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Influence of Mechanical Characteristics of Epoxy on the Formability of CFRP Sheets under Different Temperatures

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Abstract

Autoclave-molded CFRP (carbon fiber reinforced plastic) has high tensile strength and thermal resistance. However, the curing process in autoclave molding makes the cycle time extremely long. To shorten the cycle time, various forming methods such as the RTM (resin transfer molding) have been developed. Although the cycle time has been improved with these methods, the strength of the products is inferior to that of autoclave-molded CFRP.

To realize high-speed forming while maintaining a strength equivalent to that of autoclave-molded CFRP, press forming is effective. If a practical and reliable press-forming method for autoclave-molded CFRP sheets is realized, the CFRP production process can be divided into a curing process and a forming process. This means that CFRP can be formed by simply performing press forming on prepared CFRP sheets. Excluding the curing process from CFRP forming will shorten the cycle time.

Press forming requires plastic deformation, but CFRP has poor deformability at room temperature. Therefore, it has been believed that CFRP is a brittle material that is not suitable for press forming. However, recent experimental research has shown that the press formability of CFRP sheets is improved at 100ºC, compared with that at room temperature. This finding indicates the possibility of the press forming of CFRP, but the temperature dependence of the formability of CFRP has yet to be shown. To establish a press-forming method for CFRP, an analytical study of its plastic deformation is essential.

To determine the temperature dependence of the formability of CFRP, the softening of epoxy in CFRP at moderate temperatures was focused on in this study. This is because the mechanical characteristics of the resin have a strong effect on the plastic deformation of CFRP. An approximate curve based on the temperature parameters was constructed to express the stress–strain relationship at different forming temperatures. Then, press-forming simulation models were constructed to consider the effect of the mechanical characteristics of epoxy in CFRP. The approximate stress–strain curves at room temperature and 100ºC was applied to the model. Using this model, the stress distribution in CFRP sheets formed at each temperature has been shown, and the result clearly demonstrates that the formability of CFRP sheets is enhanced at higher forming temperatures.

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These results enable the accurate simulation of the deformation of CFRP sheets, which will help establish a press-forming method for autoclave-molded CFRP. Moreover, our simulation models can be applied to the deformation of various materials that contains thermosetting resin.

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Keywords: CFRP; Formability; Epoxy; Sheet forming

1. Introduction

It has been believed that CFRP (carbon fiber reinforced plastic) is not suitable for press forming, owing to its brittle behavior at room temperature. However, the enhanced formability of CFRP sheets at a moderate temperature was reported by Uriya and coworkers [1-4], who performed press forming on CFRP sheets at different temperatures. An Erichsen test on CFRP sheets was also performed by Uriya and Yanagimoto [4] showed that CFRP sheets at 100ºC have better formability than those at room temperature.

The factors that determine the formability at each temperature are unknown. However, it is considered that the mechanical characteristics of epoxy, which are temperature dependent, are an important factor in enhancing formability. In this study, the temperature dependence of the mechanical characteristics of epoxy is examined.

The stress–strain relationship of epoxy shows nonlinear behavior, and the mechanical strength decreases as temperature increases. Moreover, epoxy shows strain-softening behavior at moderate temperatures. Hasan and Boyce [5] showed the mechanism of the deformation of glassy polymers based on the concept of free volume regions in the polymer, which lead to strain-softening behavior. Miyano et al. [6] showed the effect of physical aging on the creep deformation of epoxy by performing experiments at different temperatures. To express these characteristics, we introduced a new formulation. We carried out a forming simulation using this formulation, and the results are compared with those obtained experimentally by Uriya and Yanagimoto [4]. From the results, the difference in the shear stress at room temperature and 100ºC is shown, and the effect of shear stress on the formability of CFRP is discussed.

2. Modeling

2.1. Free-volume-dependent component of stress–strain relationship for epoxy

Hasan and Boyce [5] illustrated the deformation mechanism of glassy polymers. Free volume regions, which allow local shear deformation, are scattered in the polymer. In the early stage of deformation, stretched molecular chains flow into the free volume, and the size of the deformable free volume regions sharply decreases. As the strain is increased, the regions with lower free volume become accessible for deformation and the mechanical behavior becomes increasingly nonlinear. When the elastic strain energy can no longer be stored in the polymer, new free volume regions are created to store further energy, and strain-softening behavior is observed.

According to this mechanism, the size of free volume regions decreases, and then increases. Thus, the effects of the free volume on the stress–strain relationship for epoxy can be expressed in the shape of an arch. In this study, the normal distribution curve was introduced to model the effect of the free volume,

$$\sigma_{\mathrm{fv}} = \frac{2k}{\sqrt{2\pi}\mu} \exp\left(-\frac{2(\varepsilon-\mu)^2}{\mu^2}\right), \tag{1}$$

where μ is the strain where free volume reduce to its minimum.