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Research Article

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Posted Date: September 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10979177/v1>

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A Study on the T-tube Rotational Drawing Process Using a Ball-Type Rotating Head

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Abstract

To address key issues in traditional spin-forming processes for manufacturing T-tubes, such as severe wall thinning and insufficient effective forming height, this study proposes an innovative ball-spindle structure. Spin-forming tests were conducted on 5A02 aluminum alloy tubes with an inner diameter of 40 mm and a wall thickness of 1 mm for aerospace applications to investigate the effects of spindle speed, feed rate, and spindle type on the forming quality of T-tubes. The results indicate that within the range of 30–50 r/min, spindle speed has a minimal effect on the forming quality of the branch tube, and process stability is good; however, at excessively low speeds (<10 r/min), the tube wall is prone to developing distinct helical feed marks. Excessively low feed rates tend to cause “over-forming,” resulting in material flow lag and radial accumulation, which leads to a lower branch height; process adaptability is better under medium-to-high feed rate conditions; The ball-type rotary head, with its omnidirectional adaptive rolling characteristics, effectively eliminates tangential friction and reduces feed resistance. After forming, the branch pipe height reached 4.168 mm, with a wall thinning rate of only 30.3%, demonstrating the best forming performance.

Keywords T-tube; spin-forming; ball-end cutter; branch height; forming quality

1. Introduction

T-tubes are core components for fluid distribution and pipeline connections, and are widely used in high-end aerospace piping systems such as aerospace, missile propulsion, and satellite thermal control [1-2]. Their structure offers irreplaceable advantages in enabling multi-channel fluid transport, lightweight integration, and system compactness. As new-generation aircraft continue to demand greater lightweighting, higher reliability, and more complex spatial layouts, higher requirements have been placed on the forming accuracy, wall thickness uniformity, mechanical properties, and manufacturing efficiency of T-tube fittings [3-4]. For aluminum alloy tubing such as 5A02 and 6061, the efficient production of T-shaped

structures with high branch heights, minimal wall thinning, and no forming defects—while fully leveraging the material’s plastic forming capabilities—has become a critical technical challenge requiring urgent breakthroughs in the field of advanced aerospace manufacturing [5].

Current common forming processes for T-tubes primarily include internal high-pressure forming, stamping and welding, electromagnetic flanging, and spin-drawing [6-7]. Internal high-pressure forming offers good surface quality and forming accuracy, but it requires high equipment investment, has a long forming cycle, and imposes stringent requirements on pre-drilled holes and sealing conditions, making it difficult to meet the aerospace sector’s manufacturing needs for small batches and multiple varieties; stamping and welding has a simple process, yet the weld seam is prone to creating fatigue-weak zones, making it difficult to meet the structural integrity requirements for high-reliability tubing; electromagnetic flanging involves high equipment costs and is difficult to control [8-9].

In contrast, spin-drawing, through a combination of rotational and axial feed motions, effectively improves circumferential material flow and significantly increases the forming height of branch pipes, attracting widespread attention in recent years. However, traditional spin-drawing methods typically employ rigid spinning heads that come into direct contact with the tube wall, resulting in high sliding friction resistance. This often leads to excessive local temperature rise and uneven material flow, causing severe wall thinning or even cracking, which limits its engineering applications.

To address this, this study proposes a telescopic dual-spindle assembly with a ball-bearing structure. The balls can perform passive rotation while orbiting with the main spindle, converting sliding friction between the spindle and the tube wall into rolling friction. This effectively reduces the wall thinning rate, minimizes scratches on the inner surface, and increases the maximum formable height of the branch pipe.

Regarding research on the forming process of thin-walled T-tubes, early methods employed machining or a combination of step-by-step stamping and welding [10]. These approaches suffer from high production costs and low forming quality and precision, and are far from meeting the current manufacturing demands of the aviation industry [11]. With the rapid development of technology, various new processing techniques have continuously emerged both domestically and internationally. Han [12] et al. conducted research on T-tube forming of annealed T2 copper tubes using polyurethane rubber as the internal filling medium and a composite process of bidirectional synchronous extrusion and restricted back pressure. This method effectively suppresses excessive wall thinning at the top of the branch tube, successfully producing fittings with branch heights meeting specifications, uniform wall thickness distribution, and no forming defects. Cui [13] et al. used electroforming to replace stamping flanging for the production of 5052 aluminum alloy T-tubes, significantly improving die-to-workpiece accuracy (gap < 0.3 mm) and forming height, while the high strain rate helped improve material flow. Yao [14] et al. pointed out that friction has a significant impact on the quality and performance of progressive sheet metal forming, with the dimensions of the spinning head structure being crucial to the friction coefficient during forming. Zhang [15] et al. conducted progressive hole flanging

experiments by varying the tool diameter and flange diameter, gradually reducing the sheet metal hole diameter until specimen fracture, thereby establishing and verifying the forming limits of progressive holes in sheet metal flanging.

