Inhibiting thinning in tube bending by considering a coupling effect of material compensation and friction under a boosting movement

Hao Fang
Zhineng Wang (✉ zhinengwang@hust.edu.cn)
Hunan University of Science and Technology https://orcid.org/0000-0001-9177-0243

Guangfu Bin
Weiming Lin
Yaocheng Lin
Cong Trieu Tran

Research Article

Keywords: Bending forming, Pressure dies boosting, Wall thinning, friction, material compensation

Posted Date: October 18th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3429735/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on January 23rd, 2024. See the published version at https://doi.org/10.1007/s00170-024-13047-3.
Inhibiting thinning in tube bending by considering a coupling effect of material compensation and friction under a boosting movement

Fang Hao\textsuperscript{a}, Zhineng Wang\textsuperscript{a,b,c,*}, Guangfu Bin\textsuperscript{a}, Weiming Lin\textsuperscript{b}, Yaocheng Lin\textsuperscript{b,c}, Cong Trieu Tran\textsuperscript{d}

\textsuperscript{a} Health Maintenance for Mechanical Equipment Key Lab, Hunan University of Science and Technology, Xiangtan, 411201, China
\textsuperscript{b} Zhejiang King-Mazon Intelligent Manufacturing Corp. Ltd, Lijiang, 321400, China
\textsuperscript{c} Zhejiang Province Key Laboratory of Aerospace Metal Tube Forming Technology and Equipment, Lijiang, 321400, China
\textsuperscript{d} Hydraulic Engineering department, Hanoi University of Civil Engineering-55 Giai Phong, Hanoi, Vietnam

Corresponding author at: School of Mechanical Engineering, Hunan University of Science and Technology. Taoyuan Road, Yuhu District, Xiangtan, 411201, China.

Corresponding author. E-mail addresses: E-mail: zhinengwang@hnust.edu.cn (Zhineng Wang)

Abstract: Pressure die boost is an effective method to inhibit the thinning in the manufacturing process of aerospace tubes, and its mechanism is concerned by scholars at home and abroad. Finite element and experimental methods were conducted to analyze the tube thinning with and without boost. The effects of boosting velocity and friction on the outer wall thickness of the tube are studied. Results show that frictional force generated by the boost and the material compensation effect combine to resist the outer wall thinning during the bending process. When the boosting velocity is higher than the tube bending linear velocity, the frictional force of the boost generates a specific compressive stress, which weakens the tensile stress during the bending process of the outer wall. In the meantime, the boosting effect transfers the material from the feed section to the bending section, compensating for the thinning of the tube wall during the bending process. A new theoretical model of tube bending and thinning under boost conditions is proposed to explain this coupling effect. The relative error between the new theoretical model and the experimental value is less than 1.5%, and the accuracy is improved by 5.3% compared with the traditional no-boost condition. It overcomes the poor accuracy of the existing thinning model when fitting to boosted conditions and reveals the boosted effect's mechanism on the tube thinning.

Keywords: Bending forming; Pressure dies boosting; Wall thinning; friction; material compensation

1. Introduction

The thinning defects of aviation pipelines can easily cause pipeline breakage and oil leakage, seriously threatening the safety of aircraft in service\cite{1}. Many scholars have made statistics on aviation pipeline defects and found that the probability of thinning defects in the pipeline manufacturing process is very high\cite{2, 3}. According to the relevant data, the flight accidents of global fighter aircraft due to pipeline thinning and other defects account for 60 percent of the total crashes. A Boeing 737-800 airline exploded and burned when it landed at Okinawa Airport in response to a damaged right-hand fuel line\cite{4}. These aviation accidents have caused extensive global concern about the defective thinning of aviation pipelines. Therefore, the tube thinning rate needs to be strictly controlled. The thinning rate is too large, which significantly increases the risk of tube rupture and fracture in the service process, which may cause the system to malfunction or
lead to aircraft fuel leakage, fire, and explosion, which seriously affects the flight safety of the aircraft[5, 6].

