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Deformation characteristics and process optimization in neck-spinning of variable-diameter tube

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Abstract: Neck-spinning has the advantages of short manufacturing cycle, high process flexibility, good forming ability and low production cost. It has been widely used to produce variable-diameter tubes in automotive and aerospace fields, such as gas cylinders and corrugated tube. However, the neck-spinning is a complex local loading and incremental forming process, which leads to severe local inhomogeneous deformation and the deformation state dynamically changes with loading region. These complex forming characteristics make it very difficult to predict the forming results and optimize the processing parameters in the neck-spinning. This paper reviews some typical advances on the investigations of neck-spinning, including the various deformation state, profile deflection, uneven wall thickness distribution, prediction model for wall thickness variation and process optimization method. Besides, some existing key challenges for the precision neck-spinning were outlined, such as the accurate prediction model for the wall thickness variation, the determination of maximum diameter reduction, the dynamic optimization of roller trace and processing parameters.

Keywords: Neck-spinning; Deformation characteristics; Process optimization; Accurate prediction model; Forming ability

1. Introduction

Neck-spinning is an advanced spinning technology to shrink the diameter of the end or middle part of tube components, as shown in Fig. 1. According to the position of neck-spinning on component, the neck-spinning can be classified into two types: end neck-spinning (Fig. 1(a)) and middle neck-spinning (Fig. 1(b)). The neck-spinning is a near net shape forming method, which has the characteristics of short manufacturing cycle, high process flexibility, high product accuracy, good surface quality and low production cost [1-11]. Thus, the neck-spinning has been widely used to produce gas cylinders, corrugated tube and other variable-diameter tubes in automotive and aerospace fields.

In the process of neck-spinning, spindle drives tubular blank rotate, meanwhile the roller locally loads on the tube and moves with a specified roller trace, as shown in Fig.1(b). Under the roller's incremental local loading, the tubular blank deforms gradually, so as to form the final tube component with variable diameter. Due to the characteristic of incremental local loading, the forming mechanism of neck-spinning is complex. Complex and severe deformation occurs in local region and the deformation state (stress and strain states) dynamically change with loading region during the neck-spinning. These make it prone to produce cracking, uneven wall thickness, profile distortion and other forming quality problems, as shown in Fig. 2 [2,12,13]. On the other hand, due to the process flexibility of neck-spinning, there are many processing parameters influencing the forming mechanism and results, such as roller trace, spindle speed, feed ratio, fillet radius of roller, diameter reduction amount, etc. Especially, the roller trace is a complex multi-pass curves, and there are numerous possible traces to form a same component. These characteristics bring great challenge for optimizing the processing parameters to realize precision neck-spinning.

In recent years, some researchers have conducted investigations on the forming characteristics and process optimization in the neck-spinning of variable-parameter tube, which provide important guidance for the precision neck-spinning. In this article, the forming force, stress and strain state, profile deflection, wall thickness distribution and process optimization in the neck-spinning were reviewed, and some existing key challenges for the precision neck-spinning were outlined.

2. Deformation characteristics of neck-spinning

2.1 Evolution of forming force

Usually, the forming force is a key intuitive reflection index of forming state in metal plastic forming. According to the changing law of forming force, the evolution of deformation state and occurrence of forming defects during forming process can be detected. Besides, the forming force is also an important index for selecting the tonnage of forming equipment. Therefore, some researchers

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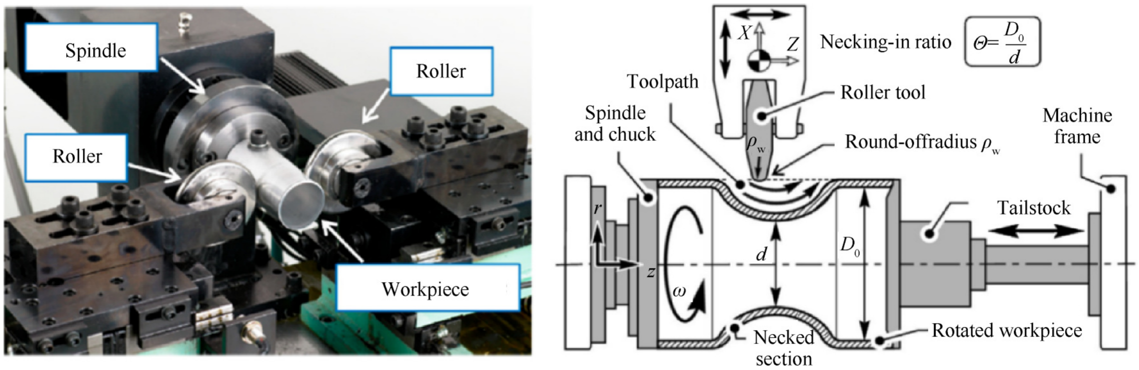

Fig. 1 Two types of neck-spinning: (a) shrink diameter at the end part of tube [4]; (b) shrink diameter at the middle part of tube [6].

