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ORIGINAL ARTICLE

A novel lubrication method for hydroforming of thin-walled aluminum alloy T-shaped tube

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Abstract
In this work, a novel lubrication approach for T-shaped tube hydroforming is developed to reduce the forming defects referred to the wrinkles that called intermediate semiring differential lubrication (ISDL), which reduced the dependence of the internal pressure and axial-feeding loading paths to make forming process easily. The T-shaped tube was divided into four zones: bulging zone, guiding zone, back zone, and middle back zone, and the ISDL method was to coat the bulging zone and whole or part of guiding zone with PTFE film and others with MoS_2. Experimental results show that the ISDL method greatly reduced wrinkles in middle back zone of the T-shaped tube without wasting time to adjust the loading path again and again. Also, formulas related to the length and width for lubrication area of ISDL method was derived to guide the tube hydroforming process. The modified tribological performance by employing regional lubrication method improved the T-shaped tube hydroforming ability.

Keywords T-shaped tube · Tube hydroforming · Lubrication method · Lubrication area · Intermediate semiring differential lubrication

1 Introduction

Huge demands for lightweight and complicated components were raised in the nuclear power, aerospace, and automotive industries in recent years. The tube hydroforming, which is a kind of advanced metal forming processes, has been increasingly favored due to its advantages of producing components with fewer formative operations and a better quality of products with complex profiles [1, 2]. In this process, tubes conform the shape of a given die cavity to form the desired shapes by applying internal pressure and axial compressive loads simultaneously. The tribology conditions at the contact surface between the tube and the tool play an important role during the expansion process [3].

The thin-walled T-shaped tube is not symmetric along its longitudinal direction so that the tube material flow velocity in the expansion zone is different from the one of its corresponding back zone in the hydroforming process, which results in the wrinkles easily. In general, the loading path of the hydraulic pressure and the axial feeding was usually optimized to avoid wrinkling on the main pipe in tube hydroforming. Liu et al. [4] analyzed the wrinkling phenomena in hydroforming of thin-walled tube and obtained the critical wrinkling loading path according to the relation between axial feeding and internal pressure. Yuan et al. [3] found that the internal and external pressure had different effects on the wrinkling behavior of thin-walled 5A02 aluminum alloy tubes in tube hydroforming. In order to determine the loading path that can avoid sidewall wrinkling in Tee-joint hydroforming, FEM methods for predicting wrinkling in stamping parts have been intensively investigated by Correia et al. [5, 6] and Wang et al. [7].

While finding appropriate match of internal pressure and axial feeding in the thin-walled T-shaped tube practical hydroforming is time-consuming and difficult, the friction coefficient is apt to be controlled by choosing the various lubrication to change the material flow. Nikhare et al. [8] and Fiorentino et al. [9] employed numerical analysis method to find that the friction coefficient played an important role in hydroforming processes, which could lead to wrinkling by influencing the material flow in the final manufactured

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Fig. 1 Tube hydroforming machine

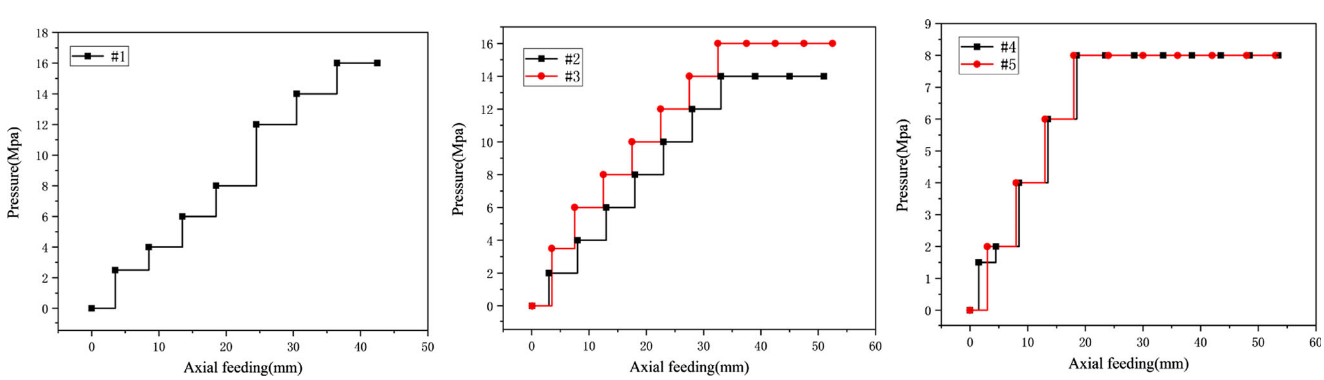
product. Bathina et al. [10] widely discussed the influence of uniform lubricating way on the wrinkle of the T-shaped tube hydroforming by finite element simulation. Guo et al. [11] carried out the experiments in which the various lubricants were chosen to coat the whole zone of tube. Those uniform lubrication methods for the whole T-shaped tube were always combined with the optimized load path method to eliminate the wrinkles. However, it did not have an evident effect on improving the material differential flow in T-shaped tube hydroforming. Thus, the differential lubrication method for different zones of tube should be considered to change the material flow state and prevent the tube wrinkling in the T-shaped tube hydroforming. Hwang et al. [12] and Ngaile et al. [13] presented that the friction zones in a typical tube hydroforming process could be divided into two zones, namely, the guiding zone and the expansion zone. The friction coefficients in guiding zone and expansion zone were evaluated by Hyaekyung et al. [14] through experimental investigation and it was found that the friction coefficient in guiding zone was lower than that in expansion zone. He et al. [15] introduced that about 30–40% friction force in the guiding zone can be reduced by using the newly proposed punch design.

