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Deformation analysis and shape prediction for sheet forming using flexibly reconfigurable roll forming

Jun-Seok Yoon[1], Jeong Kim[2], Beom-Soo Kang*

Department of Aerospace Engineering, Pusan National University, Busan 46241, South Korea

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ABSTRACT

Demand for three-dimensional (3D) curved sheet metals for the manufacture of the skin structures used in various industrial fields continues to increase. Three-dimensional curved sheet metals have generally been manufactured using conventional die forming (CDF) processes, which can ensure forming quality and productivity. However, they are not economically efficient since they incur the additional production costs associated with the development and maintenance of the forming tools. For these reasons, many investigations into alternative flexible forming technologies have been conducted. Flexible forming technologies requiring only one forming die enable the manufacture of 3D curved components while simultaneously resolving the limitations of CDF processes. In this paper, a progressive forming process called "flexibly reconfigurable roll forming" (FRRF), which utilizes adjustable punches and reconfigurable rollers as forming tools, is discussed, together with its detailed mathematical methodology. Using this methodology, curved shapes as well as arcs can be created by adopting conic section curves. This method is superior to existing flexible forming technologies. In this process, the formed shapes are not intuitively predictable since two-dimensional design lines corresponding to the reconfigurable rollers produce a 3D curved surface. To alleviate this limitation, a new predictive model for predicting the deformed shapes of the sheet metal, as derived from the mechanics of plastic deformation considering the law of volume constancy, is described with detailed techniques using a geometrical relationship. The experimental results also demonstrate that the predictive model for the FRRF process can be used to successfully ascertain the deformed shapes of the sheet metal.

1. Introduction

The use of curved sheet metal surfaces has been increasing as demands from both consumers and manufacturers continue to diversify in industries such as automobile, shipbuilding, airplane, and construction industries. The 3D curved sheet metals used for skin structures in such applications have generally been manufactured using conventional die forming (CDF) processes (Olsen, 1980), which involve the use of upper and lower dies that correspond to the final product shape, as shown in Fig. 1. This conventional die forming process remains the ideal process for ensuring forming quality and productivity. However, it is not economically efficient as a result of the additional production costs associated with the development and maintenance of the forming tools (Olsen, 1980). It is also difficult to ignore the limitations imposed by the size and shape of the forming tools. In addition, conventional die forming processes cannot be applied to the small-quantity batch production, which is common in the aerospace and shipbuilding industry.

For these reasons, many studies have been undertaken to identify alternative processes that would allow the manufacture of various shapes while resolving the problems associated with conventional die forming processes. Most of these alternative processes for producing curved sheet metals use only one forming die, thus reducing the effort needed to develop the forming tools and eliminating much of the production cost.

Nakajima (1969) proposed the first alternative forming concept. This technique used a discrete punch. He suggested the use of an automatically reconfigurable die consisting of thin wires bonded together with a retainer. The reconfigurable die could be controlled by the likes of a numerically controlled milling machine. Nishioka et al. (1972) developed a plate-bending machine consisting of a universal press with multiple piston heads, with which they con-

* Corresponding author. Tel.: +82 51 510 2310; fax: +82 51 513 3760.
E-mail addresses: hamjang21c@gmail.com (J.-S. Yoon), greatkj@pusan.ac.kr (J. Kim), bskang@pusan.ac.kr, bskang21@gmail.com (B.-S. Kang).
[1] Fax: +82 51 512 4491.
[2] Fax: +82 51 513 3760.

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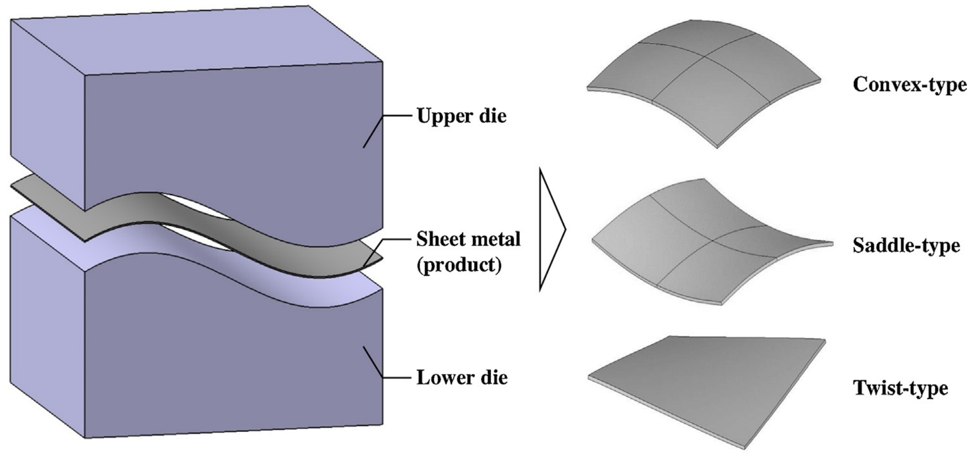

Fig. 1. Conventional die forming of sheet metals, with representative 3D curved shapes (Olsen, 1980).