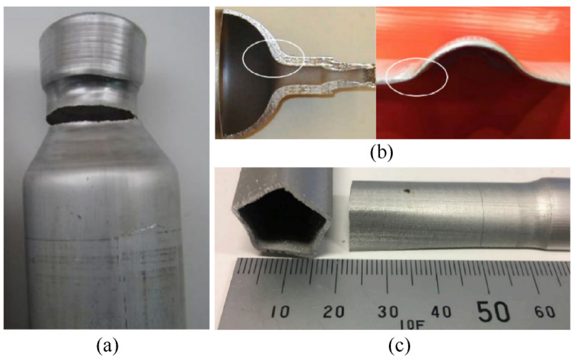

Fig. 2 Common defects in neck-spinning process: (a) crack [2]; (b) uneven wall thickness [12]; (c) profile distortion [13].

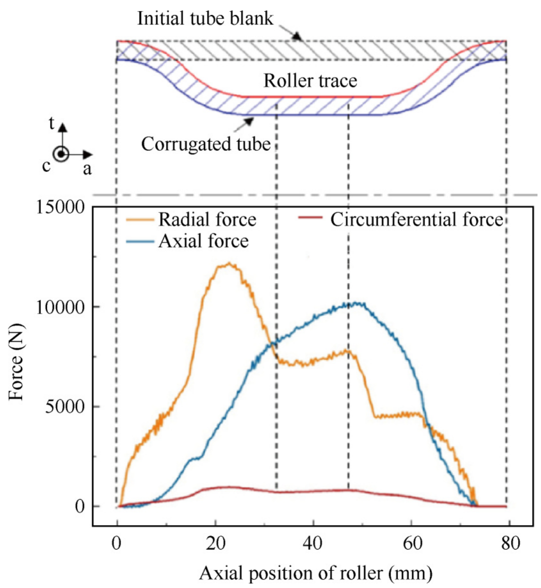

Fig. 3 Evolution of spinning force in neck-spinning of a corrugated tube.

have studied the forming force of neck-spinning [14-17].

The authors have investigated the evolution of spinning force in the middle neck-spinning of an aluminum alloy corrugated tube. During the spinning process, the spinning force was gathered in three directions, i.e., the axial force, the circumferential force and the radial force, corresponding to the a, c, t directions respectively, as shown in Fig. 3. It is found that the radial force and axial force present close load level. The radial force increases in the descent region, then decreases to a steady value in the straight line region, and finally decreases in the ascent region; the axial force increases in both the descent region and the straight line region, and decreases in the ascent region. They are both positively correlated with the diameter shrink amount. This indicates that the deformation state changes with the diameter shrink amount in the neck-spinning of corrugated tube, which will be described Section 2.2. While, the circumferential force keeps in a small level in the whole forming process.

Wang et al.[14] investigated the evolution of spinning force in the end neck-spinning of a Al6062 alloy tube with gradually-decreased diameter, as shown in Fig. 4. It can be seen that the forces in three directions all gradually increase due to the increase of diameter reduction. Besides, the radial force is the largest; the circumferential force is a little smaller than the radial force; and the axial force is the smallest. Therefore, when selecting spinning equipment, the radial and axial forces need more concern[15-17].

2.2 Evolutions of stress and strain states

Stress and strain states usually determine the forming results, such as the wall thickness, wrinkling defect, etc., in the metal plastic forming. For the neck-spinning, due to the complex incremental loading trace, the local loading and constraint conditions both change dynamically during the forming process. This makes the stress and strain states greatly change during neck-spinning, viz., presenting various deformation states in different regions of workpiece, which will then produce complex distribution of forming results. Thus, the evolutions of stress and strain states in neck-spinning has been attracting many concerns[18-26].

Xia et al.[18-19] analyzed the stress and strain states near loading region of roller in the neck-spinning, as shown in Fig. 5. They found that Region A contacted with roller undergoes a three-direction compressive stress state, which produces axial compressive strain, circumferential compressive strain and radial tensile strain. Region C and D both locate in the loaded region. Region C undergoes two-direction compressive stress, which produces circumferential compressive strain and radial tensile strain. Region D undergoes axial tensile stress and circumferential compressive stress, which produces circumferential compressive strain, radial tensile strain and radial tensile strain, respectively. In the unloaded region, Region B undergoes two-direction compressive stress in axial and circumferential directions; while Region E undergoes a one-direction compressive stress state in radial direction. While, Region B and E occurs little deformation.

The authors investigated the stress and strain states in the middle neck-spinning of an aluminum alloy corrugated tube, as shown in Fig. 6. According to the structural characteristics of the corrugated

