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Explorative study of rotary tube piercing process for producing titanium alloy thick-walled tubes with bi-modal microstructure

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ABSTRACT

In order to solve the existing problems in the manufacturing of titanium alloy thick-walled tubes (TATWs), an innovative plastic forming method for the preparation of TATWs using rotary tube piercing (RTP) process was studied. In this paper, the advantages and basic principles of the RTP process were described. A new finite element model is established to study the effect of the thermal parameters on the RTP process of TATWs. Based on the control variable method, two key problems of rolling block and severe temperature rise in the RTP process were all solved, and the TATWs with bi-modal microstructure were produced by the self-developed piercing mill. In addition, the microstructure uniformity of the pierced tube was analyzed. Based on the experimental and numerical investigations, it's found that the RTP process is a viable process for manufacturing TATWs with bi-modal microstructure.

1. Introduction

As a billet for producing hollow structural parts, many titanium alloy thick-walled tubes (TATWs) are demanded in aeronautics, astronautics, energy power, transportation and petrochemical industry [1,2]. Because of the excellent comprehensive performance of bi-modal microstructure, the demand for TATWs with bi-modal microstructure is most urgent [3]. Three methods are most commonly used to produce TATWs: punching, drawing [4] and extrusion [5]. However, these three methods have the following disadvantages: (1) large forming load; (2) low processing efficiency; (3) low utilization of materials; (4) complex manufacturing process [6]. In view of the current processing methods, the demand for modern industrial manufacturing is difficult to meet. Therefore, it is of great significance to develop an advanced processing technology to manufacture TATWs.

Rotary tube piercing (RTP) is an innovative plastic forming process which relies on local and incremental plastic deformation to transform solid billets into hollow tubes. Many scholars have conducted extensive research on the theoretical

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research of RTP process, due to the main advantages of its small forming load, high production efficiency, and high material utilization rate. Romanenko [7] and Zhao [8] studied the evolution law of tube dimension, and proposed adjusting the plug position to improve the dimensional stability of tube. Skripalenko [9] discussed the influence of plug shape on central damage, and Bariani further [10] predicted the crack position of the billet. What's more, Liu et al. [11] performed an experiment on the RTP process of stainless steel, and concluded that shear stress is the reason for the separation defect.

About the application of RTP process to the preparation of TATWs, the predecessors have done some exploratory research. Yajing et al. [12] obtained the Ti–6Al–4V alloy thin-walled tubes at 980 °C, and the ratio (length–diameter) of pierced tubes is about 10. The pierced tube consisted of the fully lamellar alpha microstructure within the beta matrix (widmanstatten microstructure). Jiming et al. [13] found that the optical micrograph map of Ti–6Al–4V alloy tubes obtained at 980 °C is the coarse lamellar alpha microstructure within the beta matrix (widmanstatten microstructure), and the ratio (length–diameter) of pierced tubes is about 10. In summary, the previous experiments were all carried out at higher temperature to ensure the smooth piercing of titanium alloy tube, which leads to the optical micrograph map of the pierced tube was widmanstatten microstructure. The plasticity and toughness of widmanstatten microstructure are poor, which is not conducive to the subsequent processing of hollow structural parts. The bi-modal microstructure, which has excellent comprehensive performance, is the goal we pursue. In addition, previous works can only produce titanium alloy tubes with a ratio (length–diameter) of 10, and there is no report on the thick-walled tubes with a ratio (length–diameter) less than 5. Compared with the thin-walled tubes, the internal expansion of thick-walled tubes is smaller and thus the phenomenon of rolling block is more likely to occur. In this paper, the factors affecting the piercing process are systematically analyzed to obtain the TATWs with bi-modal microstructure.

RTP process is a complex three-dimensional deformation process, and the cost of research using experimental methods is very high. With the development of numerical simulation technology, finite element model (FEM) has become an important tool for simulating the RTP process and its formation. FEM dramatically reduces the required number of test cycles and simplifies the followings: the development of new techniques, research on tube-forming theories, forecasts of model results, and the study of microstructure changes [14–17]. Zhao [18] discussed the influence of feed angle on the force and energy parameters by rigid plastic FEM. Also by using similar method, Yin [19] studied the effect of roll speed on rolling defects by FEM, and the concept of critical speed was put forward. Pater [20] established a three-dimensional FEM considering the thermal phenomena, and explored the influence of process parameters on the deviation of internal and external diameters. Sim [21] adopted the rigid viscoplastic FEM with intelligent remeshing technique to study the distribution of strain and temperature field. In addition, Ding et al. [22] analyzed the distributions of stress, strain, and temperature of AZ31 alloy by FEM, and the magnesium alloy seamless tube was successfully manufactured by RTP method. However, all the models did not consider the change of the plug temperature. In the process of piercing, the temperature of the plug changes greatly and can't be treated as the thermostat. In this paper, a new three-dimensional finite element model which takes into account the change of the plug temperature is established in this paper.

As a two phase alloy which consists of the alpha phase and beta phase, a lot of research about the analysis and characterization of Ti–6Al–4V alloy has been done by the predecessors. Ding [23] studied the effect of double directional solidification technique on the lamellar microstructure of Ti–Al–Nb alloys by means of TEM and SEM. Gao [24] reported the crystallographic orientation evolution of titanium alloy and its dependence on process parameters by electron backscatter diffraction (EBSD) examination. In addition, the XRD technology has been increasingly used for crystal structure analysis. For example, Jandaghi [25–27] explored the crystallographic transformations during constrained groove pressing (CGP) and post-rolling process. By measuring XRD patterns under different deformation paths and different heat treatment conditions, the slip planes were discussed in detail.

In the present study, the numerical and experimental results of TATWs production using RTP method are presented. On the basis of the 3D rigid-plastic FE model of RTP, the effect of process parameters on the rolling block and temperature rise is studied by the control variable method. Finally, the TATWs with bi-modal microstructure are manufactured by RTP method.

2. Theoretical analysis

2.1. *Definition of process parameters*

There are three types of rotary tube piercing method nowadays: disk-type, barrel-type, and cone-type, as shown in Fig. 1a. With the development of RTP process, the application of barrel roll and cone roll is more extensive than that of disk roll. Hayashi proposed that the rotary forging effect of barrel roll was stronger than that of cone roll. The rotary forging effect may be a cause of the initiation of inside bore defects. So, the cone roll is more suitable for forming less deformable material than the barrel roll. The relative position of cone roll is illustrated in Fig. 1b. From the kinematic point of view, the two rolls rotate in the same direction, and the billet does spiral movement under the action of rolls during the RTP process. When the billet passes through the plug, the billet is machined into a hollow tube. There are two important angles in the piercing process of cone roll, one is the feed angle α and the other is the cross angle β. The angle between the roll axis and the rolling line on the horizontal plane is called the feed angle α. Feed angle has a great influence on the piercing speed, and the forward speed of billet decreases with the decrease of feed angle. The angle between the roll axis and the rolling line on the vertical plane is called the cross angle β, which is peculiar to the cone roll. The other three important process parameters are roll speed W, reduction ε and plug advance against gorge C, respectively. During the RTP process, the roll speed and reduction have significant impact on temperature