In this paper, a novel lubrication approach called intermediate semiring differential lubrication (ISDL) was proposed to eliminate the wrinkles in the middle back zone of T-shaped tube in hydroforming process and improve its hydroforming efficiency instead of the optimization of loading path, and illuminates the definition of determining lubrication area in T-shaped tube hydroforming based on the new lubrication approach. Furthermore, the position and size of lubrication area can be calculated on the basis of geometrical data obtained by measuring the forming die and tube, verification of the obtained results have been carried out using experimental results to show the effectiveness of our approach. In addition, the change regulation of the wall thickness controlled by friction in the T-shaped tube hydroforming was discussed.

2 Material and methods

2.1 Experiment

To explore the practicality of the proposed lubrication method, the lubrication efficiencies of three different lubrication methods were compared in hydroforming experiments. For the comparison, the experiments were performed with 5052 aluminum alloy tube in the tube hydroforming machine as shown in Fig. 1. The five loading paths of inner pressure and axial feeding are shown in Fig. 2 and the parameters of five kinds of blanks are listed in Table 1. It is found that the maximum pressure in each of the loading paths decreases with the increase of main tube diameter and the inner pressure increases with the decrease of branch tube diameter under the same main tube diameter. This is because the tube with height diameter-thickness ratio possesses the poor pressure resistance and the T-shaped tube with small branch diameter



(a)#1 (b)#2 and #3 (c)#4 and #5

Fig. 2 **a**–**c** Pressure versus axial feeding of each blank

Table 1 Parameters of the tube blank

Parameters of the tube blank	Tube wall thickness (mm)	Main tube diameter (mm)	Branch tube diameter (mm)
#1	1	32	32
#2	1.7	45	45
#3	1.7	45	28
#4	1.2	50	50
#5	1.2	50	42

requires large pressure to be formed. Moreover, the axial feeding increases with the increase of main tube diameter. The lubricants used in this forming process can be divided into two groups: solid-state lubricants and liquid-state. While the solid lubricant was PTFE film, the liquid lubricant was MoS_2. The effects of lubrication area are studied subsequently.

2.2 Different lubrication methods

For analyzing the friction in this study, the hydroforming tube is divided into four different zones as shown in Fig. 3: the bulging one, guiding one, back one, and middle back one, which are different from the previous research. The back zone and middle back zone were innovatively defined in the hydroforming T-shaped tube. The middle back zone corresponding to the bulging branch part of T-shaped tube is apt to wrinkle because its material is difficult to flow into the bulging zone in forming process. Thus, the four zones were lubricated differentially in order to explore the effect of the different lubrication methods on the tube wrinkle in T-shaped tube hydroforming process.

In Fig. 4, the yellow represents a kind of lubricant and the cyan denotes another kind of lubricant. The common uniform lubrication method is to coat uniformly on the whole surface between the tube and the die with single or several lubricants, as shown in Fig. 4a. The differential lubrication method proposed in this article is to choose two or more different

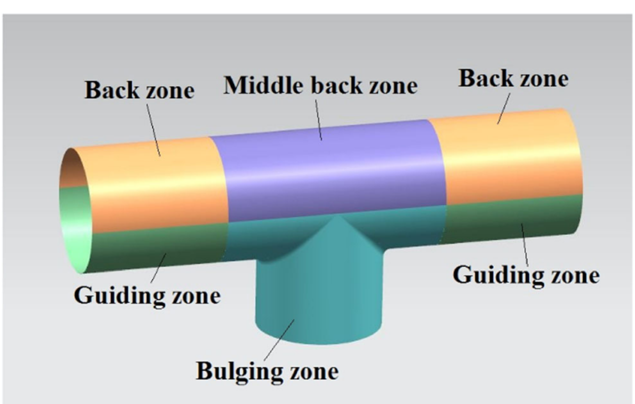


Fig. 3 Four zones divided in tube

lubricants to coat the four different zones of tube, so as to adjust the material flow velocity of different deformation zone in the hydroforming process. In consideration of material flow velocity, two different lubrication methods are proposed, intermediate annular differential lubrication (IADL) method and intermediate semiring differential lubrication (ISDL) method. IADL method is to coat the middle back zone and bulging zone of tube or more than the annular region with a kind of lubricant, and the other zones with another lubricant, as shown in Fig. 4b. ISDL method is just to coat the bulging zone and the whole or part of the guiding zone of tube with a kind of lubricant, and the other zones with another lubricant, as shown in Fig. 4c.