In the bending and forming process, the outer wall of the aviation pipeline is constantly elongated, which will inevitably produce the phenomenon of wall thickness thinning. Foreign scholars have carried out a lot of research on wall thinning. The material, size, process parameters, and other aspects of the thinning mechanism have been analyzed. For example, Tang et al[7, 8] studied the stress distribution and wall thickness changes of tubes according to the plastic deformation theory and used the finite element stress balance equation to derive the theoretical formula of tube thickness; Ouyang et al[9] explored the variation characteristics of 0Cr21Ni6Mn9N-HS tube with different friction coefficients and thinning under the gap of the molds and tubes using the finite element method; Yang et al[10] used the finite element method to study the effect of friction on the outer wall thinning of different tubes, such as aluminum alloys and stainless steels, in bending. It is found that the friction between different materials and bending die is different, and the thinning rate is also significantly different; Fang et al[11, 12] established a finite element model of high-strength 2169 stainless steel tube bending, revealing the influence of parameters such as mandrel shape, diameter, and feed rate on wall thickness; Jiang et al[13, 14] studied the variation of the wall thickness of a TA18 tube in the process of bending under the action of a mandrel ball and different bending radii; Murata et al[15] found that the strain-hardening index has a negligible effect on the change of wall thickness in the bending process of the tube; Wu et al[16] investigated the influence of parameters such as temperature, bending velocity, and grain size on the change of wall thickness of AM30 Mg-alloy steel tube in the bending process by experimental method and found that temperature changes the thinning rate by affecting the grain size. These studies have shown that the outer wall of the tube is inevitably thinning with different tubes and bending processes. To restrain the excessive thinning rate, the boost condition is often used to reduce the thinning. Domestic and foreign scholars have conducted many analyses on the parameters of the boosting process. For example, Bardeleck et al[17] studied the effect of three horizontal pressurizations on the wall thickness distribution of tubes. It is found that the thinning rate of the tube's outer wall decreases, and the inner wall's thickening rate increases under pressurization. Jyhwen et al[18] predicted the outer wall thinning of steel tubes under different loading conditions based on plasticity theory, taking into account additional axial tension and internal pressurization conditions; Zhang et al[19] introduced additional compressive stress in the theoretical analysis and considered the wall thickness thinning under the condition of die boost in the bending process and found that the outer wall thinning of tubes could be suppressed under proper boosting conditions; Li et al[20, 21] illustrated the effects of side and booster pushes on wall thinning in the bending of thin-walled aluminum alloy tubes, analyzed five different types of booster pushes in the bending process of tubes, and concluded that the booster pushes are the most significant when the thrust is applied to the end of the tube. These studies have demonstrated that the boosting effect improves the stress distribution characteristics of the tubes and thus reduces the
thinning rate of the tubes. The boosting effect changes the mechanical mode of action of the tube and produces a better material compensation effect. Mechanically, applying the boost movement adds a frictional effect to the tube, and this friction will exhibit the effect of stretching or compressive effect on the bending section of the tube. In addition, the boosting effect improves the flow effect of the material. Many engineering practices\cite{21, 22} show that materials in the feed section can flow more rapidly to the bending section under boosting, forming a material compensation effect. That is, boosting on the tube is a coupling effect of material compensation and friction. However, the mechanism of this coupling effect is still unclear.

Therefore, to solve the problem of tube wall thinning under boost conditions, the inhibition characteristics of tube thinning induced by the coupling of boosting material compensation and friction are investigated. The finite element method was used to analyze the thinning characteristics of the tube boost and non-boost. The effects of different boosting velocities and friction coefficients on the thinning of the outer wall of the tube were investigated. The experimental results showed that the compensation of booster material and friction coupling effect inhibited the thinning of the tube. On this basis, the theoretical models of boost friction, material compensation, and wall thickness are derived, and a theoretical model of outer wall thinning under boost conditions is formed.

2. Boost Condition Analysis

In the bending process, as shown in Fig 1, three sections will be formed in the tube's bending process: feed section, bend section, and clamp section. In the clamp section, the clamping die clamps the tube and rotates around the central axis of the bending die. The clamping dies, and the clamp tube remains relatively static. The tube is continuously stretched in the bending section, and the feed section material gradually enters the bend section. In the feed section, the pressure dies, the anti-wrinkle die presses the tube tightly, and the tube slides along the axial direction of the tube in the bending process. In the non-boost process, the pressure die is stationary, and this non-boost process is prone to defects such as thinning of the outer wall and even cracking for difficult-to-process tubes (as in Fig 2 (a)). In the boosting process, the press mold moves forward along with the direction of the tube, which can better inhibit the thinning of the outer wall of the tube and the phenomenon of breakage (as in Fig 2 (b)). Due to the complicated mechanism of the effect of the boost on the tube bending process, the finite element method was used to analyze the mechanism of the tube wall thinning suppression under the boost condition\cite{23, 24}.
3. Finite Element Modeling

