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Development of optical-heating-assisted incremental forming method for carbon fiber reinforced thermoplastic sheet—Forming characteristics in simple spot-forming and two-dimensional sheet-fed forming

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ABSTRACT

The aim of this study was to develop an incremental forming method for carbon fiber reinforced thermoplastics (CFRTPs) using an optical heating system. The developed forming machine was mainly composed of a vertically articulated robot to control the position of the blank sheet on the *X-Y* plane, a reciprocating mechanism to generate the reciprocating motion of the forming punch, an electrical cylinder to control the position of the reciprocating mechanism, and a halogen lamp for local heating. Discontinuous short-fiber CFRTP work sheets with thickness of 0.5, 1.0, and 1.5 mm were used for the experiment. Each work sheet was fixed to a blank holder and locally heated by a halogen lamp set under the work sheet. The heated region of the work sheet was formed using the reciprocating motion of a spherical forming punch with a punch radius of 0.5, 1.5, or 2.5 mm, which was located on the opposite side of the halogen lamp. In order to evaluate the fundamental forming characteristics of the developed system, simple spot-forming was performed without feeding a work sheet on the *X-Y* plane. The work sheet temperature was set to 200 °C at a distance of 3.0 mm from the optical axis of the halogen lamp for each work sheet thickness. This study examined the relationship between the pushing distance of the reciprocating forming punch to the work sheet and the forming height, which was the distance between the top of the formed concave portion and the flange region of the work sheet. The forming height was lower than the pushing distance of the forming punch, and this tendency was conspicuous when the work sheet was thin and the punch radius was small. Fractures in the formed part were caused by excessive thinning of the work sheet due to the tensile deformation at the sidewall of the formed shape. The symmetrical shape profile of the formed part following the forming punch shape could be obtained when the pushing distance did not exceed 7.0 mm with a work sheet thickness of 1.5 mm and punch radius of 2.5 mm. The shape profile of the formed product obtained by two-dimensional sheet-fed forming was also estimated to evaluate the advantage of the developed method. The forming characteristics in the two-dimensional sheet-fed forming were different from those in the spot-forming. The continuous formed shape according to the sheet-feeding path could be achieved by the two-dimensional sheet-fed forming, and the advantage of the developed method could be experimentally clarified.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) are widely used as structural materials for industrial products and construction because of their superior characteristics such as a low specific gravity, a high specific strength, and excellent corrosion resistance. Kaufmann et al. (2016) focused on these mechanical characteristics and proposed a bicycle seat post made of CFRP with built-in light and sensor. Song and Yu (2015) also focused on the corrosion resistance and investigated the fatigue performance of corroded reinforced concrete beams strengthened with CFRP sheets. Generally, CFRPs are roughly divided into carbon fiber reinforced thermosets (CFRTSs) and carbon fiber reinforced thermoplastics (CFRTPs). CFRTSs, which use a thermosetting resin as a matrix material, are generally used as the materials for CFRP products. Stefaniak et al. (2012) experimentally identified the process parameters inducing warpage in the autoclave process for CFRTS products. Kappel et al. (2011) investigated an analytical simulation strategy for warpage during the CFRTS autoclave process. Nele et al. (2016) investigated the

Abbreviations: CFRP, carbon fiber reinforced plastics; CFRTP, carbon fiber reinforced thermoplastics; CFRTS, carbon fiber reinforced thermosets; RTM, resin transfer molding

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Nomenclature

C_s	Spring constant (N/mm)	l_f	Fiber length (mm)
d_p	Pushing distance (mm)	L_f	Forming limit (mm)
f	Reciprocating frequency (Hz)	R_p	Punch radius (mm)
F	Feed rate of work sheet (mm/s)	S_c	Cam stroke (mm)
h_f	Forming height (mm)	t	Work sheet thickness (mm)
		V_f	Fiber volume content (%)
		τ	Reciprocating retention time (s)

optimization of the autoclave cycle for thermoset resin to achieve high-performance composite parts. Poodts et al. (2014) investigated a resin transfer molding (RTM) process for thick CFRTS products and achieved products using RTM with a mechanical performance comparable to products produced by the prepreg and autoclave process. On the other hand, CFRTS requires a long cycle time to form the product shape, and products are considered unrecyclable.