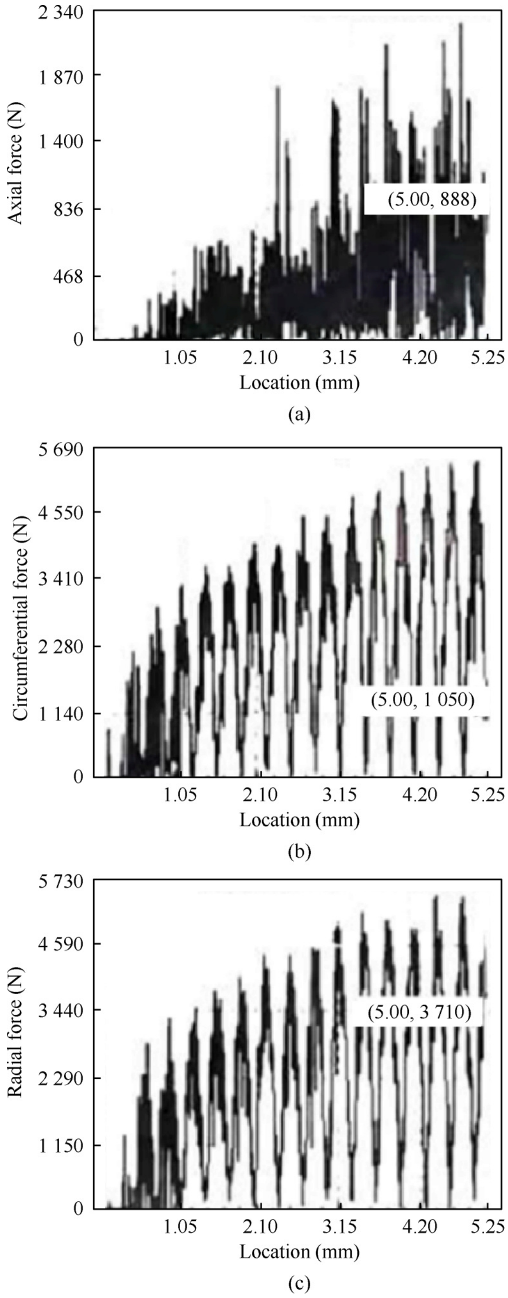

Fig. 4 Evolution of spinning force components in the neck-spinning of a Al6062 alloy tube with gradually-decreased diameter [14]: (a) Axial force; (b) Circumferential force; (c) Radial force.

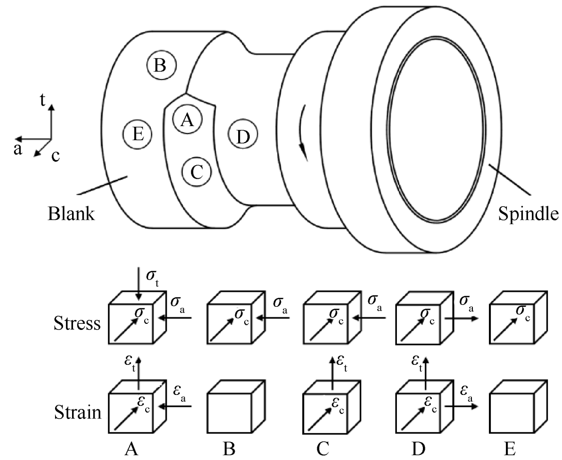

Fig. 5 Schematic of stress and strain states near loading region of roller in neck-spinning[18].

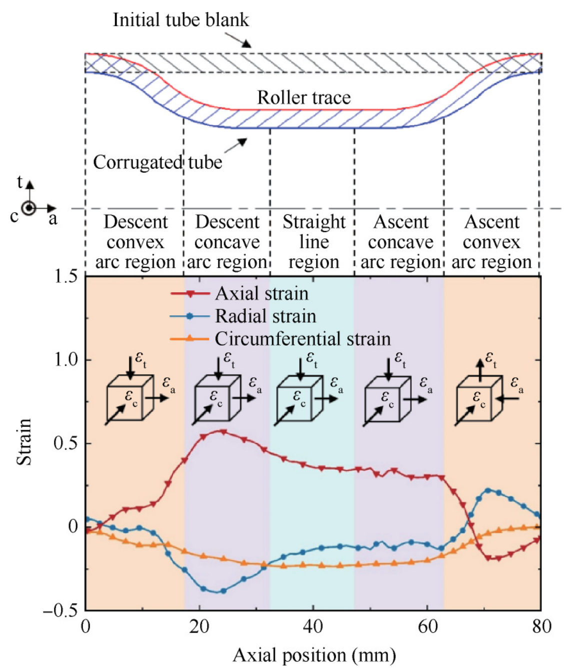

Fig. 6 Evolutions of three strain components in neck-spinning of an aluminum alloy corrugated tube.

tube, the tube was divided into five typical regions to analyze their different deformation states. Five typical regions are descent convex arc region, descent concave arc region, straight line region, ascent concave arc region, ascent convex arc region, respectively, as shown in Fig. 6. It can be seen that the strain in the descent convex arc region is relatively small, and its strain state is $\varepsilon_a > 0 > \varepsilon_t > \varepsilon_c$; the strain state at the descent concave arc is $\varepsilon_a > 0 > \varepsilon_c > \varepsilon_t$; the strain states at the straight line region and the ascent concave arc region are both $\varepsilon_a > 0 > \varepsilon_t > \varepsilon_c$; In the ascent convex arc region, the strain state changes from $\varepsilon_a > 0 > \varepsilon_t > \varepsilon_c$ to $\varepsilon_t > 0 > \varepsilon_c > \varepsilon_a$.

The above analyses show that the stress and strain states on workpiece change with the loading region, and the stress and strain states at a certain location also change with the forming time in the neck-spinning. This makes the deformation in neck-spinning very complex, and then influence the profile accuracy and wall thickness distribution of the spun part, which will be described in the following sections 2.3 and 2.4.

2.3 Profile accuracy of spun component

Profile accuracy is a key index to evaluate the quality of neck-spinning, which is usually evaluated by the accuracy of radius and ellipticity of the outer contour. By now, some investigations have been conducted on the influence of processing parameters on the profile accuracy [27-30].

