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Sequential multi-objective optimization of thin-walled aluminum alloy tube bending under various uncertainties

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Abstract: Combining the design of experiments (DOE) and three-dimensional finite element (3D-FE) method, a sequential multi-objective optimization of larger diameter thin-walled (LDTW) Al-alloy tube bending under uncertainties was proposed and implemented based on the deterministic design results. Via the fractional factorial design, the significant noise factors are obtained, viz, variations of tube properties, fluctuations of tube geometries and friction. Using the virtual Taguchi's DOE of inner and outer arrays, considering three major defects, the robust optimization of LDTW Al-alloy tube bending is achieved and validated. For the bending tools, the robust design of mandrel diameter was conducted under the fluctuations of tube properties, friction and tube geometry. For the processing parameters, considering the variations of friction, material properties and manufacture deviation of mandrel, the robust design of mandrel extension length and boosting ratio is realized.

Key words: robust optimization; tube bending; uncertainty; aluminum alloy; multi-objective optimization

1 Introduction

Larger diameter thin-walled (LDTW) aluminum alloy (Al-alloy) bent tubes, as key "bleeding" transforming components, have attracted increasing usage in several fields such as aviation and aerospace [1]. Among many bending approaches, mandrel bending is preferable to realize bending of LDTW Al-alloy tubes with good repeatability. However, the mandrel bending of LDTW Al-alloy tube is a triple nonlinear process. The features of large diameter and low elongation make the bending of LDTW Al-alloy tube much sensitive to the changes of forming parameters, viz, tooling parameters and processing parameters.

To realize precision bending, the strict coordination of various bending tools and forming parameters should be achieved via the deterministic optimization. While, there exist many uncontrollable variables induced by material fabrication processes, tooling manufacturing and bending processes, which may influence the bending quality and forming efficiency. Thus, it is urgently needed to obtain the knowledge on effects of the uncertainties on bending and to achieve the multi-objective robust design of forming parameters for mandrel bending of LDTW Al-alloy tubes.

Many studies have been done on different tube bending processes of various tubular materials. However, most studies focus on the effects of forming parameters on individual defect and few on deterministic optimization, saying nothing of robust design considering uncontrollable variables in bending [1−4]. The tooling setup was designed by the fuzzy logic through tube properties and geometry of bending [5]. Using design of experiments (DOE) and FE methods, XU et al [6] conducted the deterministic optimization of mandrel parameters for LDTW Al-alloy tube bending. Considering multiple defects, LI et al [7] developed a knowledge-based substep method to solve the multi-objective deterministic optimization of LDTW Al-alloy tube bending. However, whether the optimal results by the deterministic design work robustly in mandrel bending of Al-alloy tube is questionable. Robust optimization has become a promising and important technology in product design [8,9]. BAGCHI [8] discussed the Pareto-optimal robust design for solving

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the multi-objective design problems by genetic algorithms (GA). Using multi-objective particle swarm optimization method, SUN et al [9] presented a multi-objective robust Pareto design to consider the roles of uncertainties on draw bead optimization, in which the variations were obtained by the six sigma principle and the surrogate model was formulated by a dual response surface method (RSM). These studies provide the method references for robust design of LDTW Al-alloy tube bending.

This study attempts to develop a suitable method for multi-objective robust design of tube bending under fluctuations in Al-alloy tubes bending process. First, the significance or sensitive analysis of fluctuating factors on multi-index constraining bending quality is conducted via the fractional factorial design and 3D-FE simulation. Then, considering the significant noise factors, the robust optimization design of both tooling parameters and processing parameters are performed using virtual Taguchi's DOE of inner and outer arrays. The experiments are done to verify the robust design methods.

2 Experimental

2.1 Forming parameters and bending quality

As shown in Fig. 1, under multi-tool constraints, the unequal plastic forming occurs during bending, viz, the tension deformation at extrados and compression mode at the intrados. With inappropriate conditions, there may occur wrinkling instability, over thinning (or even fracture) and cross-sectional distortion. The inherent nonlinearity of LDTW Al-alloy tube bending makes its optimization a multi-objective problem with multiple variables and constraints [10−13].