In contrast, CFRTP can achieve high-cycle forming using dies and sheet material. Thus, many studies have been performed to investigate forming methods for CFRTP sheets. Tatsuno et al. (2017) evaluated the influence of the cooling rate on the mechanical strength of a CFRTP sheet in the press forming, and clarified the relationship between the cooling condition and flexural strength of CFRTP sheets. Hineno et al. (2014) examined the fiber deformation behavior during the press forming of a rectangle cup using dies. Isogawa et al. (2014) also employed an experimental approach to investigate an isothermal forming system using a hemispherical punch and die for a CFRTP sheet. Soulat et al. (2006) presented a forming simulation of a CFRTP sheet. Continuous fiber sheets were targeted in these studies related to forming methods for CFRTP sheets. Moreover, a CFRTP sheet with discontinuous fiber, which also has excellent mechanical characteristics, has been given attention, and studies of the properties of a CFRTP sheet with discontinuous fiber have been performed. Wan and Takahashi (2016) investigated the tensile and compressive properties of CFRTP sheets with chopped carbon fiber and clarified the influence of the fiber length on their mechanical properties. Yamashita et al. (2017) investigated the damage behavior of CFRTP with discontinuous chopped fiber under lightning strikes and compared it to the damage behavior of CFRTP with continuous fiber. In addition to the previously mentioned advantages of a CFRTP sheet, CFRTP also has high recyclability. Uhlmann and Meier (2017) reported a carbon fiber recycling method using dust from a milling process in an application of short-fiber-reinforced thermoplastics. Takahashi et al. (2007) evaluated the mechanical properties of recycled CFRTP sheets obtained by injection molding. With this background, it is expected that the use of CFRTP sheets will expand in the future. In conjunction with this, a demand for suitable processing methods for small-volume production targeting CFRTP sheets is also expected. Nakagawa et al. (2017) developed a 3D printing dieless forming method using the fused deposition modelling process. This method requires at deposition device and cannot be applied to the sheet material. Walczyk and Hosford (2003) proposed the incremental forming method for composite sheet using a reconfigurable forming tool with discrete elements. The simultaneous forming of a large work sheet area can be achieved for various forming shapes. On the other hand, a complicated system is required such as the controlling system for a discrete element in a flexible die and vacuum system. The diaphragm and interpolator are also required to obtain appropriately formed shape. Le et al. (2008) reported the influence of forming parameters on material formability of the thermoplastic material (polypropylene) by the single point incremental forming method. In this forming method, simplifying the forming system can be expected because the heat energy to generate the plasticity of the thermoplastic work sheet material can be obtained by friction between the rotated tool and the work sheet. However, it is difficult to achieve a formed product with a narrow shape of high aspect ratio because frictional heat can be hardly obtained around the end point of the tool due to very low sliding speed. Moreover, there is the concern about the influence of friction between the rotated tool and the work sheet on the orientation of the fiber when the FRP composite materials are targeted. Ikari et al. (2016) developed a novel shell-shaping method for CFRTP sheets using a localized heating system. In this forming method, a temperature measurement and control system was required, and the temperature of the localized heated region tended to be uneven because the irradiation of the halogen heater was not in a normal direction with respect to the target surface.

Based on this background, this study focused on developing a simple dieless forming method for a CFRTP sheet, using optical heating radiation for one side of the work sheet and forming on the other side of the work sheet without a measurement and control system for the heated region temperature. In addition, the fundamental forming characteristics of the spot-forming technique as a simple forming method were examined, along with the product obtained using two-dimensional sheet-fed forming.

2. Outline of developed forming method

Fig. 1 shows a schematic illustration of the developed forming method. The flange region of the CFRTP work sheet was attached to the blank holder, and the flange region was completely held. The formed part of the work sheet was locally heated by a halogen lamp to obtain the plasticity of the thermoplastic resin matrix. The heated region was formed by a hemispherical forming punch with a reciprocating motion, which was located on the same axis as the optical axis of the halogen lamp but on the opposite side of the sheet. From this mechanism, the optical axis of the halogen lamp was in the normal direction with respect to the work sheet, and punch forming could be achieved in a heated region with a concentric temperature distribution. Moreover, the reciprocating motion helped prevent the cooling of the formed part of the work sheet by heat conduction between the work sheet and forming punch. It also helped prevent the adhesion of the heated resin matrix of the work sheet to the forming punch. This mechanism allowed flexible incremental forming by feeding the work sheet on the X-Y plane and placing the forming punch in the Z direction.

3. Experimental method

3.1. Experimental setup

Fig. 2(a) shows an overview of the developed system, while Fig. 2(b) presents a detailed view of the part labeled as (A) in Fig. 2(a). The

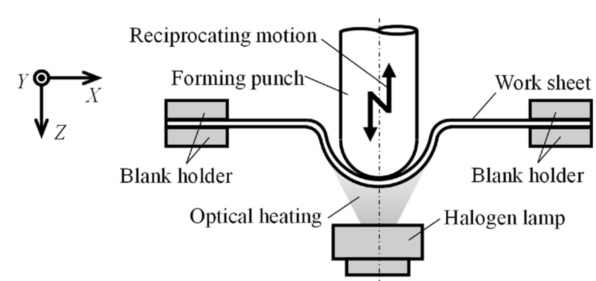

Fig. 1. Schematic illustration of developed forming method.