Hao et al. [28] investigated the influence of processing parameters on the outer contour radius in diameter-shrinkage region in the end neck-spinning of a copper tube, as shown in Fig. 7. From Fig. 7(a), it can be found that as the feed ratio increases, the outer contour radius of formed part deviates more away from the theoretical value (dashed line). As shown in Fig. 7(b), with the fillet radius of roller increasing, the deviation between the practical and theoretical outer contour radius increases. This is because with the increases of feed ratio and the fillet radius of roller, the contact area between the roller and tube blank gets larger, resulting in insufficient plastic deformation. It can be seen from Fig. 7(c) that as the diameter reduction increases, the radius expansion at the free end of formed part becomes more significant. This is because the constraint ability at the free end of tube is weak. At this condition, larger material accumulates at the free end under large diameter reduction, which will lead to more radius expansion.

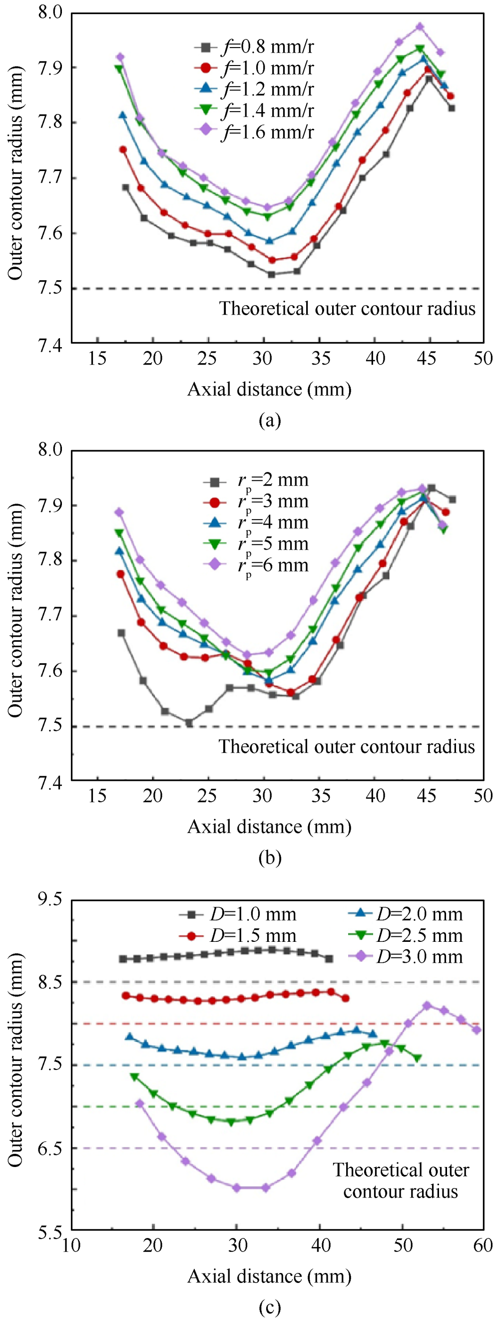

Fig. 7 Influence of processing parameters on outer contour radius in neck-spinning: (a) feed ratio; (b) fillet radius of roller; (c) diameter reduction amount[28].

Huang et al. [29] investigated the effect of processing parameters on the roundness and radius deviation of outer contour in the end neck-spinning of JIS G3141 steel, as shown in Fig. 8. They found that as the feed speed or the fillet radius of roller increases, both of ellipticity and radius of the outer contour present the increasing trend.

The authors have investigated the formed outer contour under various roller traces in the middle neck-spinning of an aluminum alloy corrugated tube. The trace of the 4th-pass is the theoretical profile and also the single pass trace, as shown in Fig. 9(a). It can be found from Fig. 9(b) that the deviation of outer contour from the theoretical one of the roller trace is similar for single-pass and multi-pass forming in the descending region and straight line region. While the single-pass forming presents smaller deviation of outer contour in the ascending region. This is because in multi-pass forming, the later spinning pass will introduce extra deviation to the formed shape in previous pass.

The above analyses suggest that the processing parameters, including the spinning pass, roller trace, feed ratio, fillet radius of roller, etc., have a great influence on the profile accuracy. It still needs more investigations on the optimization of processing parameters to improve the profile accuracy in the neck-spinning.

2.4 Distribution of wall thickness on the spun component

2.4.1 Uneven distribution of wall thickness

The wall thickness distribution is an important quality index of neck-spinning, which has large influence on the service life of the formed parts. Usually, uniform distribution of wall thickness is conducive to prolong the service life of formed parts. However, due to the complex stress and strain states in the neck-spinning, especially the variations of stress and strain states with loading region, it is prone to produce uneven distribution of wall thickness on the formed part. Thus, many researches have been conducted on the wall thickness variation during the neck-spinning [25,27-29].

The authors have investigated the wall thickness distribution in the middle neck-spinning of an aluminum alloy corrugated tube. It is found that the wall thickness variation greatly changes with the loading region, as shown in Fig. 10. In descent convex arc region, the material primarily flows in axial direction, and the wall thickness is basically unchanged; in descent concave arc region and the straight line region, the wall thickness shows a significant thinning; in the ascent concave arc region, the wall thickness gets thinning in the front stage, while gets thickening in the latter stage; in the ascent convex arc region, the wall thickness gets thickening, and whose degree decreases with the diameter reduction decreasing.