2.3 Lubrication area

To avoid material waste and improve work efficiency, the formulas of the lubrication area in ISDL method also be proposed. The lubrication area in ISDL method is presented in Fig. 5a, where a and b represented the length and width of lubrication area, respectively. The deformed shape of the tube and mold in the experiment conducted by radial direction is shown in Fig. 5b, and these main parameters in the process can be measured by forming die. The top surface of branch tube in hydroforming is camber. R_1 is the branch tube radius, r is the corner radius, D_{max} is the maximum diameter after bulging, and D_0 is the initial outer tube diameter. Because the whole density does not change, the plastic deformation of material does not change the volume of material [16]. The PTFE film used in the experiment is rectangular. The branch radius R_1 and radius of corner r are both measured by hydroforming die. Its length can be determined by Eq. (1).

$$a = 2(D_{max} - D_0) + 2R_1 + 2_r \quad (1)$$

D_0 denotes the out-diameter of tube; D_{max} is the maximum bulging diameter prior to bursting of tube. K_{max} is maximum bulging coefficient of tube blank; δ_{max} is allowable elongation of blank on tangential effect. Chow [17] resumed their relationship, which can be written:

$$K_{max} = \frac{D_{max}}{D_0} \quad (2)$$

$$K_{max} = \delta_{max} + 1 \quad (3)$$

Finally, the length and width of the PTFE film can be written:

$$a = 2(\delta_{max} D_0 + R_1 + r) \quad (4)$$

Accordingly, its width can be determined by Eq. (5).

$$b = 2R_1 + 4r \quad (5)$$

There is a margin of length r on both sides of the length and width.

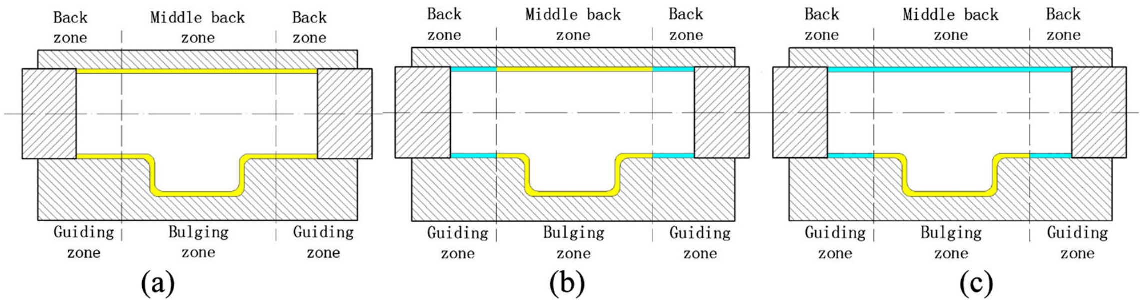


Fig. 4 Lubrication areas of three methods. **a** Uniform lubrication method. **b** IADL method. **c** ISDL method

3 Results and discussion

3.1 Friction force

In this study, the lubricating methods were applied in T-shaped tube hydroforming process. The stress mechanics of the process was revealed by analyzing stress state of tube in the forming process as shown in Fig. 6. When the dies are closed, the increased P of internal pressure forces the material flow into the deformation zone. F generated by the axial punches provides an axial feeding force to compress the main tube. N_1, N_2, and N_3 are normal pressures supported by the dies. A counterpunch is usually adopted to provide the counter pressure, N_0 on the top of the branch tube, in order to improve the stress state in the hydroforming process. f_1 and f_3 are axial friction forces between the main tube and dies, and f_2 is a friction force between the branch tube and die, which affects the pipe materials to flow into the expansion zone.

In order to discuss the effect of differential lubrication on the T-shaped tube hydroforming with the stress mechanics, three equations about friction force and normal pressure are presented as following:

$$f_1 = \mu_1 N_1 \approx \mu_1 [p(2\pi R_0)(W/2-r)] \quad (6)$$

$$f_2 = \mu_2 N_2 \approx \mu_2 [p(2\pi r)(H-R_0)] \quad (7)$$

$$f_3 = \mu_3 N_3 \approx \mu_3 [p(2\pi R_0)L/2] \quad (8)$$

where f_1, f_2, and f_3 are the friction forces, μ_1, μ_2, and μ_3 represent the different friction coefficients in guiding zone, back zone, and bulging zone during the process respectively, p is internal pressure, R_0 is the radius of tube blank, r is the radius of branch tube, H is the height, L and W is the length as shown in Fig. 6.

