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Study on the Law of Blank and Material Properties on the Free Bending of Pipes

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Short Communication

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ABSTRACT

To explore the impact of various material parameters on the three-dimensional free bending behavior of metal pipes and enhance the quality of such bending processes, this study focused on TP2 copper pipes with dimensions Φ12mm×1mm. Under uniform conditions of process parameters, free bending equipment, and key component characteristics, pipes with varying wall thicknesses and materials were investigated. The evaluation criteria were based on the maximum wall thickness thinning rate and maximum ellipticity of the pipes. The investigation aimed to understand how alterations in different material parameters affect bending radius, propulsive force, and wall thickness of the pipes. The results revealed that smaller bending radii correlate with more pronounced influences of wall thickness on pipe curvature. Additionally, an increase in wall thickness led to a decrease in pipe forming quality. The bending radius of the pipe was determined

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by multiple parameters, including the material's elastic modulus, yield strength, pipe hardening index, and strength coefficient. The maximum ellipticity of the pipe was found to be associated with material strength, while the alteration of pipe wall thickness was influenced by the hardening index, denoted as 'n'.

Keywords: Pipe; free bending; numerical simulation; material properties; forming law.

1. INTRODUCTION

As the processing technology of hollow components with complex structures becomes more and more perfect, the application fields of metal hollow components are also more extensive, such as in aviation, aerospace, medical treatment, construction and home decoration and other fields [1]. At the same time, various fields have put forward higher requirements for the forming technology of hollow pipes. Compared with the traditional bending process, the tube free bending process can complete the complex three-dimensional continuous variable curvature forming of the metal hollow member, and greatly improve the processing efficiency under the premise of ensuring higher forming quality.

The three-dimensional free-bending process of metal pipes first began with the MOS Bending technology proposed by Japanese scientist Murata [2] and his team in 1989. In recent years, a large number of scholars have conducted a lot of research on the free-bending forming law and forming quality.

Li Yusen [3] studied the influence of changes in parameters such as bending die clearance, pipe feed speed, and friction coefficient on the quality of pipe forming, and determined the optimal process parameters within the test range. The test proved that the pipes under the optimal process parameters have better Good forming quality.

Teng Kelei [4] took the solid metal skeleton inside the aluminum alloy car body as the object, designed a special mold for the skeleton, and bent the solid profile. The test showed that the three-dimensional free bending process can realize the precise three-dimensional free bending of solid metal components.

Cheng Xuan [5] studied the effect of different parameters on the forming of rectangular tubes during free bending. The research shows that as the yield strength, thickness, fillet radius, pipe die clearance, friction coefficient and guide mechanism fillet radius increase, the thickness change rate and section deformation decrease, and the pipe bending radius increases. As the axial feed rate increases, the tube thickness change rate decreases.

When Wei Wenbin [6] changed the bending curvature of pipes with different diameters, he compared the changing trend of the neutral layer and wall thickness of the pipes, and did an actual test for comparison. He concluded that the smaller the bending radius of the pipe, the more the neutral layer moves outward. Large, the change of the bending radius has a greater influence on the inner wall thickness of the pipe, but less influence on the outer wall thickness.

Li Tao [7] 's research on the spiral forming process in three-dimensional free bending found that the ellipticity of the pipe bending section is related to the helix diameter and pitch, and the outward offset of the neutral layer of the pipe during the bending process gradually decreases with the increase of the helix diameter.

Based on the three-axis free bending equipment, this paper takes the TP2 copper pipe of Φ12mm*1mm as the main research object, and studies the influence of related blanks and material properties on the bending of pipes.

2. THREE-DIMENSIONAL FREE BENDING FORMING PRINCIPLE

The key components of the three-axis free bending forming equipment are mainly composed of spherical bearings, propulsion mechanisms, bending dies, and guiding mechanisms, as shown in Fig. 1. The guide mechanism is fixed, the propulsion mechanism moves at a constant speed along the Z axis, the spherical bearing moves in the XY plane, and the bending die moves and rotates in the XY plane. Under the combined action of the bending die, the propulsion mechanism and the guide mechanism, the pipe can be bent arbitrarily in the three-dimensional direction.