To achieve high-quality forming of 5A02 aluminum alloy and meet the urgent demand for such bent tube components in the aerospace and aviation sectors, this study focuses on 5A02 aluminum alloy with an inner diameter of 40 mm and a wall thickness of 1 mm. Rotational drawing experiments were conducted to investigate the effects of spindle speed, feed rate, and mandrel type on the forming quality of T-shaped tubes.

2. Overview of the ball-rolling and drawing forming process

2.1 Features of the telescopic dual-spindle rotating drawing and forming process

T-tube rotary drawing is an advanced manufacturing process based on metal plastic deformation. A schematic diagram illustrating the principle of the rotary drawing process is shown in Fig. 1. In this method, a tube blank with a pre-formed elliptical hole is first secured in a fixture, and then a telescopic cantilever rotary head is inserted into the tube and extended; Through the combined action of spindle rotation and axial drawing feed, the spinning head applies localized pressure to the tube wall, causing the material to flow and gradually form a vertical branch tube. By precisely controlling key process parameters such as the spinning head diameter, spindle speed, and axial feed rate, high-precision forming of the branch tube can be achieved.

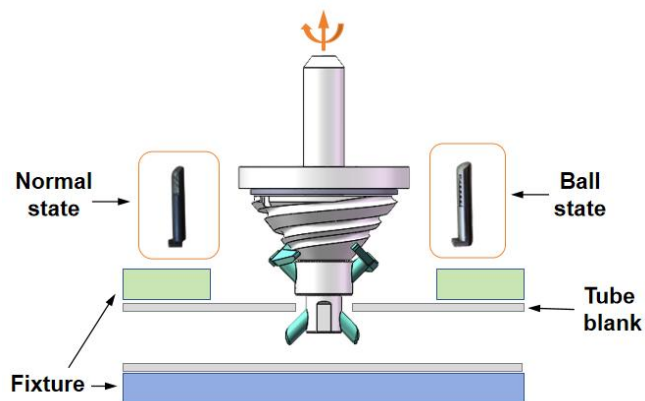


Fig. 1 Schematic diagram of mold-free rotational pull-forming of T-tubes

2.2 Principle of ball-screw rotational drawing

The core advantage of the ball-type rotating head lies in its embedded ball structure, which provides the contacting components with multi-directional rotational freedom. During the forming process, driven by friction, the balls adaptively roll along the direction of the composite velocity vector V_{rel} , as shown in Fig. 2, while simultaneously eliminating both circumferential and axial sliding friction. Compared to traditional sliding contact, the rolling friction coefficient is only 1% to 5% of that of sliding friction, significantly reducing the overall frictional resistance between the

spinning head and the tube blank. This creates an all-around “low-resistance channel” at the contact interface, effectively reducing the resistance to material flow in both the tangential and axial directions. Under these low-resistance conditions, a greater portion of the forming load is converted into effective work that promotes plastic deformation rather than being dissipated as frictional heat. This significantly enhances the metal’s ability to flow toward the top of the branch tube, ultimately achieving the maximum branch height and optimal wall thickness distribution.