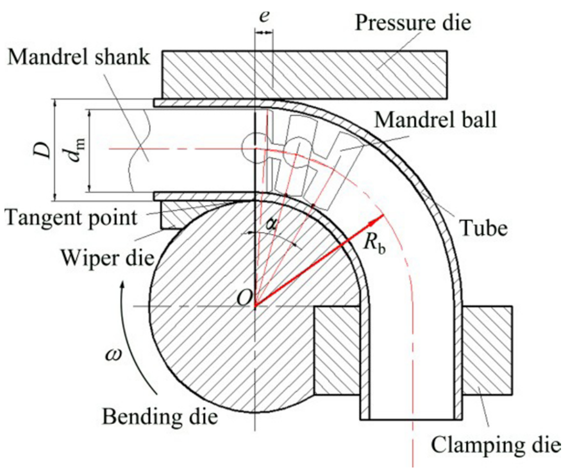

Fig. 1 Schematic of mandrel bending

Equations (1)−(4) show the indexes for bending quality, viz, wall thickness changing degree (thinning T and thickening T_k), cross-section flattening degree Q and wrinkling wave height W. The larger the values of the above indices, the worse the bending quality becomes. Generally, T should be less than 25%, Q should be less than 15% and W should be less than 2%D.

$$T=(t_0-t_{min})/t_0\times100\% \quad (1)$$

$$T_K=(t_{max}-t_0)/t_0\times100\% \quad (2)$$

$$Q=(D_0-D_{min})/D_0\times100\% \quad (3)$$

$$W=D_1-D_2 \quad (4)$$

where D_0 is out diameter; t_0 is original wall thickness; t_{min} and t_{max} are the minimum and maximum thicknesses after bending; D_{min}, D_1, D_2 are the minimum tube diameter after bending, the maximum and minimum section diameter of tube after bending, respectively.

2.2 3D-FE modeling and verification

Figure 2 shows that the whole bending procedure of LDTW Al-alloy tube is modeled based on the Abaqus Explicit/implicit algorithms. The detailed modeling issues can be found in Refs. [6,10]. The experiments are conducted to verify the established 3D-FE model.

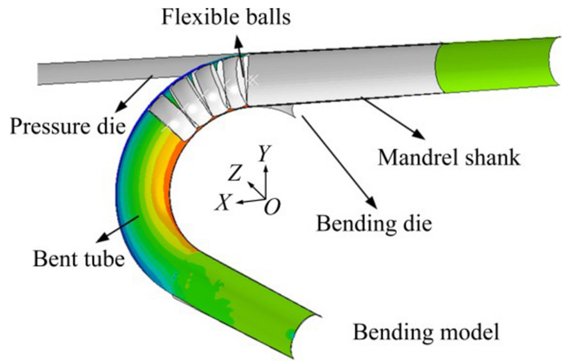

Fig. 2 3D-FE model for mandrel bending

The bending specification is 5052O d50 mm × 1 mm × 75 mm ($D \times t \times R_b$, R_b/D=1.5, where R_b is the bending radius; D is the outer diameter of tube). By uniaxial tension tests, the material properties can thus be obtained as shown in Fig. 3. The twist-compression test (TCT) [14] was used to reproduce the friction conditions between tube and bending tools, and the normal anisotropy exponent is calculated by the ratio of the width strain to thickness strain (see Table 1).

The strain hardening law is $\bar{\sigma}=438.1\bar{\varepsilon}^{0.29}$. Table 2 shows the simulation conditions. Figure 4 shows that the numerical results can reveal the bending characteristics. The maximum deviation is less than 15%. The unconformity is mostly induced by the property variations, friction conditions and instability of loading conditions such as pressure die movements.

2.3 Orthogonal design of experiment

Robust design is a method that uses DOE to improve the robustness of product manufacturing.

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