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Cold and warm V-bending test for carbon-fiber-reinforced plastic sheet

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Abstract

Although carbon-fiber-reinforced plastics (CFRPs) are the lightest and stiffest material, the use of CFRP is limited because of their higher price and lower formability than the other materials. We propose a method of stamping consolidated CFRP sheets. CFRP sheets are sandwiched by dummy metallic sheets in the stamping process. The dummy metallic sheets act as heating media, as well as protective materials for the CFRP sheets. In this paper, the springback angle of the specimens after the V-bending test under cold and warm condition was investigated and the fractures in formed CFRP sheets were observed.

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Keywords: Bending; Die bending; Plastic; Composite material; Springback; Fiber-reinforced plastic

1. Introduction

Reduction of fuel consumption has been required. High-specific-strength material can achieve reducing the weight to meet the demand. Hayashi and Nakagawa (1994) investigated forming properties of automotive panels such as formability of high-specific-strength material. Sheet forming of high-specific-strength materials have been developed by Kleiner et al. (2003). Hot stamping process reviewed by Karbasian and Tekkaya (2012) can achieve shorter cycle time than that of melting process. However, some defects such as springback occur. Preventing those

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defects and improving low shape accuracy are challenges for the research of high-specific-strength materials. Carbon-fiber-reinforced plastics (CFRPs) are focused on as a kind of high-strength materials. CFRPs have five times smaller density and ten times higher tensile strength than conventional high-strength steels. Goto et al. (2003) investigated on tensile fatigues of CFRP specimens under tensile tests and their mechanical properties such as their high strength and low elongation. Fiber orientation is an important factor for those mechanical properties. Sharma et al. (2009) investigated the relationship between fiber arrangement and mechanical properties. Meanwhile, machining method of CFRP sheets is a kind of research issues. Teri (2002) summarized the machining methods of CFRP. Press forming of CFRP sheets is difficult among those machining technology because of the low elongation. Hot stamping behavior of CFRP consists of thermoplastic resin was investigated by Meyer et al. (2009). The kinds of matrix which consists of CFRP are classified into thermosetting resin and thermoplastic resin. CFRPs consist of thermosetting resin perform higher density of fibers and shorter cycle time using press forming than that of thermoplastic resin. Tough-up epoxy was used as a matrix of the CFRP specimens. CFRPs are now applied for aircrafts as reviewed by Roberts (2007) and luxury automobiles as reviewed by Jacob (2010). Reduction of weight and improvement of safety can be achieved by applying CFRPs for structural materials.

Conventional pressing machine can be applied to the pressing of CFRP sheets. A new forming technique using ductile sheets called “dummy sheets” to support the elongation of CFRP sheet was conducted by Yanagimoto et al. (2012). Those dummy sheets are also used as heating media. The mechanism of supporting the elongation follows the knowledge of multi-layer steel sheets proposed by Oya et al. (2010) under the assumption of friction bonding.

In this paper, the forming method using dummy sheets are applied to form CFRP consist of thermosetting resin. Warm and hot working processes of V-bending tests conducted by Ikeuch and Yanagimoto (2013) are used to examine the formability of the specimen. Temperature dependency and layer arrangement of specimens are examined and discussed to determine the suitable structure of CFRP sheet for pressing.

2. Experimental procedure

2.1. Machine and parameters of V-bending

Specimens are heated by induction heating and pressed by V-shaped punch. The bending radius showed 1 mm at the edge of the punch, and the bending angle showed 90˚ as shown in Fig. 1. The specimen was heated at the rate of 50˚C/s. The temperature was held at intended value in 10 second. And the punch was dropped and held in 30 second. The forming temperature was incremented 50 ˚C between 50 and 250 ˚C.

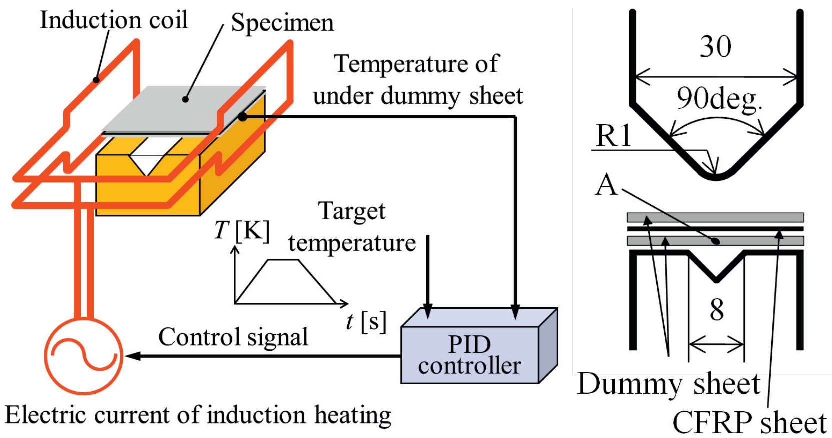

Fig. 1. Schematic of experimental overview and setup for V-bending test.