Hao et al. [28] also found that the wall thickness variation greatly changes with the loading regions in the end neck-spinning of TP2 copper tube, as shown in Fig. 11. In addition, they also investigated the effect of processing parameters on wall thickness distribution. It is found that as the feed ratio increase, the uniformity of wall thickness distribution of formed part was improved, as shown in Fig. 11 (a). This is because less material accumulates in the front of roller, so the axial elongation of the formed part is reduced. As shown in Fig. 11(b), with the fillet radius of roller increasing, the wall thickness uniformity increases. It can be seen from Fig. 11(c), as the diameter reduction increases, the wall thickness reduction is more obviously, resulting in more severe accumulation of material in front of roller, then the wall thickness reduction is further intensified.

2.4.2 Prediction of the wall thickness

The above researches in Section 2.4.1 show that the wall thickness changes greatly and present significant uneven distribution in the neck-spinning. Thus it is of great significance to predict the

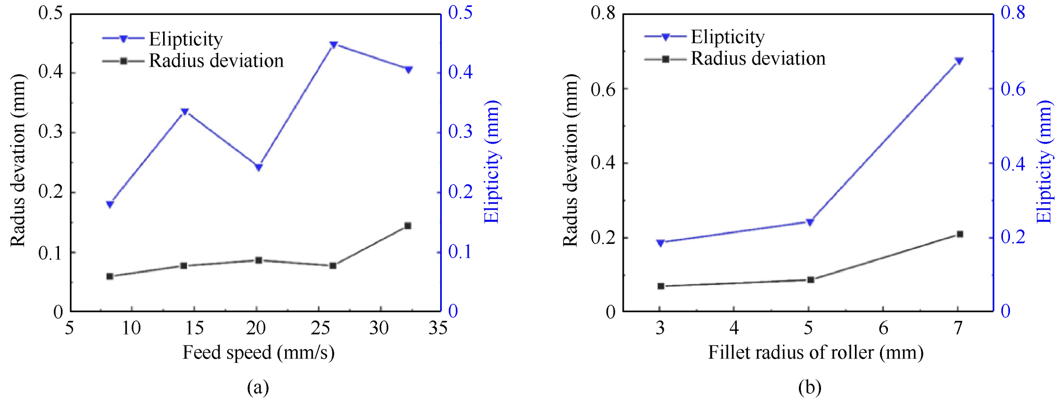

Fig. 8 Influence of processing parameters on ellipticity and radius deviation of outer contour in neck-spinning of JIS G3141 steel [29]: (a) feed speed; (b) fillet radius of roller.

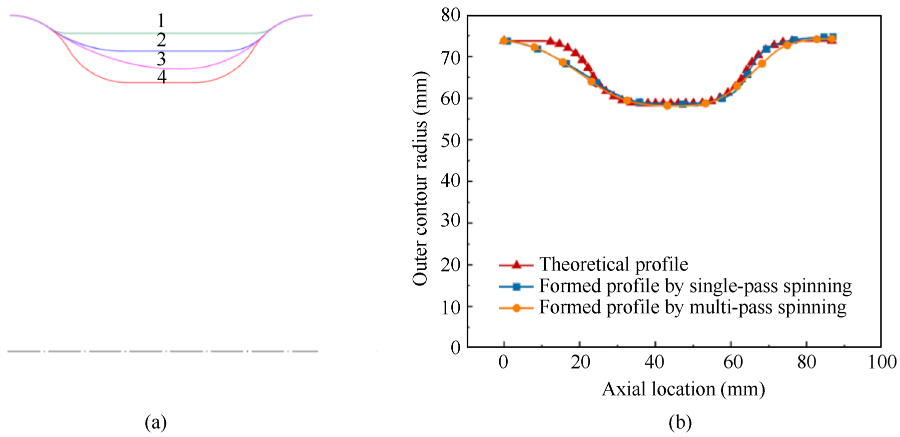

Fig. 9. Influence of various roller trace on outer contour radius in neck-spinning of an aluminum alloy corrugated tube: (a) multi-pass neck-spinning roller trace; (b) forming result of outer contour radius under various roller trace.

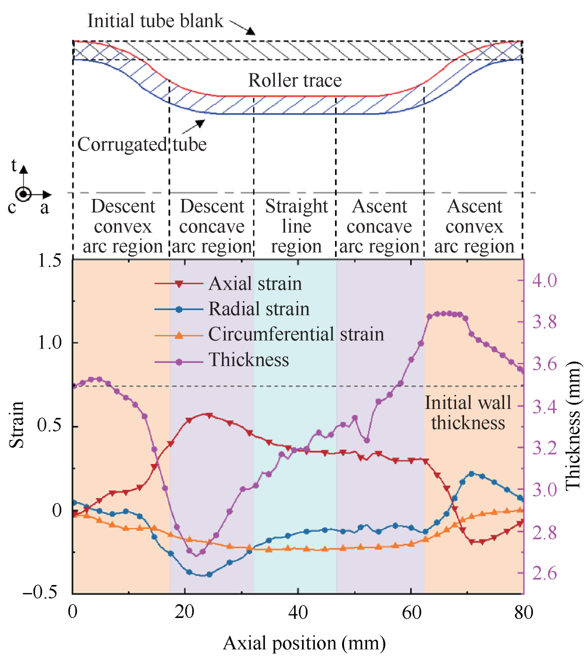

Fig. 10 Wall thickness distribution in neck-spinning of an aluminum alloy corrugated tube.

wall thickness variation in the neck-spinning. By now, there are mainly two prediction models for the wall thickness during the neck-spinning[12,31-33].