From Eqs. (6), (7), and (8), it was discovered that the friction coefficient, internal pressure, H, L, and W were variables when the target geometry of T-shaped tube was defined in hydroforming process. Then H, L, and W changed with the increase of axial feeding. It was concluded that the friction coefficient and the load path of internal pressure and feeding affected the friction forces in hydroforming process, which influenced the material flow. The research on the load path in hydroforming has been reported widely. In this paper, the different friction coefficients in guiding zone, back zone and bulging zone during the process were discussed. With the increase of the axial feeding in the hydroforming process, the friction coefficient in the guiding zone μ_1 and back zone μ_3 could be increase to prevent the fast flow of material and avoid occurring serious wrinkle. The friction coefficient in the bulging zone should be low so that the material in the guiding zone easily flows into the branch tube and the fracture does not happened. But if the friction coefficients were too high, the

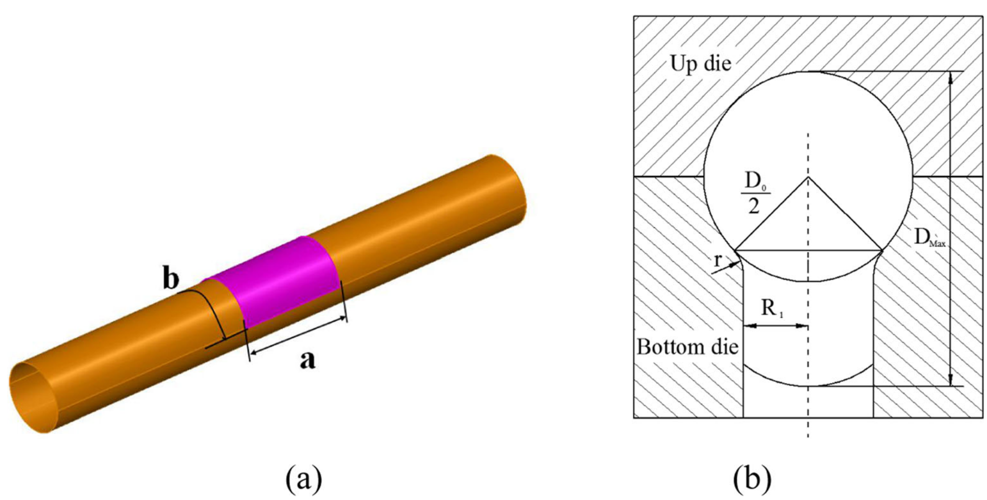


Fig. 5 Location of lubricant. **a** Diagrammatic of lubrication area. **b** Radial direction sketch

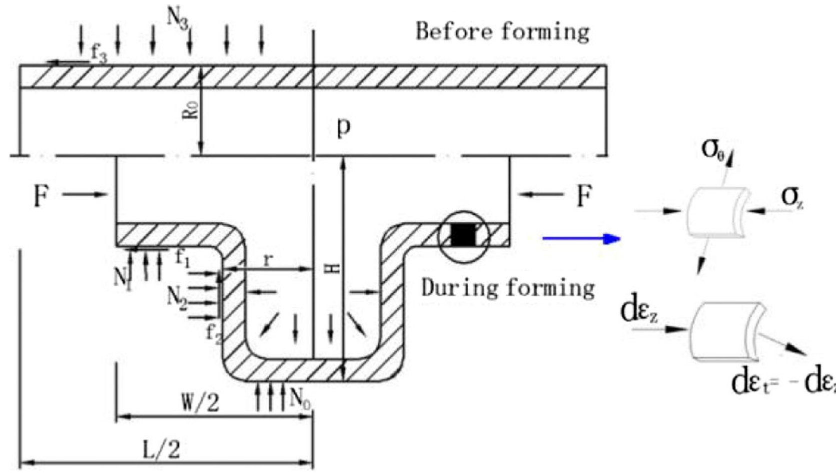


Fig. 6 Stress analysis in tube hydroforming

thickness of the main tube must be increased and the height of branch tube had to be decreased. Thus the lubrication is an important factor to control the material flow and avoid the wrinkle in hydroforming process. Therefore, considering the axial asymmetry of T-shaped tube and material flow velocity, it is necessary to analyze the effects of different lubricants on different lubrication areas so as to improve the formality of tubes in hydroforming process.

3.2 Comparison of three different lubrication methods

Experiment results of tube blank #1 on the uniform lubrication method and IADL method are shown in Fig. 7. It is obvious that the problems concerning friction are evident in forming of uniform lubrication method. The wrinkles happened obviously in the back and middle back zone of the forming T-shaped