3.1 Geometrical Modelling

Abaqus software was used to establish a three-dimensional finite element model of tube bending and forming, as shown in Fig 3. The outer diameter of the tube is 90 mm, the wall thickness is 1.5 mm, and the material is carbon steel. The length of the pressure die is 500 mm, the anti-wrinkle die is 250 mm, the clamp film is 210 mm, and the die clamp insert is 220 mm. Shells are selected for each component, in which the forming mold is defined as a discrete rigid body, and the tube is defined as a variable body. As shown in Fig. 1, $e_m$ is the mandrel protrusion; $R$ is the mandrel protrusion; $R$ is the tubing bending radius; $n$ is the number of core balls; $k$ is the core ball thickness; and $s$ is the core ball clearance.
When bending and forming the tube, a mandrel is usually installed to provide specific support to prevent the tube's lateral collapse and improve the tube's cross-section distortion. At the same time, it is matched with the anti-wrinkle die to restrain the inside of the tube from buckling and wrinkling[25, 26]. The mandrel is composed of a mandrel and a mandrel ball; the mandrel is used to support the straight section of the tube, and the mandrel ball is used to support a curved section.

For supporting straight sections of the tube, the gap between the mandrel and the inner diameter of the tube affects the material flow of the tube, which has a significant impact on the thinning of the outer wall and the thickening and wrinkling of the inner wall of the tube[27]. In addition, the extension of the mandrel projection has a specific effect on the thinning of the outer wall. When the extension amount is too large, the end of the mandrel will push against the outside of the tube when bending, resulting in a possible bulge in the tube, dramatically reducing the outside's thinning rate or even cracking it[28]. The maximum extension of the mandrel is obtained from the empirical formula:

$$e_{\text{max}} = \sqrt{(R + \frac{d}{2} - t)^2 - (R + \frac{d_m}{2})^2 + r_m}$$  \hspace{1cm} (1)

Where $d_m$ is the mandrel diameter, and $r_m$ is the mandrel chamfer.

As a result, the mandrel extension is finally determined to be 8 mm according to the tube forming requirements.

3.2 Boundary Condition Determination

The model uses Von Mises’ yield criterion, related flow rule, and motion hardening. The mechanical property parameters of the tubes are shown in Table 1.
The simulation process parameters in the tube bending and forming process are shown in Table 2. The bending die rotates around the center axis, the bending time is 10 seconds, and the bending angle is 90°. The clamping dies, the die clamp insert rotates with the bending die, and the relative position with the bending die remains unchanged. The mandrel and anti-wrinkle die remain stationary, restraining all degrees of freedom. The core ball is not constrained and retains all degrees of freedom. The pressure die pushes against the tubing feed with a boost velocity \( v \) of the same magnitude as the bending die linear velocity \( v_0 \). Therefore, the boundary conditions are set according to the above situation. The angular velocity of the bending die is set to 0.157 rad/s. The pressure die pushes the tube with the tangential linear velocity of the bending die of 31.4 mm/s.

### Table 1 Mechanical property parameters of steel tube material

<table>
<thead>
<tr>
<th>parameter</th>
<th>numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ( \rho )/(kg*mm²)</td>
<td>7.93e-6</td>
</tr>
<tr>
<td>Young’s modulus ( E/) MPa</td>
<td>2.08e5</td>
</tr>
<tr>
<td>Initial yield stress ( \sigma_s/) MPa</td>
<td>418</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Strength coefficient ( K/) MPa</td>
<td>1050</td>
</tr>
<tr>
<td>Hardening exponent ( n )</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The friction between the tube and each forming mold affects the forming quality of the tube. In particular, the friction between the die and the tube has an essential influence on the boosting effect of the die. Therefore, it is necessary to introduce suitable friction coefficients in the simulation[10, 29, 30]. According to the bending characteristics of the tube, the classical coulomb friction is used to describe the friction properties between the tube and each forming die. The friction coefficients between the tube and each forming die are shown in Table 3.

### Table 2 Process parameters boost tube bending and forming simulation

<table>
<thead>
<tr>
<th>parameter</th>
<th>numerical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final bending angle ( \theta/) (°)</td>
<td>( \pi/2 )</td>
</tr>
<tr>
<td>Bending die radius ( R/) mm</td>
<td>200</td>
</tr>
<tr>
<td>Velocity of pressure die ( v/() mm ∙ s⁻¹)</td>
<td>31.4</td>
</tr>
<tr>
<td>Bending velocity ( \omega/() rad ∙ s⁻¹)</td>
<td>0.157</td>
</tr>
<tr>
<td>Bending time ( t/) s</td>
<td>10</td>
</tr>
</tbody>
</table>