One is a geometry-based wall thickness model proposed by Akkus and Kawahara[12]. This model is established by taking an arc-shape necking-spinning as example, as shown in Fig. 12. It assumes that the spun tube presents uniform wall thickness, high profile accuracy and well roundness. Then, according to the principle of constant volume in plastic forming, the formed wall thickness can be calculated by geometric relationships, as shown in Eq.(1).

$$V(t) = V - (V_1 + V_2)$$
$$= (R_0^2 - r_0^2)\pi L_0 - \left\{(2Rt - t^2)\pi(L - L^*) + \pi\left[\int_0^{h_1} f_1^2(z)\,dz - \int_0^{h_2} g_1^2(z)\,dz + \int_{h_1}^{L^*} f_2^2(z)\,dz - \int_{h_2}^{L^*} g_2^2(z)\,dz\right]\right\} \tag{1}$$

where V is the volume of the initial tube, V_1 and V_2 are the volume of outer contour of the convex and concave arc region, R_0 and r_0 are the outside and inside diameters of the initial tube, L_0 is the original length of initial tube, L is the full length of the spinning section, L^* is the length of the arc region, and h_1 and h_2 are the lengths of the outer contour and inner contour convex arcs at the same roller position. The spinning region is divided into four parts according to the geometry, f_1 and f_2 are the outer contour of the convex and concave arc region, g_1 and g_2 are the inner contour of the convex and concave arc region. This model can roughly predict the spun wall thickness. However, it fails to capture the actual non-uniform distribution of wall thickness in neck-spinning and does not account for the

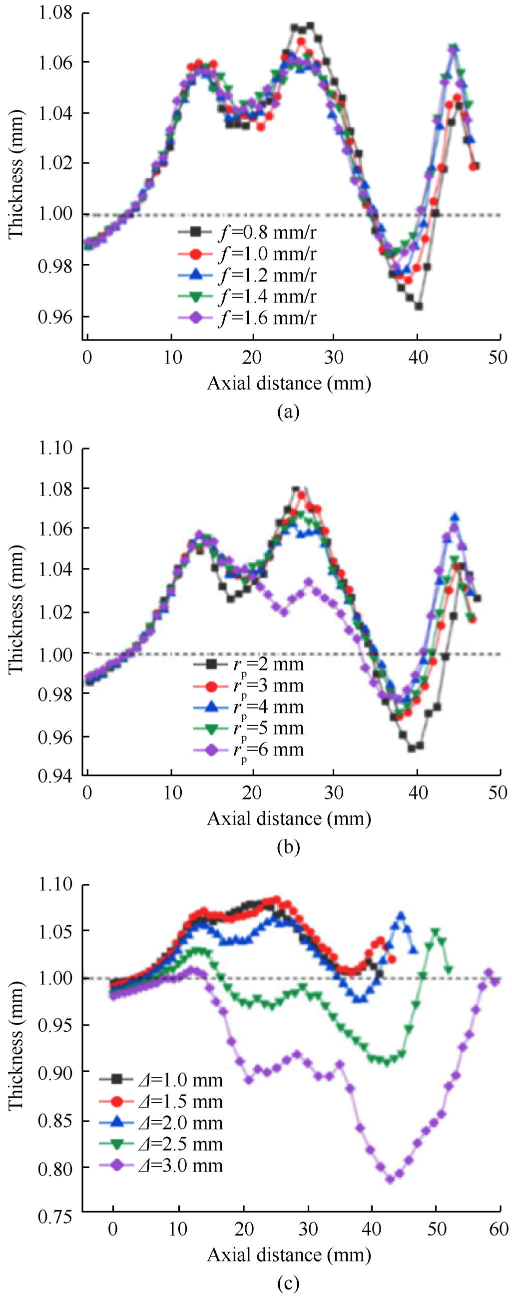

Fig. 11. Influence of process parameters on wall thickness distribution: (a) feed ratio; (b) fillet radius; (c) diameter reduction amount[28].

effect of processing parameters on the wall thickness variation.

