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Laser forming of doubly curved plates using minimum energy principle and comprehensive strain control

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ABSTRACT

Forming complex shapes is an important process for many heavy industries such as shipbuilding. The traditional forming method is line heating method, which relies on the worker experience. This paper presents a method of mechanical and thermal forming based on the minimum energy principle and comprehensive strain control. The doubly curved plate is developed into the singly curved shape using finite element method and minimum energy principle based on nonlinear deformation theory. The strain distribution can be obtained through the optimized development process and the laser heating paths are planned according to the comprehensive strain obtained from in-plane and out-of-plane strains. The heating condition is determined using geometrical difference between the doubly curved and the developed singly curved shapes based on the deformation database. The overall methodology is experimentally validated through two kinds of doubly curved surfaces.

1. Introduction

Forming complex shapes is an important process for many heavy industries such as shipbuilding and biomedical implants [1]. A three dimensional (3D) surface can mathematically be classified into two kinds. One is with zero Gaussian curvature all over the surface, which is called singly curved surface, and the other is with nonzero Gaussian curvature somewhere, which is called doubly curved surface [2]. The singly curved surface can be formed by using the process of rolling, while a doubly curved surface involving both in-plane and bending deformations is formed by line heating method which is still largely dependent on the experience of the skilled workers. Moreover, the line heating method often takes days to complete a doubly curved part due to the low forming efficiency of this method. In addition, the worker must suffer from exhaustive heat and air pollution. To overcome the problems of line heating method, a lot of other methods have been proposed such as multipoint forming, roll forming and laser forming [3].

Laser forming, similar with line heating, also uses thermal stress to deform the metal plates. The use of laser makes the prediction of heat distribution easier and more environmentally-friendly. In 3D laser forming, the process parameters including heating path and heating condition (laser power and scanning velocity) should be determined for a desired shape [4]. Hennige [5] used an irradiation pattern consisting of radial and concentric heating paths to form spherical structures. Chakraborty et al. [6] shaped a circular sheet into a bowl also by radial and circular heating paths. They studied the effects of various process parameters on the in-plane and out-of-plane (bending) deformations. These forming strategies highly depend on the researchers' experience and understanding of the forming mechanisms. Abed et al. [7] put forward the heating strategy based on the constant height lines of a surface using the temperature gradient mechanism. Kim and Na [8] proposed two criteria for planning heating paths for laser forming of singly curved plates. One was based on distance and the other was based on angle. They found that the algorithm presented for making bending points and bending angles was simple and not time-consuming. Shen et al. [9] proposed a different method, in which the forming trajectory was generated based on the probability function. However, these studies are more suitable for forming the singly curved surface. Kim and Na [10] presented a method for 3D forming based on geometric information of the workpiece to divide the workpeice into small pieces. However, the relation between the shape and the patches is not clear. Yu et al. [11] presented heating path planning algorithms that was modeled by the in-plane strain from the curved surface to its planar development based on differential geometry. However, they do not provide an explicit method on how to determine heating paths. Recently, Safari et al. [12] came up with a spiral scanning path to fabricate saddle shaped plate. Although this empirical scheme is experimentally investigated under different spiral pitches and scanning numbers, the mechanism why this scanning path could induce a saddle shaped plate is not theoretically explained. The same group [13] also carried out a scanning path composed of several parallel segments to fabricate a dome shaped plate, in which the sequence of scanning segments was elaborately ordered. A numerical research of a spider scanning strategy combined with experimental validation was

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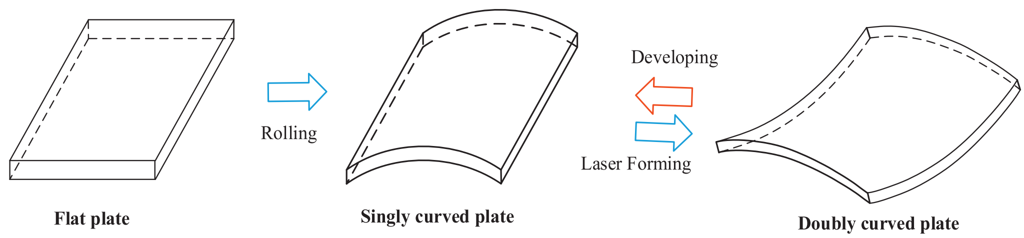

Fig. 1. Doubly curved plate forming process.

