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Study on the continuous roll forming process of swept surface sheet metal part

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ABSTRACT

Continuous roll forming (CRF) is an effective process to manufacture swept surface parts of sheet metal. The forming tool in CRF is a pair of small-diameter bendable forming rolls, a swept surface is formed continuously after the rotating rolls sweep out the whole sheet metal blank. The two bent rolls and the non-uniformly distributed roll gap along the rolls' length make the sheet metal bent in longitudinal and transverse directions simultaneously, the cross-section curve of the formed swept surface is controlled by the curved profile of the forming rolls and the spine curve is controlled by the differential elongations of sheet metal generated by roll gap. In this paper, a necessary condition for the formation of a swept surface is proposed and analyzed, the parametric equations of the formed surface in CRF are derived and the method to determine the roll gap for forming a given swept surface is presented. The numerical simulations and analyses on the CRF processes demonstrate the validity of the presented theoretical models. The experimental and measured results show that the formed surfaces are in good agreement with the desired surfaces, and swept surface parts with good forming precision can be obtained by CRF process.

1. Introduction

As is well known, sweeping is a powerful, efficient and widely used technique in surface geometric modeling for describing the shape of complex surfaces or solids, and a wide variety of three-dimensional sheet metal surface parts in many industrial sectors such as airplane manufacturing, automobile making, shipbuilding, pressure vessel manufacturing or even the fabrication of the cladding and facade of modern architecture are designed with swept surfaces. Nowadays there are more and more demands on such sheet metal parts, especially for the ones produced in single-piece or small-batch quantity, however, the widely used sheet metal forming processes such as stamping, stretching and hydroforming, etc. are only profitable for mass production, the large initial investments and long setup time make them unsuitable for manufacturing small-batch products, and the sheet metal forming process based on the principle of continuous forming and the usage of flexible forming tools will be an effective way to manufacture swept surface parts in the small-batch production.

Continuous working processes such as rolling (Montmitonnet, 2006) and roll-bending (Hua et al., 1997), etc. are characterized by highly productivity and low cost since they do not require any dedicated dies and time-consuming setup operations. Continuous sheet metal forming process combines the continuous forming idea with the flexible forming tools, it may offer highly flexibility, and thus is able to produce sheet metal parts with a variety of shapes and sizes. In recent years, Yoon and Yang (2003) and Shim et al. (2008) have developed a forming process known as the line array roll set (LARS) process, in which multiple adjustable short rolls are arranged in a linear array and three roll arrays are employed as forming tools. The sheet metal is bent by three pairs of roll arrays in the longitudinal direction while it is bent by the configuration made up of the individual short rolls in the transverse direction (Shim et al., 2009). In a later study, they found that, to improve the quality of the formed plates produced by LARS process, it is more effective to form a doubly curved plate through a singly curved shape. Continuous flexible forming (CFF) process for the fabrication of three-dimensional sheet metal parts was proposed based on the idea of roll-bending using flexible rolls (Hu et al., 2009). In traditional roll-bending, straight rigid rolls are used and only cylindrical and conical surfaces can be shaped (Lin and Hua, 2000; Zeng et al., 2008). The CFF process employs three flexible rolls controlled at multiple points as forming tools (Cai et al., 2012). The rotations of the flexible rolls drive the sheet metal feeding and make the sheet metal bent simultaneously in the longitudinal and transverse directions, thus a three-dimensional surface part is formed continuously

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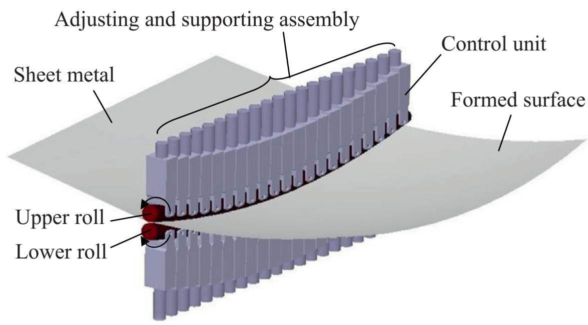

Fig. 1. Schematic illustration of continuous roll forming process.

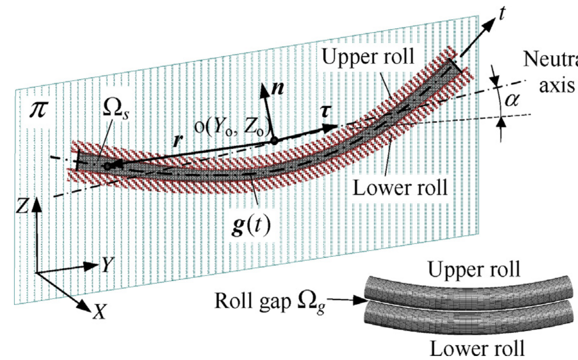

Fig. 2. Roll gap and cross-section of the deformed sheet metal.

with the flexible rolls' rotations (Cai et al., 2013). In CFF process, the flexible rolls act on the sheet metal with continuously distributed pressure, the continuous contact between the rolls and sheet metal leads to a better surface quality and higher forming precision on the formed surface part (Sui et al., 2014).