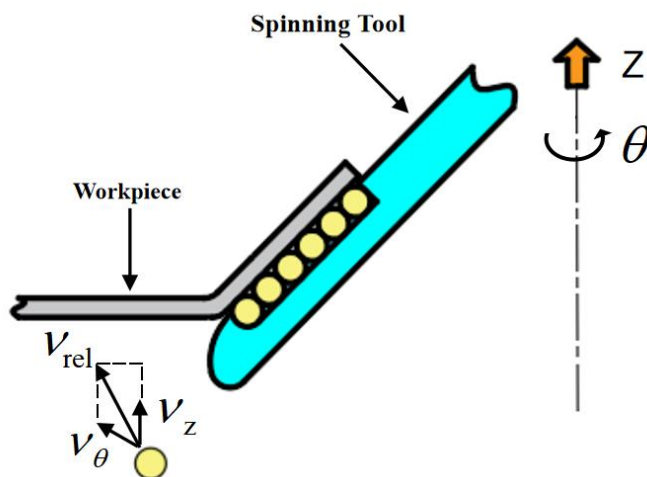


Fig. 2 Schematic diagram of velocity vector in contact zone of ball screw head

3. Finite Element Simulation Analysis

3.1 Finite Element Model Analysis

The finite element model of T-tube spin-forming consists of an initial tube blank and a simplified ball-end spinner. The tube blank has an outer diameter of 42 mm, a wall thickness of 1 mm, and a length of 100 mm; the branch pipe’s inner diameter is set at 38 mm, which falls within the typical range of 30–40 mm for branch pipes in aerospace piping systems. Referring to design guidelines for aluminum alloy lap joints, the lap length is set to $1t$ – $3t$ (where t is the wall thickness of the parent tube) to ensure that the joint’s shear strength exceeds the tensile strength of the parent material. Therefore, the minimum height of the branch tube in this study is set to 3 mm, which is three times the wall thickness of the parent tube, to meet the strength requirements for branch tubes in aerospace piping. Substituting $D = 41$ mm and $d = 39$ mm into the formula for the preformed hole [16], as shown in Eq. (1), and considering the need for a certain amount of shaping allowance after the branch pipe is spun and drawn, h is set to 4 mm and d to 38 mm. Calculations yield the major axis $2a = 31$ mm and the minor axis $2b = 15$ mm for the preformed hole, thereby determining the elliptical dimensional parameters of the preformed hole.

$$\begin{cases} a = \frac{d}{2} - h \\ b = \frac{D}{2} \sin\{90^\circ - \cos^{-1}(\frac{d}{D}) - \frac{D + 2h - D\sin[\cos^{-1}(\frac{d}{D})]}{3.14D} 180^\circ\} \end{cases} \quad (1)$$

Where a is the major axis of the elliptical preform; b is the minor axis; d is the diameter of the branch pipe's neutral plane; D is the diameter of the main pipe's neutral plane; and h is the forming height of the branch pipe.

Import the model created in SolidWorks into the finite element software ABAQUS in IGS format, assign material properties, and define cross-sections; The tube blank is discretized using quadrilateral elements, with local mesh refinement (edge refinement) applied at the edges of the pre-drilled holes to ensure computational accuracy, as shown in Fig. 3. The approximate model of the ball-bearing spindle, , uses triangular mesh elements with a mesh size of 0.2. The spindle is defined as a rigid body, and the tube blank is defined as a deformable body.

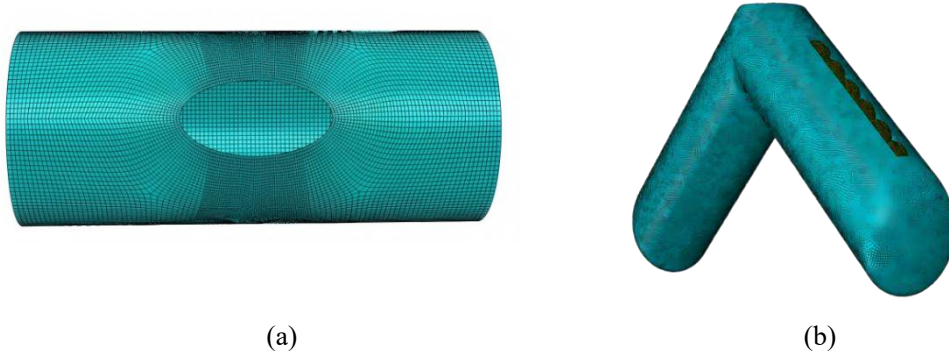


Fig. 3 (a)Tube blank model mesh partitioning,(b) Meshing for simplified rotary head model

3. 2 Material model parameters

This study uses thin-walled 5A02 aluminum alloy tubes with an inner diameter of 40 mm and a wall thickness of 1 mm as the subject of investigation. To ensure the accuracy of the finite element simulation, stress-strain curves for the 5A02 aluminum alloy were obtained through uniaxial tensile testing. The calculated stress-strain curves are shown in Fig. 4, with a tensile strain rate of 0.005 mm/s. The material parameters are listed in Table 1.

