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Optimization of Process Parameters to Study the Influence of the Friction in Tube Hydroforming

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Abstract Tube hydroforming (THF) is a well-known metal forming technology. This technology enables the manufacturing of a variety of intricate shape parts used in automobile industry. Tribology plays an important role in THF, required in the automobile industry. THF process is influenced by many process parameters. Friction between outer surface of the tube and the inner surface of the die is significant and influences the process parameters and quality of components. The aim of the proposed work is to optimize the different process parameters which influence the coefficient of friction in the THF using mathematical model based upon the tube upsetting method. Influence of friction on process parameters, mainly inner pressure and wall thickness, is analyzed and optimized. The proposed mathematical model is verified by comparison of coefficient of friction with original values for Steel35NBK and AlMgSi materials. COF (μ) decreases from 0.15 to 0.0289 for Steel35NBK and from 0.1 to 0.0136 for AlMgSi after optimization of initial tube thickness, $S_0 = 3.5$ mm and pressure $p_i = 142.9554$ MPa for Steel35NBK and pressure $p_i = 143.5730$ MPa for AlMgSi.

Keywords Coefficient of friction (COF) · Tube hydroforming (THF) · Tube upsetting · Tribology

List of symbols

- d_a Outer diameter of the tube before deformation (mm)
- d_i Inner diameter of the tube before deformation (mm)
- d_{i1} Punch-side inner diameter after deformation (mm)
- d_{i2} Inner diameter of tube at the side of a fixed punch after deformation (mm)
- $F1$ Force by punch (N)
- $F2$ Reaction force from die end (N)
- FR Force due to friction between wall and tube (N)
- H Height of tube after deformation (mm)
- H_0 Height of tube before deformation (mm)
- p_i Inner pressure of tube (N/mm^2)
- S_0 Thickness of tube before deformation (mm)
- S_1 Thickness of wall on the side of movable punch (mm)
- S_2 Thickness of wall on the side of fixed punch (mm)

1 Introduction

Nowadays automobile sector is growing up to a large extent. Tube hydroforming is required in automobile sector to produce hollow intricate shapes [1–24]. The aim is to produce high-strength component with minimum thickness. For hydroforming of such component, the friction plays an important role. As the component thickness increases, the weight of the component increases. The hydroforming process is preferred for low thickness with effective high stiffness of component [3, 4]. In the THF process, the tube to be formed is placed inside a die and internal pressure is applied by the fluid. For high-quality hydroforming, the optimization of process parameters is required, as it influences the

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quality and the cost of the component. Schmoeckel et al. [5] identified three friction zones in a THF process depending upon the compressive axial force, feed of the material, and geometrical parameters. These zones are (a) guide zone, (b) transition zone, and (c) expansion zone as shown in Fig. 1. In the guided zone, there is no deformation of the material. It is pushed to the transition zone under internal pressure by axial compressive force. In expansion zone, material takes the shape of die geometry. Prier et al. [6] performs the experiment to investigate the friction condition in the guided zone. According to the proposed method, the friction coefficient can be calculated by using the geometrical data from the deformed tube and material properties without force measurement. According to Fig. 1, there are two types of zones in hydroforming: feed zone and forming zone. The deformation of the tube in feed zone is pure elastic compression, and the deformation condition is characterized by small plastic tensile strain in circumferential direction. In forming zone, depending upon friction conditions, strain remains constant or increases. In forming zone, three-dimensional (3-D) strains occur.

Depending on the ratio of axial stress produced by the punch forces, and reduced by the friction forces in the feed zone and tangential stress generated by the inner pressure, a thickening or thinning of the wall can take place. The strains in the forming zone are large as compared to the feed zone. Because of the yielding surface, microgeometry of the tube material is continuously changing which produces different changes of the friction conditions. The following process parameters influence the COF, work piece material, geometry of work piece material, surface topography, contact pressure, lubricants, and sliding speed.

Hwang et al. [7] developed an apparatus for determination of COF in feed zone of tube hydroforming using push-through test. More information of measurement of friction in elastic zone can be found in [8, 9]. The different friction tests for the determination COF in forming zone of tube hydroforming are tube expansion test, tube upsetting test,

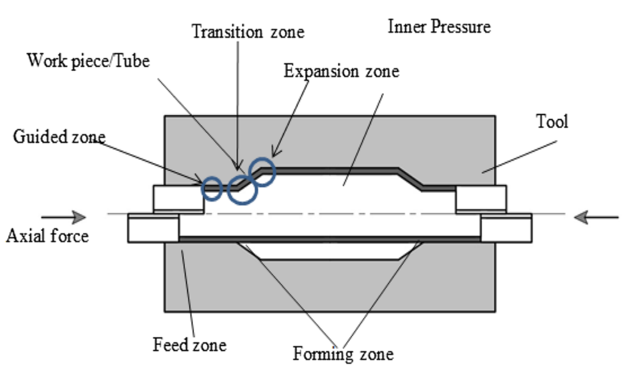

Fig. 1 Friction zones in tube hydroforming [10]