2.2. Specimen and internal layer structure

The strength of composite materials can be defined by some parameter such as the type of fiber, matrix, and direction of the fibers. Sharma et al. (2009) examined the mechanical properties of laminated CFRP sheet.
Half-cured CFRP sheet called "prepreg" was used. Carbon fibers were arranged unidirectionally inside the prepreg.Curing temperature and volume fraction of the fibers are 130 ˚C and 67%, respectively. The fibers have 5 μm of their diameter and 5 GPa of their tensile strength. The specimens are prepared laminating those prepregs. There are two structures; one has three layers of unidirectional arrangement, and the other has five layers of orthogonal arrangement as shown in Fig. 2. Those structures are shown as "t0.3_angle", "t0.5_0/90", and "t0.5_45/135", respectively. The angle shows the orientation angle between fiber direction and longitudinal direction of each specimen. There are few researches on designing the lamination of prepreg for plastic deformation. The comparison of forming characteristics between unidirectional and orthogonal arrangement of the fibers was investigated in this paper. The length and width of the specimens were 30 mm and 10~15 mm, respectively. Steel sheet called "Steel Plate Cold Commercial (SPCC)" and Aluminum alloy called "duralumin A2024" were used as the dummy sheets. The dimension of the dummy sheets was the same as the specimen of CFRP. We have evaluated the influence on the lamination of the CFRP sheets changing the forming parameters such as forming temperature and forming angle.

3. Results

In this section, visual observation of formed specimens and comparison of the springback angle were shown as follows. Visual observation was conducted to show fractures of the fibers in the formed specimens. Springback angle was conducted to show the elastic recovery under the forming.

3.1. Visual observation

The observation of the specimen during V-bending tests shows that the specimen was not constrained on the dummy sheets. The specimen was moved relatively to dummy sheets except the range around the edge of the punch. Elastic recovery resulted in high springback of the bent specimen. The amount of the springback was changed according to the thickness and fiber arrangement of the specimen. Fig. 3 shows the appearance of the specimen after bending. Some specimens were formed well though those specimens had some wrinkles. Fractures along the fibers can be seen in the figure. Formed specimens under warm condition showed no fractures and small following capability to the die shape. As the forming temperature became higher, smaller bending angle was shown. The bending angle of the specimen formed at 473 K showed nearly 90˚ regardless of the kind of structure.

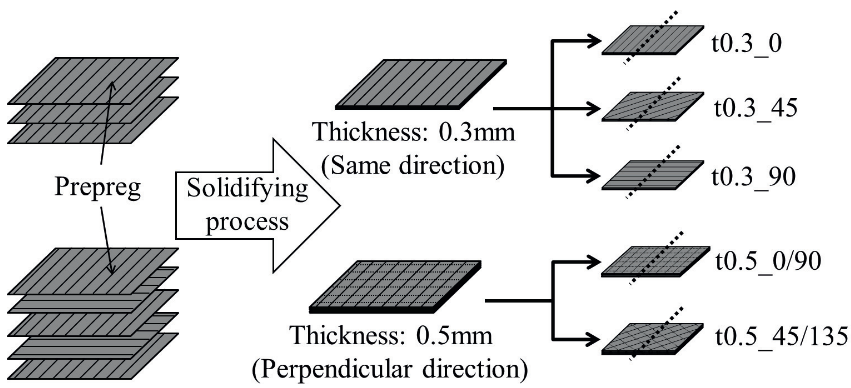

Fig. 2. Schematic of lamination of unidirectional prepreg sheets prepared for bending tests.