### Table 3 Friction coefficients between the tube and each forming mold

<table>
<thead>
<tr>
<th>contact surface</th>
<th>friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube and bending die</td>
<td>0.10</td>
</tr>
<tr>
<td>Tube and die clamp insert</td>
<td>0.95</td>
</tr>
<tr>
<td>Tubes and clamping die</td>
<td>0.95</td>
</tr>
<tr>
<td>Tube and pressure die</td>
<td>0.30</td>
</tr>
<tr>
<td>Tube and wrinkle-free die</td>
<td>0.20</td>
</tr>
<tr>
<td>Tube and mandrel</td>
<td>0.15</td>
</tr>
</tbody>
</table>
4. Analysis and Discussion of Results

The forming results are analyzed for a boosting velocity $v_0$ under the boosting condition. The wall thickness changes after the tube bending, as shown in Fig. 4. The inner thickness of the tube increases, and the maximum thickness is 1.725 mm, which increases by 0.225 mm compared with the initial wall thickness. The outer wall thickness decreases; the minimum thickness is 1.273 mm, 0.227 mm less than the initial wall thickness. Accordingly, it can be calculated that the tube thickening rate is 15.0 percent, and the thinning rate is 15.2 percent. The deformation of the tube bending part of the tube is further analyzed, as shown in Fig. 5. The strain of the outer wall is greater than that of other parts. The plastic tensile strain occurs on the outer side of the tube under the action of tensile stress, resulting in a sharp increase in the thinning rate.

![Fig. 4 Tube thickness distribution](image1)

![Fig. 5 Bending equivalent strain distribution](image2)

To investigate the change mechanism of the outer wall thickness of the tube, the spatial and temporal distribution characteristics of the tube stress during the forming process are analyzed, as shown in Fig. 6(a). In the tube's bending process, the external stress of the tube changes dynamically. In the initial forming process, by the bending deformation, the stress rises first and then falls. Plastic deformation occurs and finally stabilizes at about 380 MPa. In addition, it can be found that the time-varying characteristic curves of the external stress of the tube are more consistent at different bending points. The maximum stress is relatively stable. Still, the stress curves at different bending points show time-delay characteristics. This indicates that the stress has the characteristics of spatial transfer during the bending process, and the process and the bending rotation generate the stress wave die in the tube clamping section and are gradually transferred backward to the feed section. The spatial and temporal variation characteristics of strain are further analyzed, as shown in Fig. 6(b). The strain increases sharply with time and finally stabilizes around 0.285. Meanwhile, the strain characteristic curves are more consistent at different bending points and have a delay effect. This delay characteristic of stress and strain is the spatial transfer behavior of stress and strain. The transfer rate is related to the bending velocity. The greater the bending velocity, the shorter the lag time and the faster the transfer rate.
To investigate the inhibition mechanism of the outer tube thinning under boost conditions, the outer wall thinning characteristics of the tube boost and non-boost conditions are analyzed, as shown in Fig. 7. From the thinning results, the thinning rate of the outer wall of the tube presents bell-shaped distribution characteristics. The thinning rate shows continuous thinning at 0°-20° at the beginning of the bending. The 20°-70° position can be maintained relatively stable in the bending center section. The termination of section 70°-90° shows rapid decline characteristics. However, the thinning rate of the outer wall of the tube is stable at about 15.2% under boosted conditions, and the thinning rate is weakened by 7.3% compared with that under non-boost conditions, dramatically improving the tube's forming quality. Therefore, the boosting condition plays an essential role in producing high-quality tubes.

To study the inhibition mechanism of the boosting effect on the thinning of the tube's outer wall, the outer wall's mechanical properties in the tube-forming process were analyzed. As shown in Fig. 8, the temporal and spatial evolution of stresses of the tube boost and non-boost shows a similar rule of change, which indicates that boosting does not affect the overall deformation
tendency of the tube. Still, it can reduce the bending stresses and bending strains to a certain extent. The time-varying characteristics of stress and strain at the position of 45° bending angle of the outer wall of the tube, for example, are shown in Fig. 9. In terms of the tube stresses, the bending stress curves boost and non-boost conditions in the initial forming stage (0-6 s) overlap exceptionally well. This indicates that the boost effect does not change the stresses in the elastic deformation stage of the material. Still, in the stable forming stage (6-10 s), the bending stresses under the boosted condition are significantly lower than those under the non-boost condition. This indicates that in the plastic forming stage, the boost produces an additional compression effect on the bent section of the tube, and the tube bending process has changed into a process of compressive bending with combined force. It is clear that this boosted compression effect can offset a part of the bending tensile stresses, and this stress offset effect is conducive to mitigating the tube wall thinning characteristics.