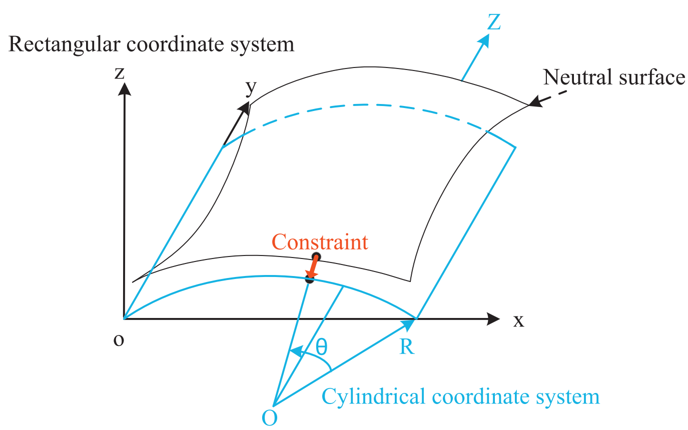

Fig. 2. The constraint of doubly curved surface in development.

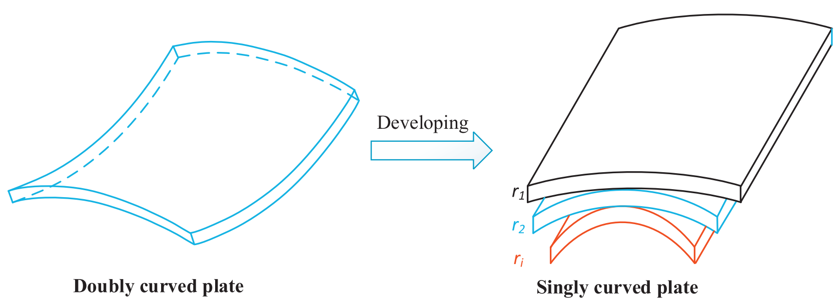

Fig. 3. Developed surface optimization.

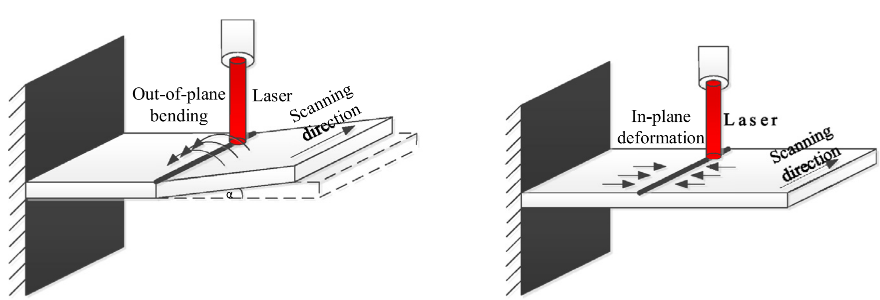

Fig. 4. Laser forming mechanism: (a) TGM: out-of-plane bending; (b) UM: in-plane deformation.

accomplished by Shahabad et al. [14], but the path is still based on a heuristic logic. Liu and Yao [15] used their algorithms to plan the heating paths according to the distribution of in-plane strain. Cheng and Yao [16] proposed a laser process design for 3D thin plates by using the large deformation elastic finite element analysis. The scanning path is generated using minimal principal in-plane strain directions based on the numerically obtained strain field. They clearly presented the way to calculate the strain distribution but do not give a reliable way between the strain distribution and the heating paths.

The studies mentioned above focus on laser forming of 3D shapes from a planar shape, in which the heating path planning is based on the in-plane strain or out-of-plane strain that is generated during the surface development process. The doubly curved shape of the shipbuilding plate in shipyard is commonly fabricated from the singly curved shape that is