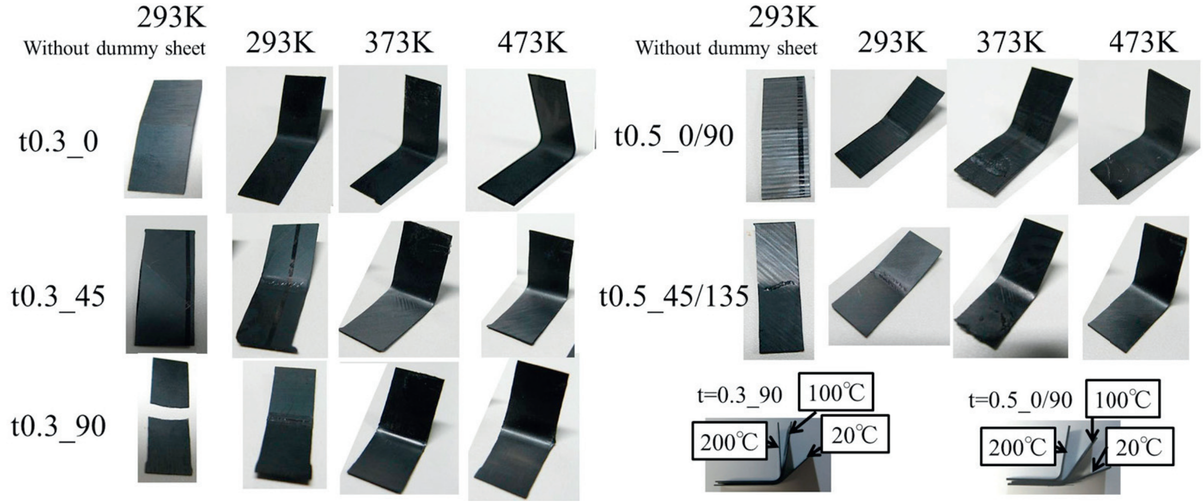

Fig. 3. CFRP specimens after V-bending test.

3.2. Comparison of the springback angle

The bending angle (θ) was evaluated by measuring the average angle between inside and outside surface of formed specimen. Intended bending angle is 90˚. The difference of the angle between θ and 90˚ was defined as springback angle ($\Delta\theta$) for quantitative evaluation.

The relation between forming temperature and springback angle was shown in Fig. 4. The larger orientation angle between the fiber and the longitudinal direction of the specimen become, the smaller springback angle become. As the forming temperature become higher, the springback angle showed smaller, than 10˚ of the minimum angle. If the fibers were arranged unidirectionally, the structure showed anisotropy and lower stiffness along fiber poor direction. The springback angle decreased around 100 ˚C and became almost 0˚ around 200˚C. This is because the matrix of the CFRP sheet was softened and the mechanical properties of the specimen changed along the change of the forming temperature. The orthogonal arrangement such as t0.5_0/90 or t0.5_45/135 showed quasi-isotropy. The influence between bending angle and the springback of t0.5 showed smaller than that of t0.3. The springback of this structure also showed decreasing trend as the forming temperature increased. The springback angle formed at 200˚C showed 30˚ smaller than that at room temperature. When the material of the dummy sheet was changed from mild steel SPCC to aluminum alloy A2024, the springback angle showed comparable level as the angle using SPCC sheets for dummy sheets. When those metal sheets themselves were bent, the angle using A2024 was larger than that using SPCC formed at lower than 100˚C.

3.3. Discussion of the springback angle

The result can be discussed by theoretical value of the springback angle. Eq. (1) shows the theoretical value of the springback as proposed by Yanagimoto et al. (2005). This Equation assumes rectangle cross-section and elastic-plastic body.

$$\Delta\theta = \frac{3}{4}\left\{\frac{3RY}{Et} - 4\left(\frac{RY}{Et}\right)^3\right\}\theta. \tag{1}$$

The variables R, Y, E, and t are the bending radius, yield stress, Young's modulus and thickness of the CFRP specimens. Following the equation, the springback become larger as the thickness become smaller or the strength become larger. The springback angle is defined by the thickness and the stiffness of the CFRP structure. The ratio between yield stress and Young's modulus (Y/E) of CFRP shows 0.021 as shown in Table 1.

Table 1 Mechanical properties of CFRP.