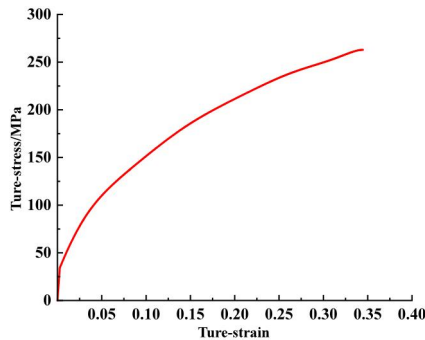


Fig. 4 True stress-strain curve of 5A02 aluminum alloy

Table 1 Material parameters of 5A02 aluminum alloy

Parameter	Elastic modulus/GPa	Yield strength/MPa	Tensile strength/MPa	K	n
Value	70000	56.51	156.2	381	0.44

3.3 Laboratory Equipment and Molds

This experiment was conducted on a modified XKA715A three-axis CNC milling machine, as shown in Fig. 5. The machine is equipped with a FANUC 0i-MC system, with a spindle speed range of 1 to 8,000 rpm and a feed rate that can be continuously adjusted from 1 to 8,000 mm/min, meeting the requirements for motion accuracy and dynamic stability in spin-forming. The fixture consists of a cover plate and a base, which clamp and position the tube blank via bolted fasteners. The fixture base features positioning slots that precisely match the machine tool's worktable, ensuring repeatable positioning accuracy on the machine.

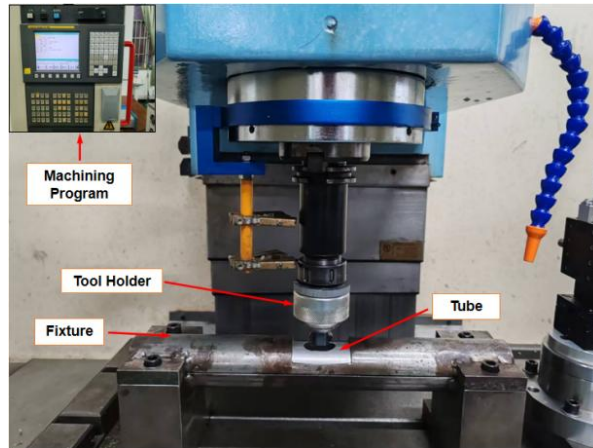


Fig. 5 T-tube branch pipe twist-pull forming experimental platform

4. Patterns of Process Parameter Influence

4.1 The effect of spindle speed on forming quality

The spindle speed determines the strain rate in the deformation zone and the helix angle of the contact trajectory between the spinning head and the inner wall of the tube blank; it is a key kinematic parameter influencing the dynamic process of T-tube spinning. At a constant axial feed rate, increasing the spinning head speed essentially alters the direction of the resultant velocity vector at the contact point. The higher the rotational speed, the more the resultant velocity vector deviates toward the circumferential tangent direction, thereby altering the direction of the frictional force and the distribution of resistance to material flow.

To thoroughly investigate the influence of spindle rotational speed on the performance of T-tube spin-forming, this study conducted 12 simulation experiments with the spindle speed ranging from 5 r/min to 60 r/min in 5 r/min increments, while

keeping other process parameters constant (feed rate 30 mm/min, friction coefficient 0.1). The simulation results are shown in Fig. 6. Within the spindle speed range of 5–60 r/min, the effective height of the branch pipe fluctuated slightly around 4.13 mm. Based on the characteristics of height variation with spindle speed, this speed window can be divided into three stages: the low-speed range (5–15 r/min), the medium-speed range (15–45 r/min), and the high-speed range (45–60 r/min).

In the low-speed segment, when the rotational speed was 5 r/min, the effective height of the branch pipe reached a local peak of 4.168 mm; however, as the speed increased to 10 r/min, the height actually decreased to 4.093 mm. Upon entering the medium-speed segment, the branch pipe height stabilized, remaining largely between 4.13 and 4.18 mm, without showing any significant upward or downward trend, demonstrating good plateau characteristics. In the high-speed range, when the rotational speed increased to 50 r/min, the height reached a maximum of 4.309 mm (considered an anomalous peak) across the entire test range; however, upon further increasing to 60 r/min, the height rapidly dropped to a minimum of 4.095 mm.

