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Surface flexible rolling for three-dimensional sheet metal parts

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ABSTRACT

To realize highly effective and continuous fabrication of three-dimensional (3D) sheet metal parts, a new forming method, surface flexible rolling forming, has been investigated. This method takes only two integral flexible rolls as the forming tool. In the forming process, a non-uniform elongation in the rolling direction and a bending deformation in the thickness direction occur simultaneously, and finally three-dimensional surface parts are formed. In this work, the basic principle and forming mechanism of surface flexible rolling are studied. A method to calculate the transversal curvature radius of the arc-shaped roll is brought forward, while the feasibility is verified by the explicit dynamic finite element analysis. An experimental device has been developed and the forming experiments have been performed. Typical 3D surface parts including the convex and saddle surface parts have been obtained. Finite element model of surface flexible rolling is established and the effect of forming parameters such as reduction, velocity, bending radius and friction on the surface shape is analyzed. The forming effects including shape errors and thickness changes are studied by the deviation analysis. The results indicate that the formed surface is quite close to the criteria one; the thickness of the parts changes gradually and keeps within a narrow range. The experimental formed parts are measured and the forming accuracy is investigated. The results show that the accuracy is high, and are consistent with the simulation.

1. Introduction

Three-dimensional (3D) sheet metal parts are widely used in civil and military fields due to their special features such as light weight and good stress state. The die forming is a traditional way to form the parts, which has the advantages of high production efficiency, precision and consistency and suits for mass production. However, the diversity and small-lot trends of the 3D surface products are becoming evident with the development of industrialization. To solve the 3D surface parts of the ship hull plate forming, Yamashita and Yamakawa (1988) made a flexible roll bending test device. The flexible roll is made up of many short rolls arranged along the axis and connected by universal joint mechanisms. During the forming process, the flexible rolls shape a bending profile with many piecewise straight lines, and the roll bending function on the sheet metal leads to the form of the 3D surface parts. The rolls of such device are not continuous and the overall smoothness is poor, making the forming effect not ideal. The incremental sheet forming is a continuous manufacturing method and it is suitable for the small batch productions because of the low setup cost. However, the time needed to form the products is relatively long and the thickness strain caused by local stretching is extremely large. To overcome these problems, Yoon and Yang (2003) put forward an incremental roll forming process that inherits the advantages of the incremental forming process and the roll forming process. The process employs a movable roll set as a forming tool to manufacture doubly curved sheet metals. The roll set consists of one upper motor-driven center roll and two pairs of lower supporting rolls similar to the ball bearing. Since the bending happens at the local contact area just under the upper center roll, the roll set needs moving line by line when the whole region is deformed in the forming process. Thus, the productivity of incremental roll forming is relatively low. In order to enhance the forming efficiency, Kim et al. (2008) changed the form of incremental roll forming and used multiple roll sets arranged in a linear array – the line array roll set (LARS). Each of the roll sets is divided into driving rolls in the central rows and the remaining idle ones in the LARS. The transverse bending of the metal plate is controlled by the configuration of the upper and lower roll sets and the longitudinal bending is regulated by the driving rolls in the central rows and a pair of idle roll rows. The rotation of the central roll array drives the metal plate moving and the doubly curved plates are formed using the friction between the rolls and the plate. Shim et al. (2010) evaluated the quality of the plates produced by the LARS process and found that it is more effective to manufacture a doubly curved plate through a singly curved shape in order to improve the quality of the formed plate. A doubly curved plate can be formed with only one pass using the LARS process. However, the sheet metal is pressed by the individual discrete rolls that cannot swing along the radial direction in the

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LARS process. Therefore, the transverse outline of the formed parts may lack of great smoothness. Li et al. (2007) analyzed and compared the common flexible forming methods and brought forward the surface continuous forming method based on the flexible roll bending process. The process employs continuous flexible rolls as a forming tool and the plate is bent in the longitudinal and transverse directions at the same time. With the rotation of the flexible rolls, the sheet metal feeds continuously and deforms plastically. Li et al. (2012) put forward the continuous forming method based on the rolling process using bended roll. The process employs the integral, smooth and flexible rolls as a forming tool and depends on the bending deformation in one direction and the non-uniform elongation in other directions to realize the forming of 3D surface parts.

Based on the previous works, this paper investigates the influences of the reduction changes on the shape of the parts when the flexible rolls are arc-shaped by means of the numerical simulation and analyzes the shape errors and the thickness distributions through deviation analysis in order to obtain the universal and practical roll radius calculating and shape adjusting methods. Rolling technology is a metal forming process in which metal stock passed through a pair of rolls and the rotating rolls pull the sheet metal into the middle of them by the friction. The rolling force makes the sheet metal deforming plastically. Surface flexible rolling process employs integral flexible rolls as a forming tool and obtains the non-uniform roll gap by controlling the roll shapes. Different sheet metal parts can be formed by the rotation of the rolls under the combined effect of rolling force and the friction. Since surface flexible rolling process needs only two rolls, the device is simple and manageable and can manufacture 3D parts continuously and flexibly.

