speeds. As the glass fiber content increases, the limit strain values decrease for the same forming conditions. Because the necking in positive biaxial strain states was diffuse, it was often difficult to determine whether or not a neck

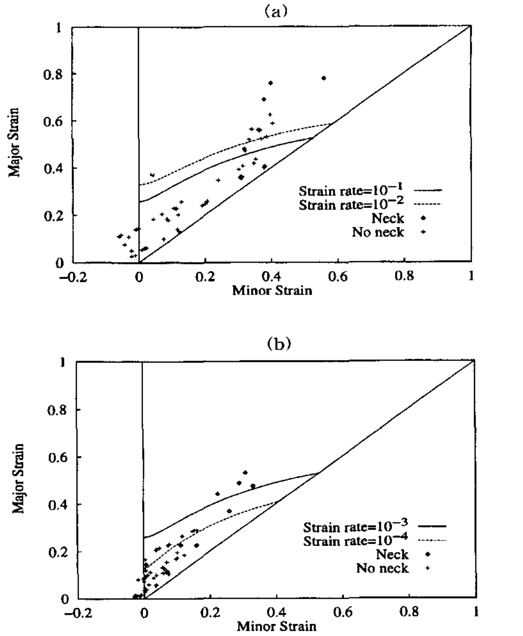

Fig. 4 Measured strains for necked and non-necked regions with theoretical results for the 20% glass composite at 100 ℃ and punch speeds of (a) 1 cm/sec and (b) 0.01 cm/sec.

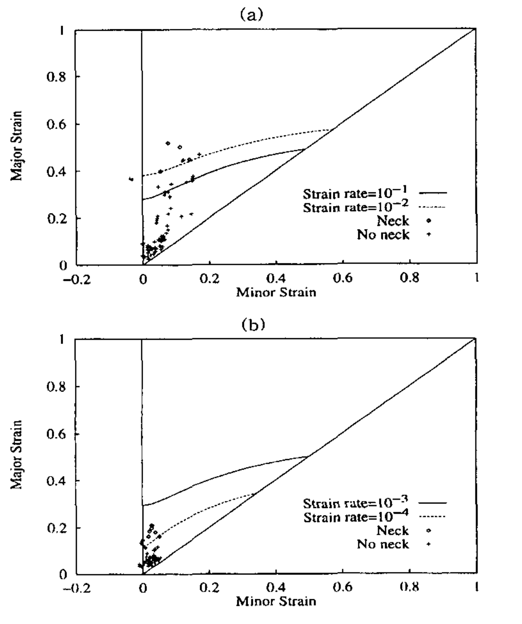

Fig. 5 Measured strains for necked and non-necked regions with theoretical results for the 35% glass composite at 100 ℃ and punch speeds of (a) 1 cm/sec and (b) 0.01 cm/sec.

was present. The criterion used here to determine if a neck existed was the presence of an indentation on the surface of the formed part.

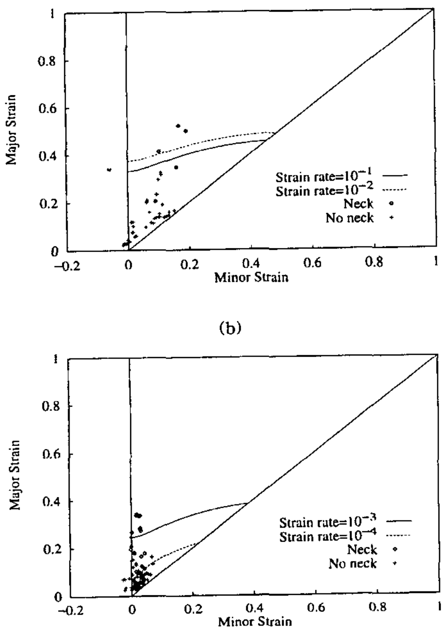

Fig. 6 Measured strains for necked and non-necked regions with theoretical results for the 40% glass composite at 100 ℃ and punch speeds of (a) 1 cm/sec and (b) 0.01 cm/sec.

For a relatively homogeneous material, even a slight change in the imperfection value f has a very strong influence on the process, causing a loss of stability and a dramatic change in the limiting strain. However, the degree of inhomogeneity of the composite materials cannot be measured easily because the inhomogeneity includes the effects of thickness variations as well as the effect of nonuniform fiber distribution and other imperfections. For a comparison of theoretical results with the experimental results, the imperfection value f was chosen to be 0.98. The anisotropy parameter R was set to the average measured values of 1.72 for 20%, 2.12 for 35%, and 3.00 for 40% glass materials. For the forming limit plots, the measured strain rate sensitivity q corresponding to the forming temperature and forming speed was used for the theoretical results. The measured strain rate sensitivity q values reported in the cited work[8] are summarized in Table 2. As in the uniaxial tensile deformation, the limit strains are very sensitive to both the punch speed and the forming temperature.