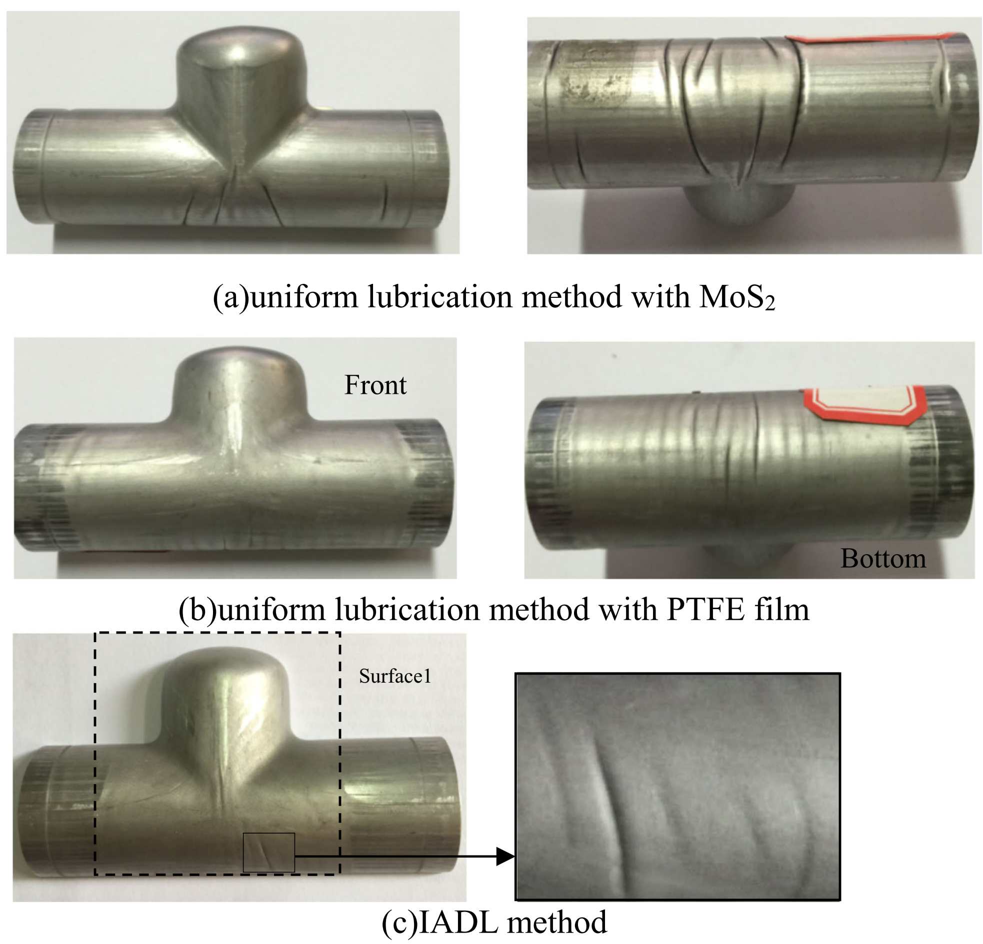
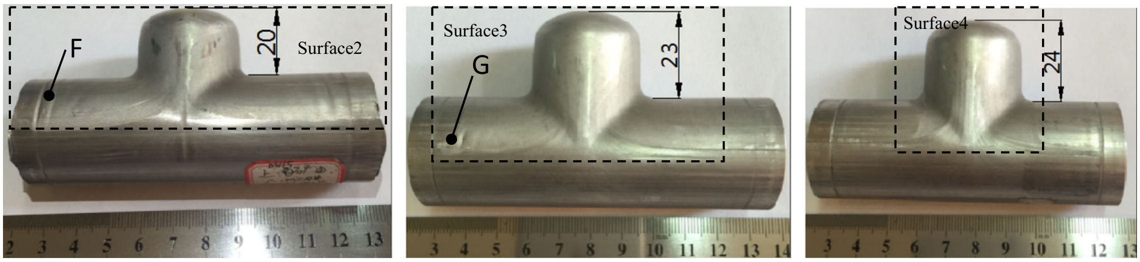


Fig. 7 Experiment results of tube blank #1 using three lubrication methods. a Uniform lubrication method with MoS2. b Uniform lubrication method with PTFE film. c IADL method



(a)type1 (b)type2 (c)type3

Fig. 8 Three types of ISDL methods covered with the PTFE film of tube blank #1: **a** the whole guiding and bugling zone, **b** part of the guiding and bugling zone, **c** nearly the bugling zone

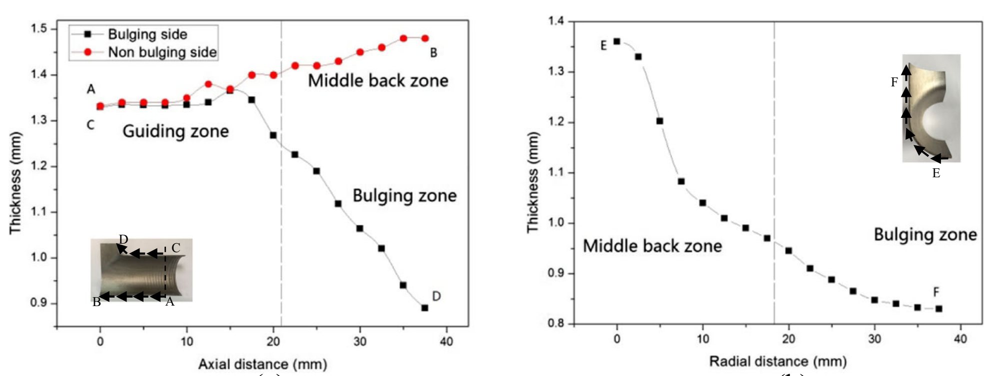
tube via the two uniform lubrication methods. By IADL method, the surface 1 of the workpiece was covered with the PTFE film and had no any scratch, the other surface smeared with MoS_2 was left evident signs. Importantly, several wrinkles were appeared in the middle back zone. The reason was that the materials in the back zone flowed more difficultly into the bulging zone than the materials flowed in the guiding zone, because of the axial dissymmetric of T-shaped tube and mechanical behavior of tube, so the material accumulation happened easily in the middle back zone.