Material	Yield stress (GPa)	Young's modulus (GPa)	Volume fraction (%)	Y/E
Carbon fiber (T700SC)	4.9	230	67	0.021
Epoxy matrix	0.03 – 0.08	1.9 – 4.9	33	0.002
CFRP-UD (CF - Epoxy)	3.3	155	-	0.021

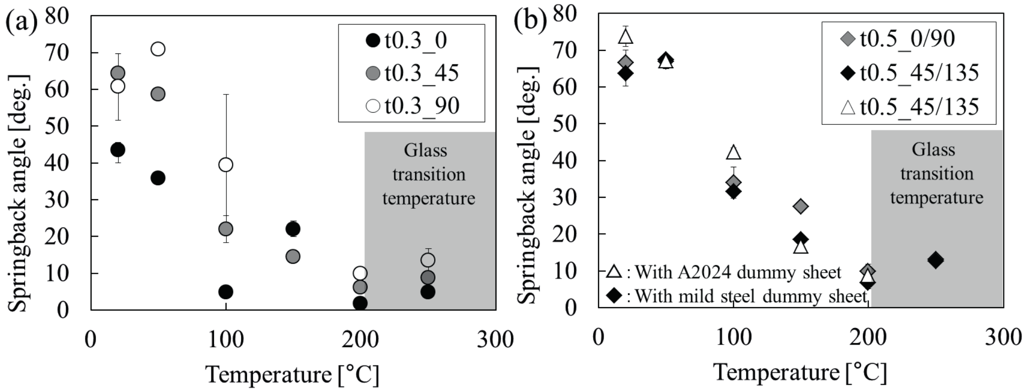

Fig. 4. Relationship between springback angle and forming temperature of CFRP sheets with (a) unidirectional and (b) orthogonal structures.

This value is larger than that of metal materials thus; the springback angle of CFRP is larger than that of metal materials. Temperature influences the stiffness of the structure. If the specimen is formed above the glass-transition point, the specimen can be formed into intended shape. If the specimen is formed at around 100-150 ˚C, the springback became smaller as the temperature became higher. This is because the tensile strength became smaller by softening of the matrix as investigated by Gupta et al. (1985).

3.4. Observation of the bent specimen using optical microscopy

The side-sectional images of the bent specimen formed at 200˚C were observed in order to evaluate internal conditions. White dot pattern in the Fig. 5 shows the cross-sectional surface of the fibers. The specimen of t0.3_0 had no fracture such as disarray or delamination. Compressive area of t0.3_90 specimen showed some disarrays because of the shear force caused by the compression. The load decreased while the fibers were cut and the continuous long fibers became chopped short fibers. This implies that the strength of the bent area needs to be evaluated. The specimen of t0.5 had a delamination at the outside of the bending. Second-outside layer shows the beginning of the disarraying of the fibers. Delamination was shown between the layers. This is because the stresses on the surface of each layer were different and the adhesion on the boundary face was weak.

4. Conclusions

Forming method using dummy sheets has been applied. Then springback angle has been examined.

(1). The CFRP specimens formed with dummy sheets showed fewer fractures than formed without dummy sheets at room temperature.

(2). The relation between forming temperature, structure and springback was clarified. A decreasing trend between forming temperature and springback angle was shown. The angle showed less than 10% when the specimen was heated at higher temperature than 150˚C.

(3). Disarray of the fibers and delamination showed as fractures of CFRP specimens. Further research of evaluation of boundary face is required.

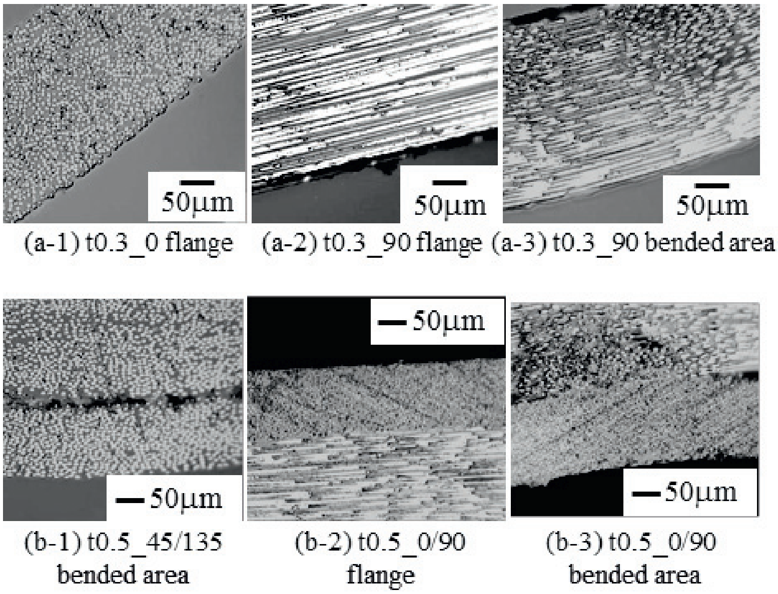

Fig. 5. Observation of bent specimen with (a) unidirectional and (b) orthogonal structures using optical microscopy.

Acknowledgments

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