In both the LARS and the CFF processes, the doubly curved surface part is formed by bending sheet metal in two orthogonal directions, therefore, at least three flexible rolls or three roll arrays have to be employed to make sheet metal bent in the longitudinal direction. More recently, Cai and Li (2013) proposed a sheet metal continuous roll forming (CRF) process for three-dimensional surface parts. CRF is developed based on rolling process, it has a pair of bendable rolls controlled at a series points as the forming tool (Li et al., 2014), and the three-dimensional surface part is continuously formed after the sheet metal passes through the roll gap. In contrast to those in LARS and CFF processes, the forming system in the novel process is greatly simplified and therefore readily controlled since only two rolls are employed in CRF process.

The CRF process is very suitable for the manufacturing of swept surface parts. In this study, the necessary condition for the formation of a swept surface will be discussed and presented in a concise model, the equations of the formed surface of CRF will be derived based on the necessary condition and the approaches to design the roll gap for forming a desired surface will provided. The presented theoretical models and methods will be finally verified by numerical simulated results and experimental results.

2. Roll forming process for swept surface by using two bent rolls

2.1. Description of continuous roll forming process

A schematic illustration of the continuous roll forming (CRF) process of sheet metal is shown in Fig. 1. The forming rolls are a pair of small-diameter shafts, they are straight in their free states and can be elastically bent into the curved shapes with small deflections. The forming roll is piecewise controlled by a shape-adjusting and supporting assembly composed of a series of control units. Each unit controls a point at the forming roll and the unit is positioned in vertical direction by means of feed screw. The bended shape of the roll is configured by adjusting the relative position of each control unit. By use of small-diameter rolls, it is also possible that the rolls revolve on their own bended axes under the action of the applied torque, meanwhile their bended shapes are held by the shape-adjusting assemblies.

The two bent rolls are revolving at the same angular speed but in opposite directions in CRF process, a flat sheet metal is fed into a pair of bent rolls by friction and subsequently compressed between them, the sheet metal compressed by rolls gets bent in both transverse direction (perpendicular to rolling direction) and longitudinal direction (rolling direction), after the forming rolls have moved from one end to the other end of sheet metal, the sheet metal is finally formed into a surface exhibiting curvatures both in longitudinal and transverse directions.

The rolling deformation of sheet metal produced by two rotating rolls decreases the thickness and increases the length of metal fiber. The elongation percentage of material depends on the gap between the two rolls. The smaller the roll gap, the more a metal fiber is reduced in the thickness and the more it is elongated in the length. In order to obtain an uneven distributed roll gap along the rolls' length, the curved profile of the upper roll is a little different from that of the lower roll in CRF process. The non-uniform roll gap leads to a non-uniformly distributed elongation of material across the width of sheet metal. When the elongation distribution is appropriate, the deformed sheet metal will get a longitudinal bending deformation after it passing through between the rolls and thereby be turned into a doubly curved surface.

Geometrically, a swept surface is created by sweeping out a cross-section curve in the plane normal to a spine curve (Salomon, 2006). In CRF process, the cross-section curve of the formed swept surface results from the transverse bending deformation of sheet metal caused by the curved profiles of the upper and lower rolls, the spine curve of the swept surface results from the longitudinal bending deformation of sheet metal, and the longitudinal bending is a consequence of the differential elongations of material across the width of the sheet metal generated by the non-uniformly distributed roll gap.

2.2. Necessary condition for the formation of a swept surface

A non-uniform roll gap may result in flatness defects due to the buckling of the strip during the rolling process (Fischer et al., 2003), and it is undesirable in traditional strip rolling. But when bent rolls instead of straight ones are used in the rolling process, the longitudinal deformation of the deformed sheet metal will be controllable, and a smooth three-dimensional surface instead of a flat sheet with waves or ripples can then be achieved.

The roll gap Ω_g is defined as the space between the curved profile of the upper roll and that of the lower roll, as shown in Fig. 2, it is generally a thin arc area in configuration. The cross-section of the deformed sheet metal is denoted by Ω_s (as shown by the shade area of Fig. 2), it is identical to the roll gap Ω_g in geometry if the elastic deformation of material is omitted.

The transverse curvature of the surface formed by CRF is generally very small and the width-to-thickness ratio of sheet metal is very large, the lateral spreading of the sheet metal is negligible and uniform reduction in thickness can be assumed. Therefore, the plastic deformation of the sheet metal between the rolls can be simplified as plane strain deformation and described by the material elongation produced by the rotating rolls.