From a mechanical perspective, the relative velocity at the contact point between the rotating head and the tube blank is the vector sum of the axial feed velocity and the circumferential velocity; the direction of the frictional force is always opposite to this resultant velocity. Under conditions of constant normal pressure and friction coefficient, the total frictional force remains essentially constant; however, as the rotational speed increases, its axial component decreases, thereby reducing the resistance to upward material flow, which theoretically favors an increase in branch height. However, when the rotational speed is too high, intense circumferential shear dissipates a significant amount of plastic deformation energy, reducing the energy available to drive axial material flow. This, in turn, inhibits height growth, which reasonably explains the phenomenon of branch pipe height first increasing and then decreasing in the high-speed range.

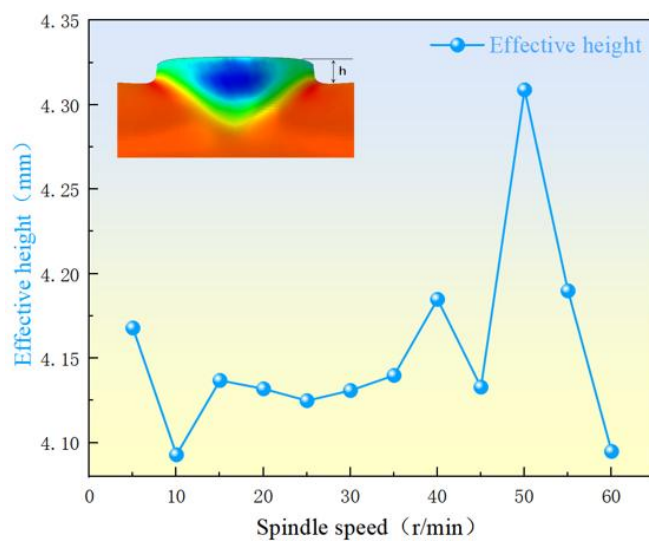


Fig. 6 Relationship curve between spindle speed and effective height of branch pipe

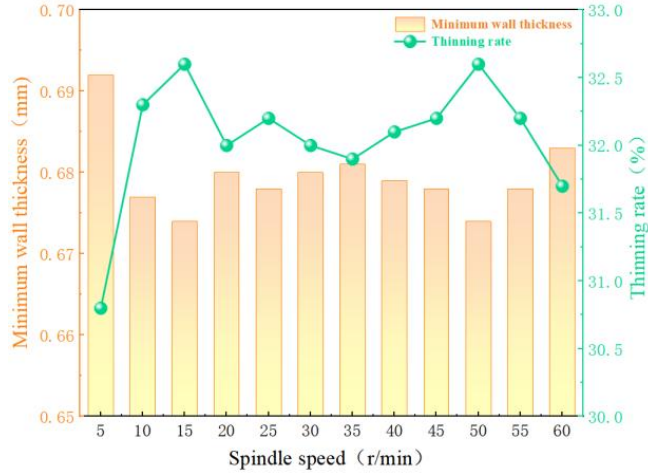


Fig. 7 Effect of spindle speed on minimum wall thickness and thinning rate of branch pipes

In all 12 experimental sets, the minimum wall thickness of the branch pipe ranged from 0.674 mm to 0.692 mm, with a range of only 0.018 mm, indicating minimal variation in wall thickness. As shown in Fig. 7 wall thickness remained highly stable even as the spindle speed varied over a wide range. The fundamental reason for this is that, in T-tube spin-forming, the branch pipe wall thickness is primarily determined by the geometric clearance between the spindle's maximum outer diameter and the initial diameter of the pre-drilled hole, as well as the law of conservation of mass; thus, it is insensitive to changes in spindle speed.

Specifically, in the low-speed range (<10 r/min), although the wall thinning rate is slightly lower, noticeable helical surface feed marks are prone to form, affecting surface integrity and reducing fatigue performance; whereas in the medium speed range (>30 r/min), the formed surface quality is uniform and wall thickness parameters are stable, demonstrating that this process exhibits good robustness and forming consistency within a specific speed range.