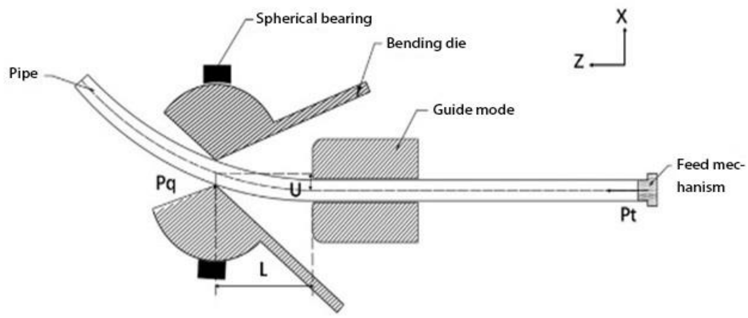


Fig. 1. Structural diagram of triaxial free bending

When the pipe is bent, it is subjected to the bending moment exerted by the bending die and the propulsion mechanism. The bending moment of the pipe during the bending process is [8]:

$$M = P_q L + P_t U$$

Among them, U is the eccentricity of the spherical bearing, L is the length of the bending deformation zone, the propulsion force of the spherical bearing on the pipe is P_q , and the propulsion force of the propulsion mechanism on the pipe is P_t.

3. TUBE MECHANICAL PERFORMANCE TEST AND FREE BENDING FINITE ELEMENT SIMULATION

3.1 Pipe Mechanical Performance Test

In order to obtain the mechanical performance parameters of the TP2 pipe and ensure the accuracy of the numerical simulation, the tensile test of the TP2 copper pipe is carried out with a universal tensile testing machine, and the pipe is stretched in one direction, assuming that the pipe material is isotropic. Before stretching, it is necessary to make a special fixture plug to prevent serious deformation at both ends of the pipe [9], which will affect the accuracy of the test. The gauge length section of the pipe is 50mm, the tensile speed is 2mm/min, and the tensile test is repeated three times to obtain the average value. Table 1 displays the mechanical properties of TP2 copper tube acquired through tensile tests.

Constitutive relation of TP2 pipe in elastic stage

$$\sigma = E\varepsilon$$

Because of the work hardening phenomenon of the pipe during the bending forming process, the power exponent hardening model is used to express the plastic deformation part of the pipe.

$$\sigma = K\varepsilon^n + b$$

The fitting curve of the power exponential hardening model selected for the plastic stage of TP2 pipe is shown in Fig. 3.

(a) (b) (c)

Fig. 2. (a) Universal testing machine (b) Sample and plug (c) Broken tube

Table 1. Mechanical property parameters of TP2 pipe

Elastic modulus(GPa)	Yield strength(MPa)	Tensile strength(MPa)	Density(kg/m^3)	Poisson's ratio
115	33.48	376.87	8940	0.31

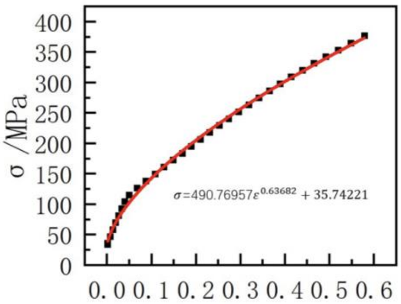
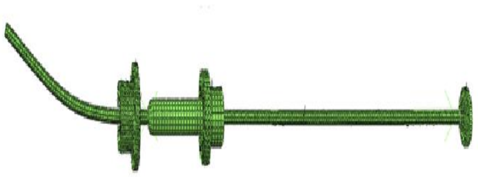