Regarding the tube strain, in the initial forming stage (0-6 s), the strain under the boosted condition is lower than that under the non-boost condition. At this stage, the boost effect does not change the stress significantly. This suggests that the strain drop phenomenon in the elastic phase is not related to the boost compression effect. Boosting produces not only mechanical compression effects but also material compensation effects. During the boosting process, the tube in the feed section is strained, and part of the material is transferred to the bending section, compensating for the outer wall's thinning. During the stable forming phase (6-10 s), the strain under the boost condition decreases sharply compared with that of the non-boost condition, which is caused by the combination of the material compensation effect in the feed section and the offsetting effect of the compressive stress in the bending section.

As shown in Fig. 10(a), from the spatial distribution characteristics of the maximum stress and strain applied to the bend section of the tube, the boost effect has a particular weakening effect on the material stress during the forming process, and the weakening amount is about 2.4%. Although the boost effect has little effect on weakening stress, the deformation suppression is highly significant, as shown in Fig. 10(b). the boost effect, the deformation is weakened by 7.8% compared with the non-boost condition. A comparison of the weakening effects of stress and strain shows that the strain weakening is more significant than the stress weakening effect. This further suggests that, besides weakening the deformation by reducing the stress, the boosting effect can compensate by pushing part of the material directly from the feed section to the reduced outer wall thinning in the bend section.
To continue to explore the mechanism of improving the quality of the outer wall of the tube under the condition of pushing the die, finite element simulation was used to regulate the parameters affecting the effect of the pressure-assisting die, such as the pressure-assisting velocity $v$, the friction coefficient $\mu$ between the pressure-assisting die and the tube and the relative bending radius $R/d$[31].
etc., and to observe the change characteristics of the thinning rate of the outer wall of the tube.

Fig. 11 Relationship between die boosting velocity and tube outer thinning rate

The control variable method was used to change only the boosting velocity of the press mold, as shown in Fig. 11. The boosting velocity greatly influences the thinning rate. In the range of boosting velocity from $0.9 \sigma_0$ to $1.1 \sigma_0$, the thinning rate of the outer wall of the tube shows a sharp decrease with increasing velocity. In the bending and forming process, the friction force is generated when the die and the tube slide relative to each other. When the boosting velocity is less than $\sigma_0$, the sliding friction force on the outer wall of the tube is in the opposite direction to the feeding direction, which plays a pulling role in the curved section and dramatically reduces the thickness of the outer wall. When the boosting velocity is more significant than $\sigma_0$, the velocity increases, gradually changing the direction of the friction force and forming a compression effect on the bending section of the tube. At the same time, the tensile effect on the feed section is formed, which can promote the material flow and compensate for the thinning of the outer wall of the bending section. In addition, increasing the boosting velocity will not change the friction when the boosting velocity is large enough, and the friction is entirely steered. The material flow effect will change little, and the boost effect will not change significantly. Therefore, it is possible to improve the quality of the tube by controlling the die-boosting velocity in the process of bending forming, which is of great importance for the improvement of the reliability of the tube in engineering.

Fig. 12 Relationship between coefficient of friction and external pipe thinning
The friction coefficient of the contact surface between the die and the tube significantly affects the die's boosting effect. Because the contact between the die and the tube is under the Coulomb friction model, the friction coefficient between the two becomes the key to influencing the friction force when the positive pressure is constant. As shown in Fig. 12, in the condition of non-boost or the boosting velocity is less than $v_0$, the friction coefficient $\mu$ increases, which can increase the reverse friction and enhance the stretching effect of the bending section during the boosting process, so that the thinning rate of the outer wall is further increased; On the contrary, when the boosting velocity is more significant than $v_0$, as the friction coefficient $\mu$ increases, the compression effect of the bend section is enhanced during the boosting process. It also improves the compensation effect of the material from the feed section to the bend section, which reduces the outer thinning rate of the tube under the combined effect of the twos. Therefore, in the condition of non-boost, the friction coefficient between the die and the tube should be reduced as much as possible so that the die only plays a supporting role and reduces its reverse friction. Alternatively, the boosting velocity of the compression mold is greater than the linear velocity $v_0$ of the tube bending, in this case, changing the direction of friction so that the material compensation effect takes effect with the compressive stress in the bending section and reduces its outer thinning rate.