4. 2 The effect of spindle speed on forming quality

Feed rate refers to the speed at which the rotating head advances (or pulls) along the axis of the tube blank branch. It not only directly affects machining efficiency but also determines the rate of strain accumulation in the deformation zone and the volume of material flow per unit time, thereby significantly influencing the stress state and the uniformity of wall thickness distribution in the branch forming zone.

Excessively high feed rates significantly increase the material's strain rate. Too rapid a loading rate can easily induce rheological instability, causing stress to rise sharply; if the material flow rate lags behind the rotary head's axial feed rate, it may lead to wall tearing or severe localized thinning of the branch pipe.

Conversely, while an excessively low feed rate can prevent the aforementioned defects, it significantly reduces production efficiency; simultaneously, the slow advancement of the rotating head prolongs the contact time per unit area with the tube wall, causing repeated compression in localized areas and the accumulation of frictional heat, which can easily lead to damage such as excessive thinning or adhesive wear.

Therefore, the axial feed rate must be selected appropriately to balance forming quality and processing efficiency.

In this study, the process window for axial feed rate was set from 5 mm/min to 60 mm/min, with 12 sets of comparative simulation experiments designed in 5 mm/min increments. The remaining parameters were consistent with those used in other single-parameter analyses. The simulation results are shown in Fig. 8.