Fig. 3. $\sigma - \varepsilon$ fitting curve



ig. 4. Finite element model of pipe bending

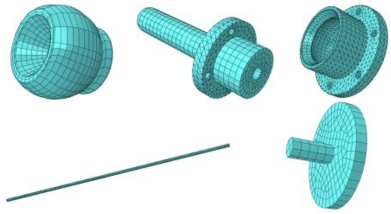


Fig. 5. Mesh division of each component

3.2 Pipe Finite Element Model Establishment

Based on the finite element analysis software ABAQUS, a three-dimensional finite element model of the pipe bending process was established, and the model diagram is shown in Fig. 4. Spherical bearings, guiding mechanisms, bending dies, and propulsion mechanisms are set as discrete rigid bodies, and pipes are set as deformable entities. When using Abaqus software for simulation, the Auaqus/Explicit solver is selected for analysis. In order to speed up the calculation and make the simulation results more accurate [10], the mass scaling factor is set to 25, the friction coefficient is 0.1, and the general contact is set. The pipe is set as a shell, and the SR4 general-purpose shell element is used to divide the mesh. The bending die adopts the C3D8R eight-node hexahedron element to divide the mesh. Other rigid body models use the R3D4 mesh. The mesh division is shown in Fig. 5.

The evaluation indicators of pipe forming quality mainly include pipe wall thickness change rate and pipe ellipticity:

$$\text{Rate of wall thickness thinning} = \frac{t - t_{min}}{t} \times 100\%$$

t -the original wall thickness of the pipe (mm), t_{min} -the minimum wall thickness of the pipe (mm). In engineering, it is considered that the wall thickness reduction rate of the elbow should not be higher than 10% to be qualified [11].

$$\text{Ellipticity} = \frac{D_{max} - D_{min}}{D_{max}} \times 100\%$$

D_{max} -the maximum cross-sectional diameter of the pipe, D_{min} -the minimum cross-sectional diameter of the pipe. In industrial pipelines, the ellipticity of copper tubes is required to be no higher than 8%.

4. ANALYSIS OF THE INFLUENCE LAW OF PIPE PARAMETERS ON FORMING

4.1 Analysis of the Influence of Different Wall Thickness Pipes on Forming

TP2 copper tubes with wall thicknesses of 0.5mm, 1mm, and 2mm were respectively selected for simulation. It can be seen from Fig. 6 that in the transition section of 0-1s, as the eccentricity of the bending die increases, the bending pipe gradually changes from the elastic deformation stage to the plastic deformation stage, and the thrust of the pipe in the Z-axis direction also gradually increases. In the arc segment of -4s, the bending moment on the pipe remains unchanged during the moving process, and the Z-axis thrust on the pipe gradually becomes stable. As the wall thickness increases, the Z-axis thrust on the pipe gradually increases.

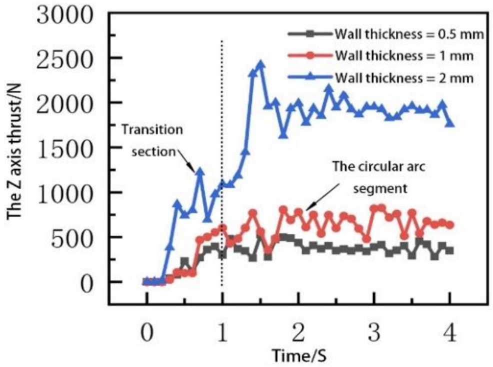


Fig. 6. Variation of z-axis thrust of tube under different wall thickness

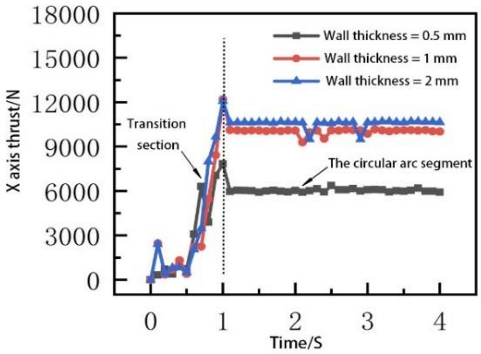


Fig. 7. Variation of x-axis thrust of tube under different wall thickness

The thrust of pipes with different wall thicknesses in the X-axis direction is shown in Fig. 7. The increase in wall thickness gradually increases the thrust of the X-axis during the bending process of the pipes. Small, when the wall thickness is 2mm, the maximum X-axis thrust at 1s exceeds 10000N.