2. Surface flexible rolling

2.1. Basic principle of surface flexible rolling

The key forming components of surface flexible rolling forming are the integral flexible rolls and the shape-adjusting units as shown in Fig. 1. The flexible rolls generate a bending curvature in the transverse direction perpendicular to the longitudinal rolling direction and can shape a non-uniform roll gap (Fig. 1). The uneven extension caused by the non-uniform gap during the process brings about a curvature along the rolling direction. Under the combined effects of the transverse bending deformation and longitudinal non-uniform extension, the plate is deformed in both directions and transferred continuously along the rolling direction, taking advantage of the rolling force and the friction between the rolls and the metal plate. A schematic diagram of the surface flexible rolling forming process is shown in Fig. 1.

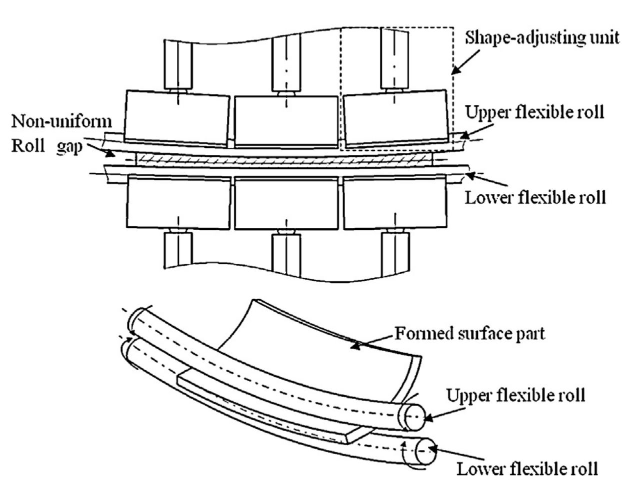

Fig. 1. Surface flexible rolling forming process.

Several shape-adjusting units are set on the rolls according to the forming precision requirements. The units adjust and keep the roll shapes and the gap between the upper and lower rolls to ensure the rotation around the axis.

The roll diameter is as small as possible in order to benefit the adjustment of bending curvatures. The roll materials are highly elastic and strong and they are straight in a free state and can also rotate around the curved axis with a small deflection bending under the restriction of adjusting units.

The roll gap is composed of the roll profiles and its most important feature is non-uniform. Under the effect of such gap, the compressive deformation of the plate in the thickness direction is different at the same cross-section and leads to a different longitudinal extension amount. The key technology of surface flexible rolling is about the design and control of multi-adjusting flexible roll structures. Three-dimensional sheet metal parts with different shapes and dimensions will be obtained if the bending profile of the flexible rolls and the distribution of roll gap are changed.

2.2. Forming mechanisms

During the surface flexible rolling forming process, the transverse bending, the thickness thinning and the longitudinal extension occur. The longitudinal extension differs point to point due to non-uniform distribution of the roll gap. The uneven elongation leads to vertical bending in the case of the presence of a transverse bending deformation due to the continuity of the material as shown in Fig. 2.

Assumed that the direction along the rolling is longitude and the direction perpendicular to it is transverse, the longitudinal and transverse curvatures of the formed parts are ρ_L and ρ_T, respectively; the middle and the side elongations are Δl_m and Δl_s, respectively. If the roll gap is smaller in the middle, the extension of the middle will be bigger than that of the sides, namely $\Delta l_m > \Delta l_s$ (Fig. 2a) and the convex surface parts will be formed, the Gaussian curvature $\rho_L^{-1} \cdot \rho_T^{-1} > 0$. If the roll gap is bigger in the middle, the extension of the middle will be smaller than that of the sides, namely $\Delta l_m < \Delta l_s$ (Fig. 2b) and the saddle shaped surface parts will be obtained, the Gaussian curvature $\rho_L^{-1} \cdot \rho_T^{-1} < 0$. If the roll gap is uniform and the extension at each point is equal, there will be no longitudinal curvature and the cylindrical parts will be formed, the Gaussian curvature $\rho_L^{-1} \cdot \rho_T^{-1} = 0$.

2.3. Appearance analysis of arc-shaped bended rolls

The different roll gap distributions will cause the different longitudinal elongation state of the plate and ultimately affect the whole forming of the sheet metal. The roll gap distribution depends on the morphology of the flexible roll shapes, namely, the roll bending form. According to the geometric parameters and reduction characteristics, various forms of the profile curves of the upper and lower rolls can be drawn, such as circular arc, parabolic function, hyperbolic curve and inverse proportion function. Li et al. (2013) proposed the method to adjust the working roll shape into circular arc for the reason that it is convenient to approximately solve and regulate the shape of roll and also beneficial for both computing and producing. This work further organizes and optimizes it to solve the problem of regulation handily. In this case, the gap distribution is the space between two circular arcs of two non-concentric and different radius circles in a certain length range.