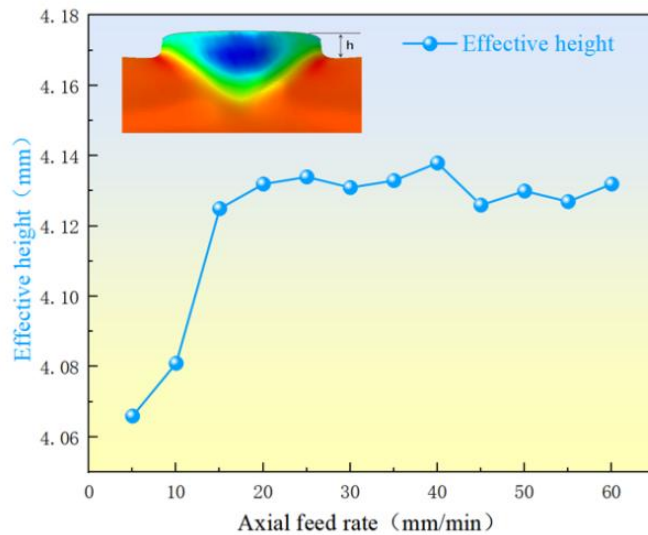


Fig. 8 Relationship curve between feed rate and effective height of branch pipe

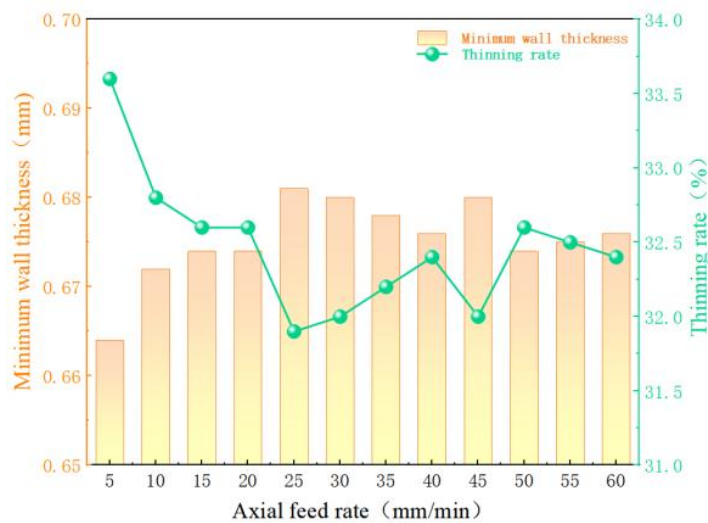


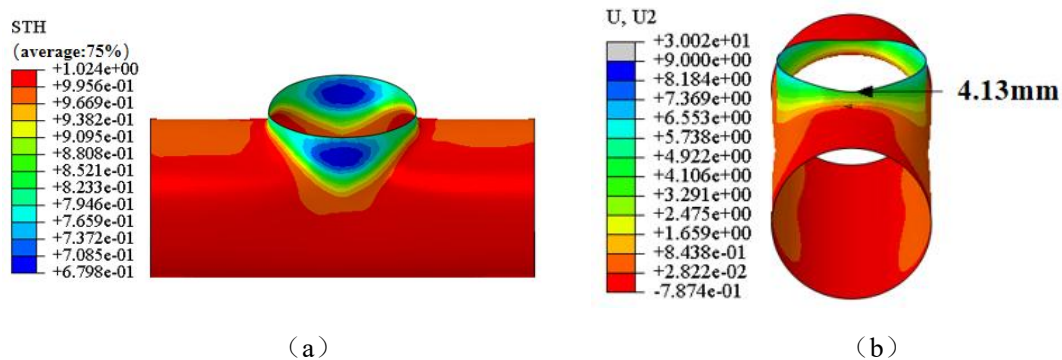
Fig. 9 Effect of feed rate on minimum wall thickness and thinning rate of branch pipes

The effect of feed rate on branch height initially increases and then stabilizes. In the low-speed range (5–15 mm/min), the height increased from 4.066 mm to 4.125 mm, indicating that axial material flow is restricted at low speeds; When the feed rate enters the 15–60 mm/min range, and especially after exceeding 20 mm/min, the branch height stabilizes at approximately 4.13 mm, with fluctuations not exceeding 0.008 mm. Even when the feed rate increases to 60 mm/min, the height remains stable at 4.132 mm. The reason for these characteristics is that as the feed rate increases, the rotational motion of the spindle provides sufficient axial driving force, forcing the material to be rapidly

pushed into the branch tube forming zone before it has time to undergo radial flow, thereby significantly improving the axial utilization of the material. The results of the effect of feed rate on wall thickness are shown in Fig. 9; at extremely low feed rates (5 mm/min), the thinning rate reaches as high as 33.6%. The fundamental reason lies in the fact that high-frequency repetitive loading subjects the material to sustained high local stresses, leading to a sharp increase in dislocation density and significant grain fragmentation; the root area thins noticeably due to excessive crushing, which not only reduces production efficiency but also weakens wall thickness strength, triggering “overforming” failure. As the axial feed rate of the rotary head increases, the minimum wall thickness rapidly recovers, indicating a significant improvement in forming quality. In the medium-speed range (25–30 mm/min), the rotary die feed rate aligns well with the material’s natural plastic flow rate, avoiding both excessive rolling caused by too slow a feed and necking caused by too fast a feed. When the feed rate was increased to 40–60 mm/min, the minimum wall thickness did not increase further but instead showed a slight decrease and fluctuation. This is because high strain rates cause an increase in material rheological stress and deformation resistance, hindering plastic flow; under forced feeding conditions, tensile stress within the tube wall intensifies, leading to slight thinning.

4. 3 The effect of cutter head type on forming quality

In the spin-drawing process for T-tubes, the spin head structure is a key factor affecting forming quality. Different structures directly influence the stress distribution on the inner wall of the tube blank, the uniformity of deformation, and the forming limit. A well-designed spin head can effectively alleviate stress concentration and promote uniform metal flow in the deformation zone, thereby significantly improving the forming accuracy and surface quality of T-shaped tubes. To systematically investigate the influence of die head structure on forming performance, two types of die heads—ball-type and monolithic—were selected for comparative simulation. While keeping other process parameters constant, corresponding finite element models were established for each, and simulations were conducted to obtain the branch height and wall thickness distribution in the T-tube forming zone, as shown in Fig. 10.



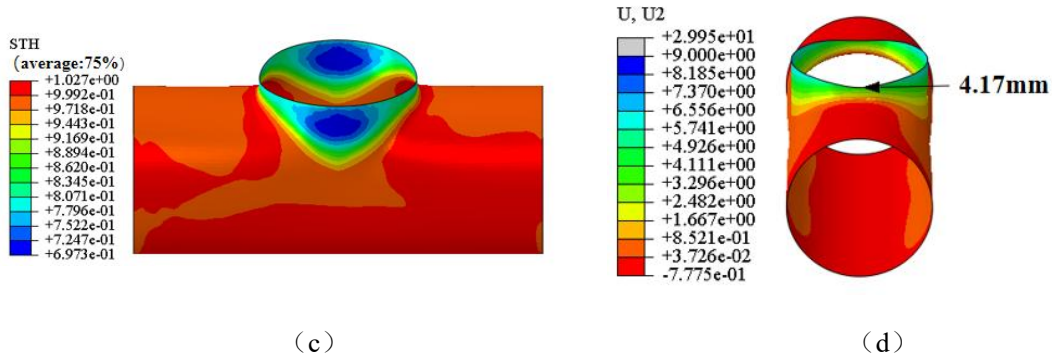


Fig. 10 Influence of swivel head structure on simulation performance of t-pipe swivel-pull forming (a)Integral rotary head forming wall thickness(b) Integral rotary head forming height(c) Ball-type rotary head forming wall thickness(d) Ball-type rotary head forming height