The change rate of the pipe with different wall thickness is shown in Fig. 8. The change rate of the inner and outer wall thickness of the pipe increases with the increase of the pipe wall thickness, but the change range is small. The ellipticity of the pipe increases with the increase of the pipe wall thickness. Compared with 2mm It can be seen from the wall thickness pipe and 0.5mm wall thickness pipe that the ellipse rate of the 2mm wall thickness pipe increases significantly, exceeding 7%.

The bending deformation diagram of the pipe under different wall thickness is shown in Fig. 9. It can be seen from the figure that different pipe wall thicknesses also have an impact on the pipe bending radius, among which the 2mm wall thickness has the largest bending radius and the 1mm wall thickness has the smallest bending radius. However, the ellipticity of the pipe with thick wall thickness is relatively large in the bending transition section, and the maximum stress of the pipe gradually decreases with the increase of the bending radius.

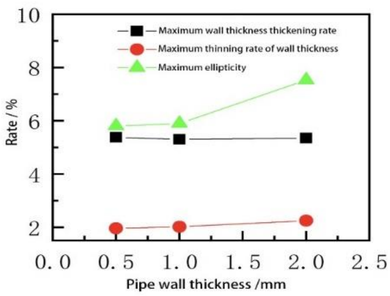


Fig. 8. Relationship between tube change rate and wall thickness

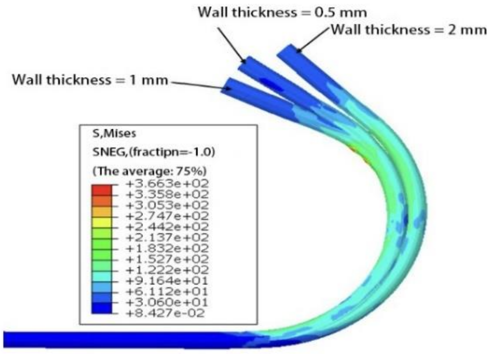


Fig. 9. Bending deformation of tube under different wall thickness

In order to further explore the forming laws of pipes with different wall thicknesses under different bending radii and bending angles, the conditions of bending die eccentricity U=4mm, 6mm, 8mm, and 10mm were selected for further research, and the pipe bending radius, The maximum wall thickness reduction rate and the maximum ellipticity are analyzed, as shown in Table 2.

When the eccentricity of the bending die is small, the difference in the bending radii of the pipes with different wall thicknesses is small and changes irregularly. When the eccentricity is large, the difference in the bending radii of the copper pipes with three wall thicknesses is more obvious. The larger the wall thickness of the pipe, the greater the bending moment required under the same radius. The moment required for pipe bending is determined by the eccentricity U of the bending die and the length L of the bending deformation zone of the pipe. The values of U and L remain unchanged when the equipment is working. The bending moment of the thick pipe during bending is equal, so the larger the wall thickness, the larger the bending radius of the pipe. The reason why the wall thickness and bending radius of the pipe have no obvious regular changes under the small eccentricity may be that the bending angle of the pipe is small, and factors such as bending springback and friction change have a great influence on the accuracy of the pipe bending radius. Under the same eccentricity, the wall thickness reduction rate of the pipe is positively correlated with the wall thickness. At a large eccentricity, the maximum wall thickness reduction rate of the thick-walled pipe increases significantly. In addition, the maximum wall thickness reduction rate of thick-walled pipes is higher than that of thin-walled pipes under large eccentricity, but the maximum wall thickness reduction rate is still within the acceptable range. It can be seen that the change of wall thickness has a significant impact on the maximum wall thickness reduction rate of pipes. Thinness affects, but only to a limited extent. As the eccentricity increases, the maximum ellipticity of pipes with different wall thicknesses also varies greatly. When the wall thickness of the pipe is 1mm, the maximum ellipticity of the elbow under the eccentricity of 10mm exceeds 8%. The maximum ellipticity of the elbow under the eccentricity exceeds 10%, that is, the bending produces serious defects.