![Fig. 13 Relative bending radius versus outer tube thinning rate](image-url)
Table 5 Boosting effect of different relative bending radii

<table>
<thead>
<tr>
<th>R/d</th>
<th>non-boost condition ζ_max</th>
<th>boosted condition ζ_max</th>
<th>Δζ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>37.02%</td>
<td>20.46%</td>
<td>16.56%</td>
</tr>
<tr>
<td>2</td>
<td>23.06%</td>
<td>14.60%</td>
<td>8.46%</td>
</tr>
<tr>
<td>2.5</td>
<td>16.68%</td>
<td>11.63%</td>
<td>5.05%</td>
</tr>
<tr>
<td>3</td>
<td>13.89%</td>
<td>9.86%</td>
<td>4.03%</td>
</tr>
</tbody>
</table>

Minor radius bending is likely to reduce the thinning rate of the tube, as shown in Fig 13. It is evident that the smaller the relative bending radius R/d, the greater the thinning rate of the outer wall of the tube. However, the effect of its boost on the thinning of the outer wall of the tube is not the same for different bending radii. As shown in Table 5, when R/d is 1.5, the maximum thinning rate is 20.46% under the boost condition, which is 37.02% under the non-boost condition, and there is a decrease of 16.56% in the maximum thinning rate. Similarly, compared to the non-boost condition, the maximum thinning rate decreases by 8.46%, 5.05%, and 4.03% for R/d of 2, 2.5, and 3, respectively, in the boost condition. Accordingly, in the boosted condition, the material compensation effect of the feed section is more significant in the small radius bending condition. This is because the smaller the bending radius, the shorter the length of the bending section of the tube, and the compensation materials generated by the boost can be more fully transferred to the thinning area of the outer wall to decline its thinning rate. Therefore, in the engineering of small radius bending forming, the compression mold boosting method can be used to advance the outer wall thinning.

5. Experimental Verification

A bending machine was used to bend the tube forming, as shown in Fig 14. The structural parameters of the tube machine mold and the bending and forming process are the same as those analyzed in the simulation. It is the dry friction between the tube and the die; There is no relative sliding between the tube and the inner concave surface of the clamping die and the die clamp insert. The bending die, clamping die, and die clamp insert rotate around the axis of the bending die simultaneously. The pressing die moves along the bending die's direction under the impetus of the booster cylinder. The tube undergoes bending deformation under the driving action of the dies.
Firstly, the experimental results were measured and analyzed for the non-boosted condition, as shown in Fig. 2(a). During small-radius bending, the outer wall of the tube fractured near the bending angle of 15°, and the wall thickness near the crack in the outer wall was 0.981 mm, with a thinning rate of 34.6%. This indicates that during the tube bending process, the outer wall thickness of the tube continues to decrease at the start of the bend, while the cracking phenomenon occurs when the wall thickness drops to a certain level. However, the tube is smoothly bent and formed under the boosting condition, as shown in Fig. 15. At the same time, the wall thickness simulation calculation value of the corresponding bending angle of the tube is extracted, and the change curve of the outer wall thickness of the tube with different measurement angles is plotted.

The simulation and experimental results show that the outer thinning rate shows the same trend with different bending angles, as shown in Fig. 16. The thinning rate increases continuously in the initial bending section. Still, it decreases sharply in the end stage and tends to be stable in the middle.
bending section. In addition, the maximum thinning rate in the experimental result is 16.51%, which is 1.34% higher than the simulation result. The main reason for the deviation of the thinning rate is the inconsistency of the friction state of the contact surfaces. In the experiment, the tube bending process will cause the contact to rise in temperature, and the friction coefficient between the mold and the tube is difficult to control.

In contrast, the friction coefficient of each contact surface in the simulation is constant and homogeneous, and this ideal situation deviates from the experiment. In addition, some factors, such as the tube's material properties, the mold's wear and tear, and the experimental environment, can also affect the tube forming. However, on the whole, the simulation results are consistent with the tube shape obtained from the experimental results, and the distribution trends of the parameters, such as the thinning rate, are the same, which can fully illustrate that the simulation model constructed in this paper is reliable. The corresponding essential technology processing is reasonable and feasible.