Table 2 Measured strain rate sensitivity constant q

% Glass Content	Temp. (℃)	Strain Rate (sec^{-1}) $10^{-5} \rightarrow 10^{-4}$	$10^{-3} \rightarrow 10^{-2}$	$10^{-1} \rightarrow 10^{0}$
20	75	-0.906	-0.868	
20	100	-0.947	-0.859	-0.910
20	125	-0.953	-0.904	-0.803
20	150	-0.965	-0.916	-0.835
35	75	-0.910	-0.859	
35	100	-0.966	-0.843	-0.902
35	125	-0.976	-0.909	-0.805
35	150	-0.981	-0.935	-0.832
40	75	-0.938	-0.845	
40	100	-0.972	-0.855	-0.883
40	125	-0.978	-0.923	-0.853
40	150	-0.985	-0.924	-0.876

The influence of strain rate sensitivity on the forming limit curve can be seen in Figures 4-6. As can be seen, the process of local strain concentration becomes slower in the groove region with increasing q values. As a result, the effective strain outside the neck increases with increasing q values. The strain ratio α also has a very strong effect on the limit strain as can be seen in these figures. The increase in the strain ratio α from 0 to 1, that is, from plane strain to equibiaxial strain, causes an overall increase in the limit strain.

The influence of the forming temperature on the forming limit curve can be seen in Figure 7. For a given forming temperature, an optimal forming speed can be observed that leads to the highest limit strain without necking. Similar trends were observed for all three glass contents tested.

5 CONCLUSION

Marciniak's imperfection theory was applied to

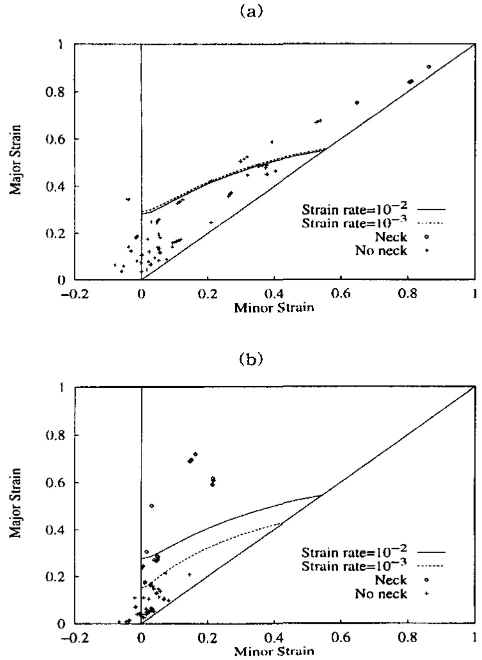

Fig. 7 Measured strains for necked and non-necked regions with theoretical results for the 20% glass composite at punch speed 0.1 cm/sec and forming temperatures of (a) 75 ℃ and (b) 125 ℃.

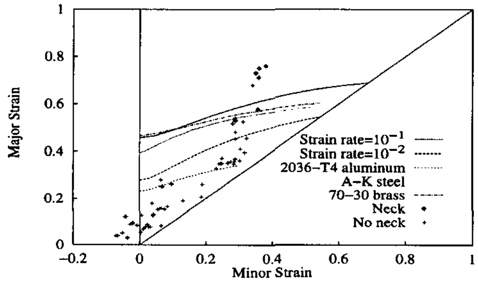

Fig. 8 Comparison of the limit strains of 20% material at 125 ℃ with traditional metallic materials.

predict the necking in the biaxial stretch forming of glass reinforced polypropylene composite sheet. This theory can approximately predict the limit strains based on the computed average strain rate. Because of the comparatively high strain rate sensitivity, localized necking is observed to be significantly delayed under certain conditions, with the maximum limit strains strongly dependent on temperature, strain rate, and principal strain ratio.

The forming limit diagrams were plotted for selected punch speeds and temperatures for the 20%, 35%, 40% glass content materials. This kind of forming limit diagram can be used as a tool for identifying safe forming conditions. While more data would be required to obtain the complete experimental forming limit diagrams, the trends in limiting strain values are well predicted by the analysis presented here. As shown in Figure 8, this material can exhibit formability as good as traditional metallic materials by choosing the optimal forming conditions. The forming limits of the traditional metallic material shown here were replotted from data presented by Ghosh[21]. Results suggest that these composites are very suitable for solid-phase forming in the biaxial stretching mode when appropriate forming temperatures and punch speeds are chosen.

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