On the other hand, Kwiatkowski et al. 6 developed a "shear-necking" model for the wall thickness variation in the neck-spinning. This model considers that each micro-element undergoes a "shear deformation" with the length remaining constant, as shown in Fig. 13(a) and (b). To calculate the thickness of the sheared element, the element is simplified into a rectangular geometry, as shown in Fig. 13(c). As a result, the deformed wall thickness can be represented as a function of radial positions, half cone angle and initial wall thickness, as shown in Eq.(2).

$$s(z) = \frac{D_0}{d(z)} s_0 \cos\alpha = \Theta(z) s_0 \cos\alpha \tag{2}$$

where D_0 is initial diameter and d is the final diameter of the tube, Θ is the necking-in ratio, that is the ratio of D_0 and d; α is the transition angle, s_0 is initial thickness and s is the thickness of infinitesimal element. This model is suitable for the case that there is a tailstock at the tube end and the material flow along axial direction is limited during the neck-spinning process. It can provide a more accurate prediction of wall thickness variation than the Akkus' model, since it considers the effects of diameter reduction and half cone angle of roller trace on the wall thickness variation. However, this model does not incorporate the effects of processing parameters, such as spindle speed and feed ratio, etc., on the wall thickness variation.

As analyzed in section 2.4.1, the wall thickness variation is a complex and uniform behavior depending on multi-factors, including the material parameters, roller trace, roller geometry, loading parameters, etc., in the neck-spinning. However, the above two models do not totally incorporate these influencing factors, which makes them present limitations in the prediction accuracy and universality. Therefore, it is still necessary to develop more accurate and universal model for the wall thickness variation in the neck-spinning.

3. Process optimization for neck-spinning

As for the process optimization for the neck-spinning, it mainly includes the processing parameters optimization and roller trace optimization. The optimization of processing parameters is mainly conducted by the single factor test or orthogonal test at present. Zhan et al.[20] conducted a single factor test to analyze the effects of processing parameters on the forming quality in the neck-spinning of a corrugated tube. They found that smaller spindle speed, larger roller fillet radius and smaller feed ratio are helpful to obtain well forming quality. Moreover, they suggested an optimized processing scheme, i.e., the spindle speed is 2 r/s, the fillet radius of roller is 12 mm, and feed ration is 3 mm/r. Using the optimized processing scheme, they formed a corrugated tube with good forming quality, as shown in Fig. 14.

As mentioned above, the neck-spinning is an incremental forming process, its roller trace plays a great role in the forming quality. Kwiatkowski et al.[6] designed two roller traces to improve the wall thickness uniformity of the formed part. Fig. 15 shows the original roller trace TP1, and the designed roller traces TP2 and TP3. TP2 is a multi-pass and variable loading angle roller trace, as shown in Fig. 15(b). It includes three spinning passes, and the loading angle (angle between the slash region of roller trace and the horizontal direction) increases with the spinning pass; TP3 forms the workpiece in two half regions sequentially, as shown in Fig. 15(c). Its roller trace starts at the center of the workpiece and shapes the workpiece alternately to two sides. The experimental results show that both of TP2 and TP3 can significantly improve the wall thickness uniformity, in which the wall thickness of the pipe formed by the TP3 method is more uniform, as shown in Fig. 15 (d) - (f).

It should be pointed out that, at present, the roller trace and processing parameters are respectively optimized before spinning forming and keep constant in the spinning forming. This cannot consider the coupling effects of roller trace and processing parameters and the dynamic change of forming laws during the neck-spinning, which restricts the optimization results.

4. Summary and prospect

In this paper, the recent researches on the forming mechanism, forming quality and process optimization of neck-spinning have been reviewed. It can be found the neck-spinning is a potential technology to form the tube component with variable diameter. Howev-

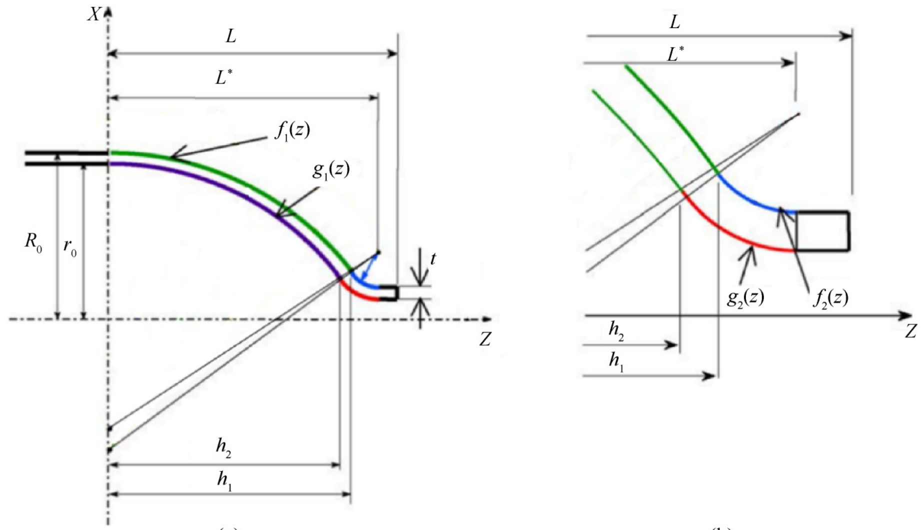

Fig. 12 Schematic of geometric relationship in deformed [12]: (a) integrated region; (b) locally enlarged concave arc region.