Fig. 16 Comparison of experimental and simulated outer wall thinning rate change

6. Theoretical Modeling Construction for The Thinning Suppression of Boost

In the tube bending process, a large number of scholars have adopted the traditional modeling theory without considering the effects of the boost friction effect and material compensation mechanism on the thinning of the bending section under the boost condition, whose outer wall thinning model[32] is expressed as follows:

$$\Delta t_o = \frac{1}{2} [(R + t + r) - \sqrt{(R + t + r)^2 - 4rt(1 + \sin \alpha)}]$$

(2)

Where \(r\) is the outer diameter of the tube, \(t\) is the tube's wall thickness, \(R\) is the tube's bending radius and \(\alpha\) is the neutral layer deviation angle[33]. The neutral layer deviation angle \(\alpha\) can be obtained by the following equation:

$$\alpha = \arccos \frac{\sqrt{R^2 - r^2} - R}{r} - \frac{\pi}{2}$$

(3)
From equations (2) and (3), it can be seen that the traditional tube outer wall thinning model is related to critical factors, such as the bending radius, tube outer diameter, and wall thickness, but not considering the influence of other relevant factors. This theoretical model is adaptable to non-boost bending, but its error is significant for boosted conditions. Therefore, to establish the thinning model under boosted conditions, it is necessary to consider other factors, such as the boosted friction effect and the material compensation effect.

(1) Analysis of booster friction effects

In the forming process, the compression mold applies a large uniform load to the tube under the action of the compression cylinder, as shown in Fig. 1. The compression length of the compression mold is \( L_p \), and a uniform load \( q \) is applied to the tube. The bending moment formed by the uniform load is:

\[
M = \frac{1}{2} qL_p^2
\]

\( M \) is the bending moment, \( q \) is the uniform load, and \( L_p \) is the load acting length.

According to the condition of the moment balance, the bending moment formed by uniform load should be balanced with the central driving moment of the bending die. The bending moment of tube plastic forming is analyzed, and it is concluded that the bending moment of tube bending forming needs to satisfy the following equation:

\[
M = 2(r + \frac{t}{2})^2 t \left[ \frac{4}{\sqrt{3}} \sigma_s (1 - \frac{K}{E}) \cos \alpha + \frac{2Kr \pi}{3(R - r \sin \alpha)} \right]
\]

(5)

Where \( \sigma_s \) is the material yield strength, \( K \) is the material hardening index, and \( E \) is the material elastic modulus.

Therefore, according to equations (4) and (5), it can be derived that the homogeneous load of the compression mold needs to satisfy the following expression:

\[
q = 4(r + \frac{t}{2})^2 \frac{t}{L_p} \left[ \frac{4}{\sqrt{3}} \sigma_s (1 - \frac{K}{E}) \cos \alpha + \frac{2Kr \pi}{3(R - r \sin \alpha)} \right]
\]

(6)

In the boosting condition, the die creates a friction force on the tube as follows:

\[
F_f = \mu qL_p
\]

(7)

Where \( F_f \) is the friction between the die and the tube \( \mu \) is the friction coefficient.

When the compression mold velocity \( v \) is greater than the bending mold linear velocity \( v_0 \), the friction will produce compressive stress on the outer wall of the bending section. Conversely, it will act as a tensile force on the outer wall of the bending section.

\[
\sigma_p = -\frac{2F_f}{\pi dt}
\]

(8)

At the same time, the compression effect is formed in the bending section because of the friction action. The compressive strain should satisfy the following equation:
\[ \varepsilon_p = \frac{\sigma_p}{K} \]  

(9)

Where \( \varepsilon_p \) refers to the friction compression strain.

According to the principle of conservation of mass, without considering the circumferential diffusion of the material, the reduction in compression of the outer wall of the tube will be compensated by the wall thickness, which can be expressed as:

\[ \varepsilon_r = -\varepsilon_p \]  

(10)

During the bending process of the tube, its axial strain obeys the following relationship:

\[ \varepsilon_r = \ln \frac{t - \Delta t_0}{t} \]  

(11)

Thus, the compressive thickening \( \Delta t_1 \) caused by the boost friction effect can be expressed as:

\[ \Delta t_1 = t - t e^{-\varepsilon_p} \]  

(12)

(2) Analysis of the compensation effect of booster materials

Extensive finite element analyses were carried out to investigate the compensation mechanism. Regression analysis calculations were performed on the obtained data to derive the relationship between material compensation \( \Delta L \) and \( \mu \) and \( v \) in boosted working conditions:

\[ \Delta L = k_1 \mu + k_2 v + C_2 \]  

(13)

Where \( k_1 \) is the friction slip coefficient, \( k_2 \) is the velocity slip coefficient, and \( C_2 \) is the bending slip constant.