In the following experiments, the ISDL method on tube blank #1 wad also utilized to coat the bulging zone and the whole or part of the guiding zone of tube with the PTFE film and the other zones with MoS2. Therefore, the PTFE film in ISDL method was designed with three kinds of sizes. The forming results using ISDL method are shown in Fig. 8. Surface 2, surface 3, and surface 4 had no any scratch because of the protection of film and the obvious signs were left in the other zones of the workpieces. The workpiece has wrinkled obviously in Fig. 8a, which influenced its branch length. The branch lengths of workpieces in Fig. 8b, c were similar, which met the requirement of 10 mm for welding.

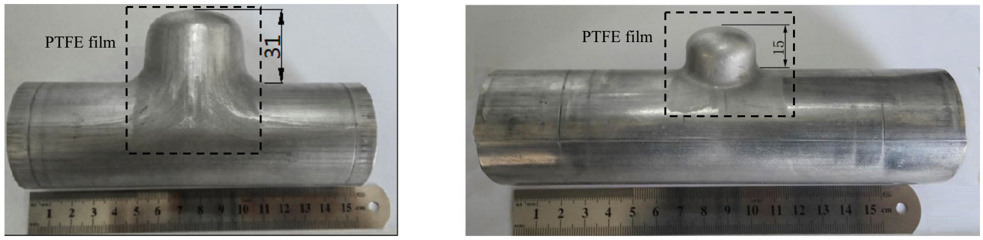
Surface 2 in Fig. 8a was composed of the whole guiding and bulging zone, which was covered with the PTFE film, and the other zones were smeared with MoS_2 as type1, and there were some wrinkles in the guiding zone. The low coefficient of friction of the PTFE film led to the material flow velocity increased, resulted in some wrinkles that appeared at point F as shown in Fig. 8a. It was also shown that the MoS_2 reduced the material flow velocity in the back and middle back zones, and a few wrinkles appeared in the bottom of the main tube. The guiding and bulging zones are covered with PTFE film, and the other zones were smeared with MoS_2 as type 2 which is shown in Fig. 8b, and only few wrinkles appeared in point G of surface 3, which was covered with PTFE film. The results also demonstrated that the increase of the friction coefficient of guiding zone facilitated to remove the wrinkles and there was no any defect in the bottom of the main tube. In Fig. 8c, most area of the bulging zone was covered with the PTFE film and the other zones were smeared with MoS_2 as type 3, the trace of PTFE film was easily to be found. It can be seen that the place covered with PTFE film and the other regions smeared with MoS_2 did not have any wrinkles. The result indicated that the increase of the friction coefficients in the guiding zone, back zone, and middle back zone and the decrease of the friction coefficients in the bulging zone were able to eliminate completely the wrinkles in the middle back zone of T-shaped tube in hydroforming process. The wrinkles were obviously fewer in the ISDL method than in the uniform lubrication method and IADL method.

The wall thickness distribution of the hydroforming blank #1 part by using type 3 ISDL method is shown in Fig. 9. The

Fig. 9 The wall thickness distribution of tube blank #1 by using ISDL method hydroforming part. **a** Longitudinal direction. **b** Transverse direction



(a) (b)



(a)BD = 45mm (b) BD = 28mm

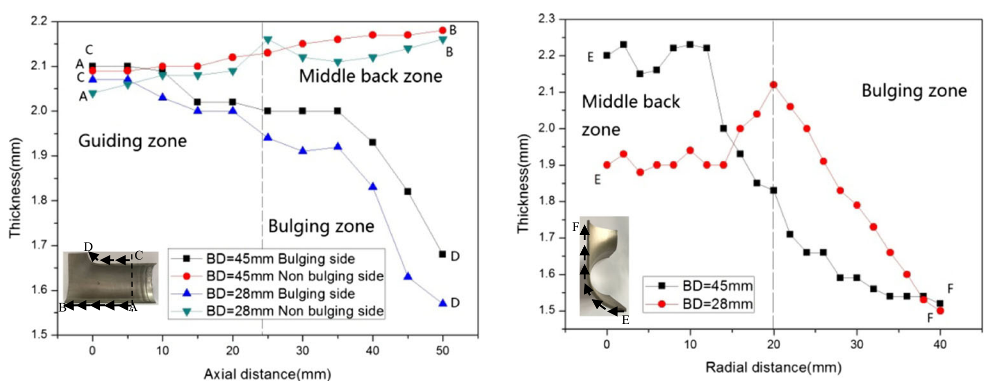
Fig. 10 Experiment results of blanks #2 and #3 with different branch diameter. **a** BD = 45 mm. **b** BD = 28 mm

thinnest part occurred in the top of the branch of T-shaped tube and since the top of branch tube would be cut and removed in practice, the minimum thickness was about 0.87 mm. The maximum thickness of bulge zone was about 1.35 mm that appeared in the middle back zone, the material flowed slowly in the back and middle back zones which results from the high friction coefficient of MoS_2 and led material to accumulate in the middle back zone, and the thickness of the bottom of the main tube was uniform.