First, regarding the effective height of the branch pipe, the ball-type spinning head achieved the highest branch pipe height, reaching 4.17 mm. Compared to the 4.13 mm achieved by the traditional monolithic spinning head, this represents a slight increase of approximately 0.9%. This indicates that, under existing process parameters, simply altering the spinning head structure has a limited effect on increasing the axial limit height of the branch pipe, with the forming heights of all designs being approximately 4.1 mm. However, regarding key forming quality indicators such as wall thickness distribution and thinning rate, the different mandrel designs exhibited significant differences, with the ball-type mandrel demonstrating the best wall thickness control. Its minimum wall thickness was maintained at 0.697 mm, corresponding to a wall thinning rate of only 30.3%. Compared to the 32.0% thinning rate of the solid mandrel, the ball-type structure effectively reduced the thinning by approximately 1.7%, indicating that it causes the least “damage” to the material during the forming process and is most conducive to ensuring branch tube strength.

To investigate the impact of the spinning head structure on branch tube forming quality, spinning and drawing experiments were conducted using both solid and ball-type spinning heads while keeping other process parameters consistent. The surface morphology of the inner surface of the formed branch tubes is shown in Fig. 11.

The inner wall of the branch pipe formed by the solid-body spinning head exhibits distinct circumferential spiral machining marks. This is primarily due to sliding friction between the head and the tube blank; the carbide spinning head continuously squeezes and scrapes the tube wall during the spinning process, forming typical extrusion/cutting patterns.

In contrast, the inner wall of the branch pipe formed by the ball-type spinning head is smooth, exhibiting only extremely fine and faint patterns, indicating that the material surface underwent sufficient plastic smoothing, resulting in significantly superior surface integrity. This advantage stems from the conversion of sliding friction into multidirectional rolling friction, which substantially reduces frictional resistance; simultaneously, the balls perform high-frequency, low-resistance rolling on the metal surface in the contact zone, effectively promoting the formation of a dense, smooth

surface.



Fig. 11 Surface topography of branch pipes after two types of rotary head forming (a) Integral rotary head (b) Ball-type rotary head

5 Conclusions

This paper investigates the effects of spindle speed, feed rate, and tool head type on the forming quality of T-shaped tubes through experiments and finite element simulations. The main conclusions are as follows:

1. The spindle speed exhibits a nonlinear relationship with forming results. At extremely low speeds (<10 r/min), the feed per revolution is excessive, which tends to create distinct spiral feed marks on the tube wall. Therefore, spindle speed selection should balance surface integrity and machining efficiency rather than solely pursuing dimensional accuracy; the medium-to-high speed range (30–50 r/min) demonstrates superior overall process performance.
2. Feed rate has a complex effect on forming quality: extremely low speeds (5 mm/min) cause “over-forming,” leading to delayed material flow and radial accumulation, resulting in the lowest branch height and severe thinning at the root; high speeds (>40 mm/min) cause a slight decrease in wall thickness due to strain rate hardening. Therefore, under single-factor conditions, the medium-speed range of 25–30 mm/min achieves the optimal balance between material flow and tool movement.
3. The ball-type rotating head, leveraging its omnidirectional adaptive rolling characteristics, effectively eliminates tangential friction and reduces axial feed resistance, thereby achieving the highest branch height (4.168 mm) and the lowest wall thinning rate (30.3%), resulting in the optimal forming performance.

Funding This research was funded by the National Natural Science Foundation of China (No. 52575395), National Science and Technology Major Special Project (No. J2019 VII-0014-0154), Natural Science Foundation of Jiangxi Province (No. 20224BAB214050), and National Defense Key Disciplines Laboratory of Light Alloy

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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