According to the principle of volume invariance, the amount of material compensation from the feed section to the bend section should meet the following formula:

\[ \pi [(r + t)^2 - r^2] \Delta L = 2 \pi r R \theta \Delta t_2 \]  

(14)

Therefore, the resulting wall thickness increment \( \Delta t_2 \) caused by the material compensation effect can be expressed as:

\[ \Delta t_2 = \frac{\Delta L [(r + t)^2 - r^2]}{2 r R \theta} \]  

(15)

Under the boosting condition and based on the traditional tube outer wall thinning formula, a new expression for the thinning can be derived as follows by considering the coupling of boosting friction and material compensation effect:

\[ \Delta t = \Delta t_0 + \Delta t_1 + \Delta t_2 \]  

(16)

During the tube bending, the tensile outer side of the tube will cause the wall thickness thinning. The wall thickness thinning rate is often used to measure the thinning degree, as shown in the
following formula:

\[ \zeta = \frac{\Delta t}{t} \times 100\% \]  

(17)

Fig. 17 Comparison of theoretical and experimental results

In the case of different bending radius R and tube diameter d ratios, the changes of the traditional theoretical model and the new theoretical model of tube wall thinning rate are derived and analyzed by comparing with the experimental results, as shown in Fig. 17. The trends of the thinning rates of the traditional theoretical model, the new theoretical model, and the experimental results are similar. Among them, the thinning rate of the new theoretical model decreased by about 5.3% compared with the traditional model, and it was more similar to the experimental value with a relative error of less than 1.5%. The research shows that the boost friction and material compensation effects cannot be neglected under the boost condition. Considering both of them, the new theoretical model of tube wall thinning is more accurate in predicting the outer wall thinning phenomenon of the tube.

7. Conclusions

This paper investigates the inhibitory effect of boosting conditions on tube bending and forming thinning. The finite element method, experimental research, and theoretical modeling were used to study the effect of boosting on the thinning of the outer wall of the tube. The main conclusions are as follows:

(1) The mechanism of boost friction and material compensation for the bending section of the boost effect has been clarified, which reveals the problem of the unknown mechanism of the boost effect on the thinning of the material. On the one hand, the friction generated by the boost can produce a certain amount of compressive stress and weaken the tensile stress in the bending process of the outer wall. On the other hand, the feed section of the material was transferred to the bending section under the boosting effect, which compensates for the phenomenon of the tube wall thinning in the bending process.
(2) The boost friction effect exhibits two opposite effects before and after the bending linear velocity $v_0$ of the tube. When the boosting velocity is lower than $v_0$, the outer wall of the tube slips faster than the boosting mold, and the friction shows a stretching effect on the material in the bending section. When the boosting velocity is higher than $v_0$, the friction force exhibits a compression effect on the material of the bend section, and the larger the friction coefficient is, the more pronounced the compression effect is; therefore, to inhibit the rate of thinning of the outer wall, it is recommended that the boosting velocity is not lower than $v_0$.

(3) The compensating effect of the booster material is highly effective in small-radius bending conditions with high friction coefficients. Increasing the friction coefficient can effectively increase the friction between the mold and the tube to quickly push the material to the bend section from the feed section. Especially for the small radius bending severe condition, the greater the amount of material compensation and the shorter the tube arc length to be compensated, the more fully transferred to the outer wall of the thinning region of the compensation material. Thus, the outer wall thinning will be effectively suppressed.

(4) A theoretical model of tube thinning considering the coupling of boost friction and material compensation effect is proposed, which overcomes the problem of poor adaptability of the existing thinning rate model to the boost condition. The study results show that the new theoretical model reduces the thinning rate by about 5.3% compared with the traditional model, the relative error with the experimental value is within 1.5%, and the outer wall thinning phenomenon of the tube can be accurately predicted.

Declaration of competing interest

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.

Credit authorship contribution statement

Hao Fang: Investigation, Software, Measurements, Data analysis and interpretation, Model development, Writing - original draft, Formal analysis. Zhineng Wang: Conceptualization, Methodology, Writing - review & editing, Project administration, Supervision. Guangfu Bin: Conceptualization, Methodology, Investigation, Project administration, Supervision. Weiming Lin: Conceptualization, Methodology, Investigation. Yaochen Lin: Conceptualization, Methodology, Investigation. Cong Trieu Tran: Conceptualization, Methodology, Investigation.

Acknowledgment

Science and Technology Research Project of Zhejiang Jinmasun Intelligent Manufacturing Corp, LTD. "Research on Instability Inhibition Mechanism of Flexible Small Radius Forming of Bending Members"[Grant No. D1226]; This work was supported by the National Natural Science Foundation of China [Grant No. 52175091].

Introduction

[1] X. Shen, K. Feng, H. Xu, G. Wang, Y. Zhang, Y. Dai, W. Yun, Reliability analysis of bending fatigue life of
hydraulic pipeline, RELIABILITY ENGINEERING & SYSTEM SAFETY 231 (2023).