Based on the experiment results of blank #1, the experiments of blank #2 and blank #3 using type 3 ISDL method were also performed. The experiment results are shown in Fig. 10. Though the branch diameters are different, it could be seen that the T-shaped tubes without any wrinkles in the middle back zone were obtained. The branch lengths of workpieces are shown in Fig. 10a, b, which also met the requirement of 10 mm for welding. The wall thickness distribution of blank #2 and #3 hydroforming part is shown in Fig. 11. When the branch diameters are 45 mm and 28 mm, the minimum thicknesses of the tube wall are 1.54 mm and 1.50 mm, the thinnest elements are located at the top of the branch. The maximum thicknesses of tube walls are 2.22 mm and 2.16 mm, and located at the bottom of the tube, the thicknesses of the main tubes also have not changed much.

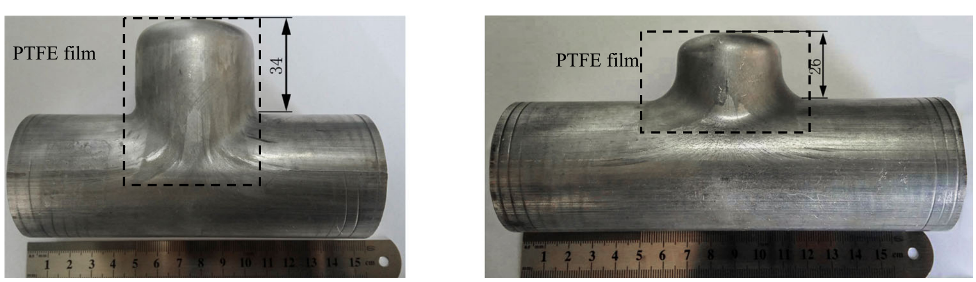
3.3 Validate formulas applicability

In order to verify the formulas about ISDL method lubrication area proposed above, experiments research were conducted by



(a) (b)

Fig. 11 The wall thickness distribution of tube blank #2 and #3 hydroforming part. **a** Longitudinal direction. **b** Transverse direction



(a) BD = 50mm (b) BD = 42mm

Fig. 12 Experiment results of tube blanks #4 and #5 with different branch diameters. **a** BD = 50 mm. **b** BD = 42 mm

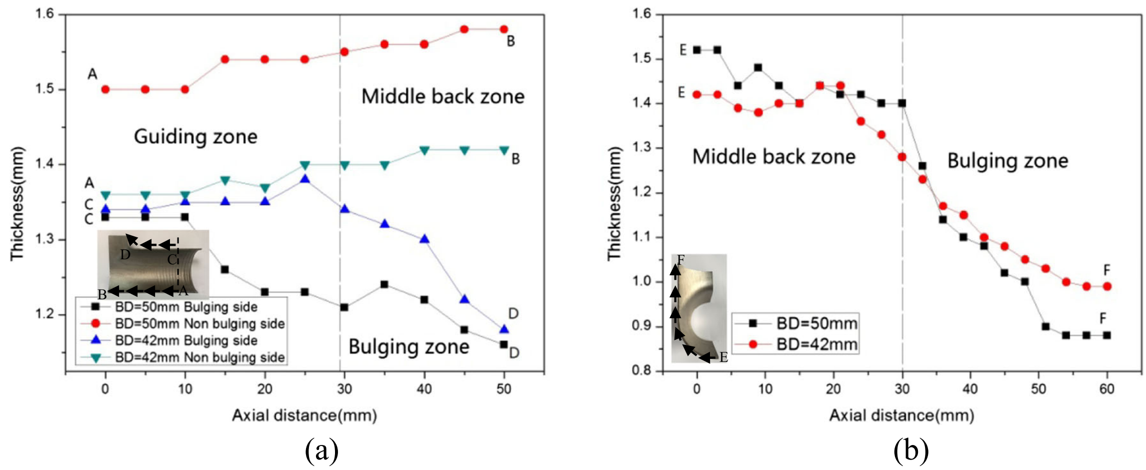


Fig. 13 The wall thickness distribution of the tube blank #4 and #5 hydroforming part. a Longitudinal direction. **b** Transverse direction

forming two kinds of branch diameter on blanks #4 and #5, an equal diameter T-shaped tube and a different diameter T-shaped tube. Using PTFE film to confirm the lubrication region with length of a and width of b determined by Eqs. (4) and (5). The lengths of a are 82.5 mm and 75 mm, the widths of b are 66 mm and 58 mm of PTFE film used in blank #4 and blank #5 respectively, the results of the blank #4 and #5 hydroforming parts are shown in Fig. 12, and the wall thickness distributions are shown in Fig. 13. The branch lengths of workpieces were shown in Fig. 12a, b, which also met the requirement of 10 mm for welding. It was evident to see the protrudent surfaces and bottom profile of each part were smooth with no wrinkles, the ISDL method shows good shaping effect, and the thicknesses of the main body of the T-shaped tube were uniform. The result also confirms that the proposed formulas of lubrication area can effectively determine the position and size of the lubrication area, which is feasible and operates without too much rely on the internal pressure and axial feeding loading paths.