In summary, it can be seen that under the same process parameters, the bending radius increases with the increase of the wall thickness, and the required Z-axis thrust and X-axis thrust are also larger. As the wall thickness of the pipe increases, the maximum wall thickness of the pipe decreases As the ratio increases, the maximum ellipticity also increases, and the quality of pipe forming decreases.

4.2 Analysis of the Influence of Different Material Pipes on Forming

There are great differences in the mechanical performance parameters of metal pipes of different materials, and there are great differences in the forming parameters such as bending angle, bending forming limit, springback, ellipticity, and wall thickness change rate during the bending process of the pipe. In this paper, TP2 copper pipes, Ta1 pipes, and 6061 aluminum alloy pipes are respectively selected for finite element analysis, the outer diameter of the pipes is φ12mm, and the wall thickness is 1mm, and the bending and forming laws of the three different materials are studied. The material parameters are shown in Table 3.

Table 2. Tube forming parameters under different wall thickness and different eccentricity of bending die

Wall thickness h(mm)	Bending die eccentricity U(mm)	Bending radius R(mm)	Maximum wall thickness thinning rate (%)	Maximum ellipticity (%)
	4	162.42	1.74	3.32
0.5	6	130.88	1.96	5.77
	8	98.48	2.72	6.58
	10	67.79	3.88	7.89
	4	160.81	1.77	4.46
1	6	136.46	2.02	5.16
	8	106.60	2.91	7.72
	10	76.65	4.42	8.69
	4	164.32	1.79	5.21
2	6	143.82	2.13	7.68
	8	114.91	2.96	10.42
	10	85.16	4.68	12.03

Table 3. Material properties of three metal tubes

Materil	Density (tonne/mm^3)	Modulus of elasticity (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Poissonbee	Hardening index n
TP2 pipe	$8.94*10^{-9}$	115	33.48	376.87	0.31	0.6321
Ta1 pipe	$4.5*10^{-9}$	105	187.14	456.26	0.34	0.6561
6061-ALpipe	$2.7*10^{-9}$	69	253.73	347.44	0.33	0.0982