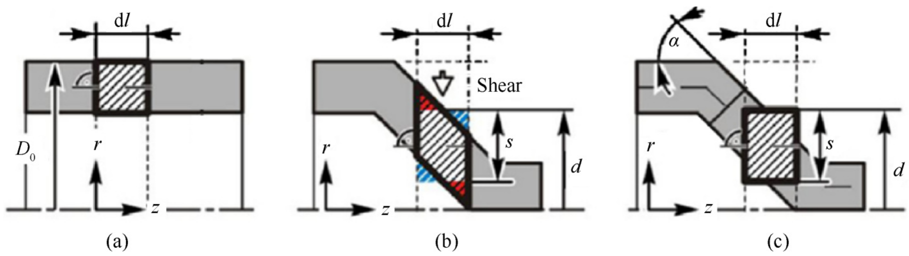

Fig. 13 Schematic of "shear deformation" of a micro-element in neck-spinning[6]: (a) initial tube blank; (b) deformed tube; (c) geometric analysis of the "shear deformation".

Fig. 14 Formed corrugated tube with optimized processing parameters[20].

er, it is a complex local loading and incremental forming process, where various deformation states, uneven distribution of wall thickness variation and profile deflection may occur. These complex forming characteristics make it very difficult to predict the forming results and optimize the processing parameters in the neck-spinning. At present, there are still some challenges in the neck-spinning need to be addressed as follows:

(1) The underlying mechanism and accurate prediction model for the wall thickness variation in the neck spinning. It is still needed to reveal the dependence of wall thickness variation on local workpiece structure and loading conditions, so as to understand the uniform distribution of wall thickness in the neck spinning. Besides, the effects of multi-parameters, including the material parameters, roller trace, roller geometry, loading parameters, etc, on the wall thickness is also needs more concerns. On these bases, a more accurate and universal prediction model incorporating the effects of multi-parameters should be developed for the wall thickness variation in the neck-spinning.

(2) The determination of feasible maximum diameter reduction in the neck-spinning, i.e., the forming limit of neck-spinning. With the rapid development of high-end equipment, the size of variable-diameter tube gets more and more extreme. The ratio of necked diameter to initial diameter gets larger and larger, which may lead to forming defects such as crack, wrinkle, thus, brings greater challenge to the neck-spinning. However, little researches have concerned on the feasible maximum diameter reduction in the neck-spinning.

(3) The collaborative and dynamic optimization of roller trace and processing parameters for the neck-spinning. The roller trace and processing parameters have coupling effects on the forming quality; moreover, the deformation state dynamically changes with loading region during the neck-spinning. However, at present, the roller trace and processing parameters are respectively optimized before spinning forming and keep constant in the spinning forming. Therefore, it is still needed to develop new process optimization method to realize the collaborative and dynamic optimization of roller trace and processing parameters in the neck-spinning.

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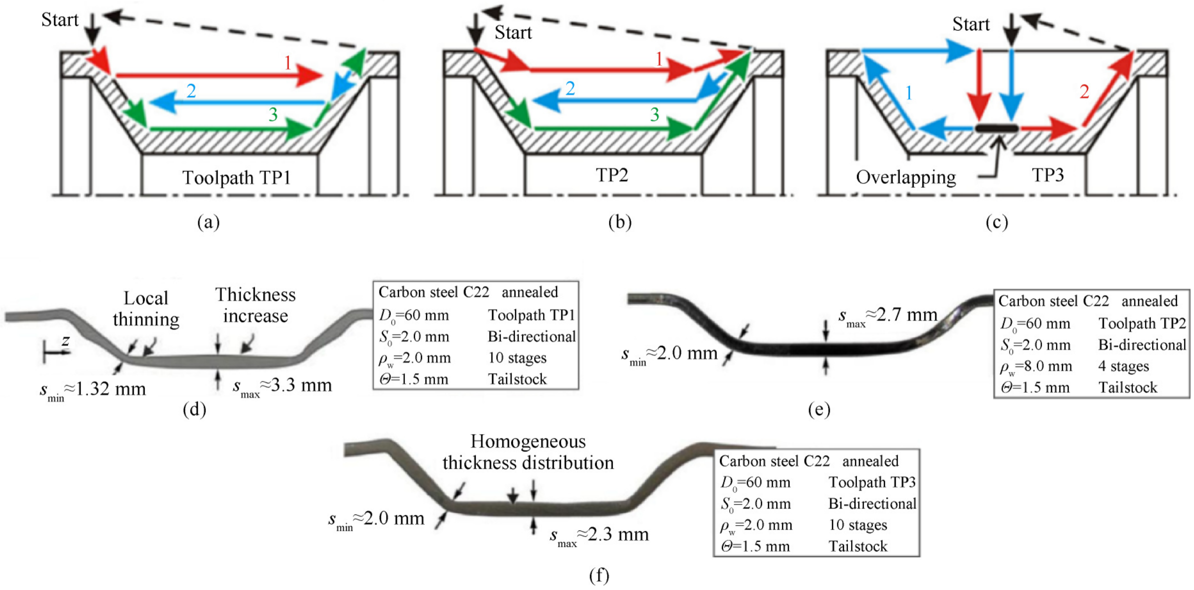

Fig. 15 Roller traces and forming results for the neck-spinning of tube[6]: (a) original path TP1; (b) roller trace TP2 with multi-pass and variable loading angle; (c) roller trace TP3 forming the workpiece in two half regions sequentially; (d) forming results of roller trace TP1; (e) forming results of roller trace TP2 result; (f) forming results of roller trace TP3 result.

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