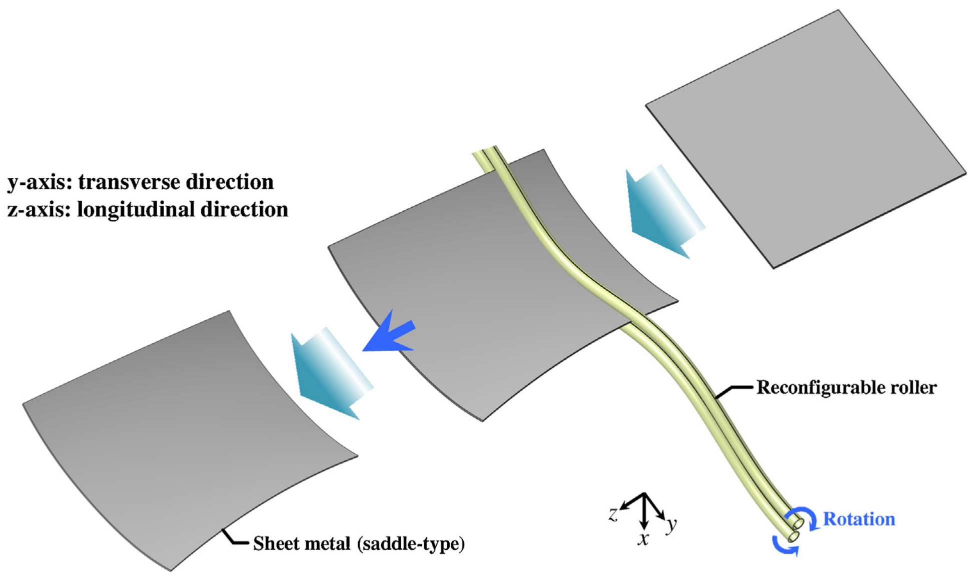

Fig. 2. Graphical explanation of forming procedure.

ducted research related to the hardware of the universal press, in particular the numerically controlled (NC) screw-jack mechanism. Olsen (1980) suggested a discrete die surface (DDS) system controlled by mechanical design and shape control algorithms for the discrete die tooling, which is well known as a type of reconfigurable tooling for flexible forming technologies. Zhang et al. (2006) developed a multi-point sandwich forming (MPSF) process involving a polyurethane upper die, a workpiece, a polyurethane interpolator, a die sheet, and a multi-point die. However, this process suffered from inherent weaknesses owing to the application of non-reusable parts such as the upper die and the die sheet. Yoon and Yang (2005) proposed an incremental roll forming process that employed several rollers moving back and forth across the plate. Park et al. (2000) proposed a fluid dieless forming process that was novel in that it used fluid or elastomer materials instead of a solid die. Li et al. (1999) developed a multi-point forming (MPF) process that uses densely configured discrete punches for the plate and sheet metal. Among these alternatives, called "flexible forming technologies," MPF is the most practical process to the small-quantity batch production since it can reduce the production costs and time required compared with the others. However, further research is required to resolve its limitations, such as the dimples and wrinkles that appear in the formed sheet metal as a result of the irregular gaps between the metal and the discrete punches. To resolve this inherent drawback, Li et al. (2002) devised a method that smoothed the non-continuous forming surface with an elastic pad. Additional studies of the elastic recovery of the material have also been performed to achieve precise shapes through the numerical and experimental approaches (Heo et al., 2012).

Although many alternatives have been devised for producing curved sheet metals, as mentioned above, each process nevertheless presents many limitations. In response to this, a new process called continuous flexible forming (CFF) process for producing 3D curved surface parts, which utilizes adjustable points and three bendable rollers as the forming tools, was introduced with experiments (Hu et al., 2009). Cai et al. (2012) demonstrated the industrial validity of CFF process through experiments and numerical analysis including the effects of elastic behavior. Wang et al. (2014) carried out comparative study of simulations and experiments for reducing the shape error in flexible rolling process which utilizes upper and lower bendable rolls. Cai et al. (2014) demonstrated the feasibility and validity of continuous roll forming (CRF) through analytical equations and experiments. Kang and Yoon (2014) also studied on flexible forming technologies named "flexibly-reconfigurable roll forming" (FRRF) using adjustable punches and two reconfigurable rollers, like that shown in Fig. 2. This process utilizes rollers