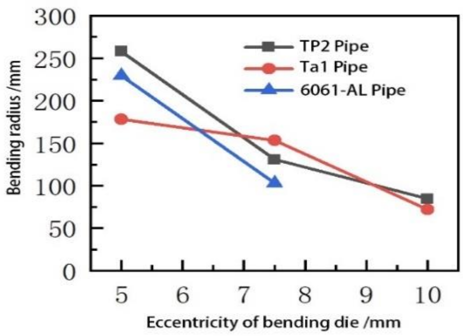


Fig. 10. Comparison of bending radius of different tubes

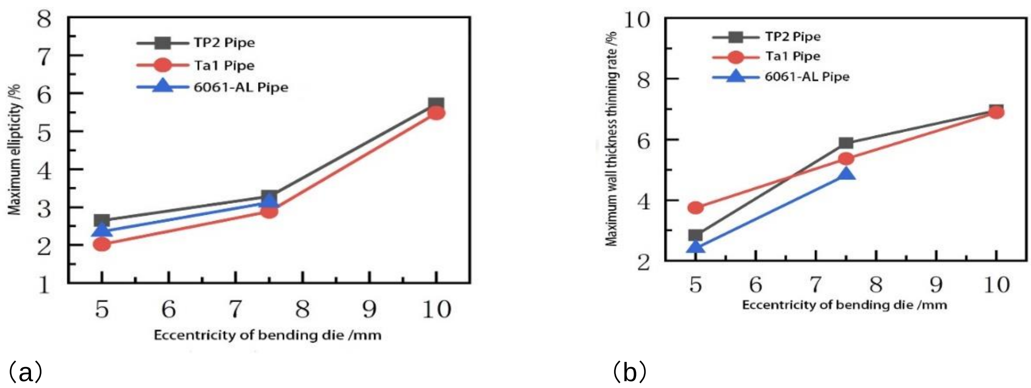


Fig. 11. Variation of maximum change rate of different tubes with eccentricity

Fig. 10. is a schematic diagram of the variation of the bending radius of three kinds of pipes. When the eccentricity is 10mm, the 6061-AL pipe is seriously distorted and cannot be formed normally. Theoretically, the greater the yield strength, the greater the resistance to plastic deformation of the pipe, and the lower the yield strength, the better the cold forming performance of the pipe. Under the same bending force, the greater the yield strength of the material, the greater the bending radius of the pipe. Young's modulus is a physical quantity that describes the ability of a solid material to resist deformation. This parameter can represent the rigidity of the material. The greater the rigidity, the less likely it is to deform. Therefore, the greater the Young's modulus of the material, the greater the bending radius of the pipe. However, in the actual bending process, the bending radii of the three kinds of elbows did not show a theoretical regular change, so it can be speculated that the bending radius of the pipe is not only determined by the elastic modulus and yield strength. Parameters such as the hardening index and strength coefficient of the pipe may also affect the bending radius of the pipe. Under the multi-parameter coupling, the pipes of different materials show irregular changes under the three eccentricities.

The maximum wall thickness reduction rate and maximum ellipticity changes of different pipes are shown in Fig. 11. It can be seen from Fig. a. that as the eccentricity of the bending die increases, the maximum ellipticity of different pipes increases. From the horizontal comparison of different pipes, under the same bending die eccentricity distance, the maximum ellipticity of Ta1 pipe is the lowest, and the maximum ellipticity of TP2 pipe is the highest. This is because the greater the strength of the material, the stronger the material's ability to resist cross-sectional deformation. The yield strength of TP2 pipes is much lower than that of Ta1 pipes and 6061-AL pipes, and the tensile strength is slightly higher than that of 6061-AL pipes and Ta1 pipes. The difference is large, so the maximum ellipticity of the TP2 pipe has the largest value among the three pipes. The yield strength of Ta1 pipe is lower than that of 6061-AL pipe, but the tensile strength is higher than that of 6061-AL pipe. On the whole, the strength of Ta1 pipe is higher, so the maximum ellipticity is lower than that of 6061-AL pipe.

It can be seen from Fig. b. that the maximum wall thickness reduction rate of different pipes increases with the increase of eccentricity. When the bending die eccentricity is 7.5mm and 10mm, the maximum wall thickness reduction rate of TP2 pipe is higher than that of Ta1 pipe. higher. This is because the change of the wall thickness of the pipe is affected by the hardening index n, the high hardening index, the strong hardening effect of the material, and the increase in the ductility of the material. According to the principle of incompressibility of the material, the tangential strain of the pipe increases, and the maximum wall thickness The thinning ratio also increases. The hardening index of TP2 pipe is slightly higher than that of Ta1 pipe, so the maximum wall thickness reduction rate of TP2 pipe is larger under the same eccentricity, and the hardening index of 6061-AL pipe is much lower than that of other materials, so the maximum wall thickness reduction rate is at three lowest among the materials. However, when the eccentricity of the bending die is 5 mm, the maximum wall thickness reduction rate of TP2 tube is smaller than that of Ta1 tube. This may be because the bending radius of TP2 tube is larger than that of Ta1 tube when the eccentricity distance is 5 mm, resulting in the maximum wall thickness reduction rate. decrease.

5. CONCLUSION

(1) Analyze the principle of three-axis free bending based on the three-axis free bending equipment, and establish a mechanical model. Taking TP2 copper pipe as the main research object, the mechanical performance parameters of the material are obtained by tensile test, the maximum wall thickness reduction rate and the maximum ellipticity of the pipe are determined as the evaluation indicators of the pipe forming quality, and the blank and material are analyzed by the finite element method. Effect of properties on pipe forming.

(2) Through the study of pipes with different wall thicknesses, it is found that the wall thickness has an impact on the bending radius of the pipe, and the smaller the bending radius, the more significant the effect. As the wall thickness of the pipe increases, the forming quality of the pipe decreases. By studying pipes of different materials, it is found that the bending radius of pipes is determined by multiple parameters such as material elastic modulus, yield strength, pipe hardening index and strength coefficient. The maximum ellipticity of the pipe is related to the strength of the material, and the change of the wall thickness of the pipe is affected by the hardening index n.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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