4 Conclusion

- In order to obtain the qualified T-tube with sufficient height of branch tube, the friction coefficient in the bulging zone is decreased to improve material flow and the friction coefficient of other zones is increasing properly to prevent the material accumulation in the middle back zone.
- For thin-walled 5052 aluminum alloy, the ISDL method obtained the better T-shaped tube without any wrinkles than the uniform and IADL method under the condition of the same loading path of hydroforming, whereas the uniform and IADL method did not eliminate the wrinkling phenomenon. Moreover, the type 3 of the ISDL method can get the best formability of tube.
- The ISDL method considers the axial dissymmetric of T-shaped tube, increase the material flow of the bulging zone to ensure the branch forming, decrease the material flow of the guiding zone, back zone, and middle back zone to avoid material accumulation, and make this hydroforming process not have much dependent on adjusting repeatedly the loading path of the pressure and feeding. Thus, it is a new promising way to enhance the tube hydroforming quality and efficiency.
- A series of experiments were performed for proving the formula of the optimum lubrication area, the optimum lubrication area can be obtained and calculated, which can guide the forming process to have good forming effect without wrinkling.

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References

1. Alaswad A, Benyounis KY, Olabi AG (2012) Tube hydroforming process: a reference guide. Mater Des 33(1):328–339
2. Lee MG, Korkolis YP, Ji HK (2015) Recent developments in hydroforming technology. Proc Inst Mech Eng B 229(4):572–596
3. Yuan SJ, Cui XL, Wang XS (2015) Investigation into wrinkling behavior of thin-walled 5a02 aluminum alloy tubes under internal and external pressure. Int J Mech Sci 92:245–258
4. Liu G, Peng J, Yuan S, Teng B, Li K (2015) Analysis on critical conditions of sidewall wrinkling for hydroforming of thin-walled tee-joint. Int J Mach Tool Manu 97(97):42–49
5. Correia JPDM, Ferron G (2002) Wrinkling predictions in the deep-drawing process of anisotropic metal sheets. J Mater Process Technol 128(1–3):178–190

6. Correia JPDM, Ferron G, Moreira LP (2003) Analytical and numerical investigation of wrinkling for deep-drawn anisotropic metal sheets. Int J Mech Sci 45(6):1167–1180
7. Wang SG, Wang D, Gao FS (2014) Analysis of tee pipe hydroforming process parameters. Appl Mech Mater 651–653: 643–646
8. Nikhare C, Weiss M, Hodgson PD (2009) FEA comparison of high and low pressure tube hydroforming of trip steel. Comput Mater Sci 47(1):146–152
9. Fiorentino A, Ceretti E, Giardini C (2013) Tube hydroforming compression test for friction estimation—numerical inverse method, application, and analysis. Int J Adv Manuf Technol 64(5–8):695–705
10. Sreenivasulu B, Prasanthi G (2014) FEA simulation analysis of tube hydroforming process using DEFORM-3D. Procedia Eng 97:1187–1197
11. Guo XZ, Liu ZL, Wang H, Wang LA, Ma FY, Sun XJ, Tao J (2016) Hydroforming simulation and experiment of clad t-shapes. Int J Adv Manuf Technol 83(1–4):381–387
12. Hwang Y (2005) Friction tests in tube hydroforming. Proc Inst Mech Eng B 219(8):587–593
13. Ngaile G, Jaeger S, Altan T (2004) Lubrication in tube hydroforming (THF): Part I. Lubrication mechanisms and development of model tests to evaluate lubricants and die coatings in the transition and expansion zones. J Mater Process Technol 146(1): 108–115
14. Hyaekyung YI, Yim HS, Lee GY, Lee SM, Chung GS, Moon YH (2011) Experimental investigation of friction coefficient in tube hydroforming. Trans Nonferrous Metal Soc 21(supp-S1):194–−198
15. He ZB, Yuan SJ, Li L, Fan XB (2012) Reduction of friction in the guiding zone during tube hydroforming. Proc Inst Mech Eng B J Eng 226(B7):1275–1280
16. Dohmann F, Hartl C (1997) Tube hydroforming-research and practical application. J Mater Process Technol 71(1):174–186
17. Chow CL, Yang XJ (2002) Bursting for fixed tubular and restrained hydroforming. J Mater Process Technol 130(02):107–114