and direct measurement test. Vollertsen et al. [10] developed a measuring principal for determination of COF at the tube–die interface, based on tube upsetting method which shows that in plastic zone, during deformation, tube wall deforms non-uniformly along the tube height, i.e., wall thickness at the side of movable punch is higher than that of the fixed punch. This is due to friction between the tube and the die. Optimization of process parameters and obtaining their optimal values are very critical because it influences the quality and cost of the product. Many researchers use finite element approach [FEA] for optimization of process parameters in THF. Trana [11], Lang et al. [12], and Abedrabbo et al. [13] used FEA simulation for study of effect of axial feed and internal pressure on thickness distribution. Zadeh et al. [14] used FEA simulation to study the effect of coefficient of friction, strain hardening exponent, and fillet radius on protrusion height and thickness distribution for an unequal *T* joint. Manabe et al. [15] used LS-Dyna to study the effect of process parameters and material properties on thickness distribution. Sedighiamiri et al. [16] also use finite element simulation of frictional, elastic–plastic contact between two cylinders as well as a cylinder and a flat surface. Some deterministic analytical approaches have also been proposed to approximate the roughness of surfaces and provide valuable numerical information. Hebber et al. [17] did the experimental work consisting of modeling the phenomenon of wear of various materials under the influence of the most imposing factors on wear like speed, the load applied, the viscosity of the lubricant, and the nature of materials of the parts in contact, whereas Mendas et al. [18] performed the experimental and numerical analysis of the scratch behavior of steel to study the effect of hardening of various materials. Fiorentino et al. [19] proposed a numerical inverse method to estimate the coulombian friction coefficient by using experimental and FE simulation test. A new sealing method is used in [20, 22] to eliminate the internal pressure in the feeding zone. As a result of this, the friction force between the tube and the die is removed from this zone and flowing of the material toward the deformation zone is improved. Peng et al. [21] proposed a multistage punch to change the internal pressure distribution in the guiding zone and to reduce the friction force between the tube and the die. Experiments of hydroforming of aluminum alloy Y-shaped tube were carried out, in which the thickness distribution and thinning ratio distribution were investigated.

From the above literature review, it is observed that for high quality of hydroformed components, the process parameters have to be optimized. According to Plancak et al. [9], there is linear relation between COF and slope of wall thickness. Increasing friction results in increase in wall thickness inhomogeneity. Optimization of process parameters gives lower COF than obtained by Plancak et al. [10] which reduces wall thickness inhomogeneity and will improve the

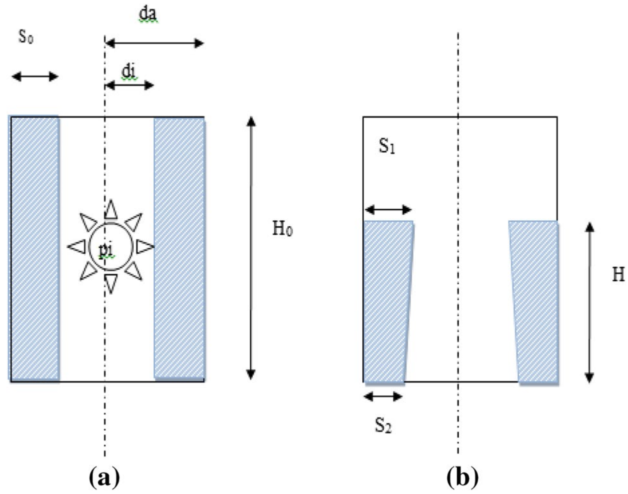

Fig. 2 Tube upsetting hydroforming [10]. **a** Initial position. **b** Final position after hydroforming

quality of the component. The proposed work presented in this paper comprises the development of new mathematical model to optimize the process parameters such as wall thickness and hydroforming pressure to minimize the coefficient of friction in the forming zone of tube hydroforming, based upon tube upsetting method and analyzes the influence of friction on wall thickness and hydroforming pressure.

2 Mathematical Model of COF

The mathematical model for determination of COF is based upon tube upsetting method. A tube is placed in a closed die, subjected to inner pressure and axial punch force at both ends. The force applied by the punch is equal to the sum of reaction force from die and frictional force. If there is no friction between the tube and the die wall (hypothetically considered), the tube wall deforms uniformly, e.g., the tube-wall thickness is constant along the tube height. In actual practice, it is not possible. Some friction is there, so the wall will not deform uniformly. The maximum wall thickening takes place at the side of the punch and minimum thickness will be near to the other end which is non-movable, i.e., fixed side of die as shown in Figs. 2 and 3.

Theoretical analysis is based upon the following assumptions:

- Coulomb friction law is adopted.
- Frictional resistance due to wall is constant along periphery of pipe.
- The deformation is considered as one dimensional only.
- Wall thickness gradually decreases along length of pipe.
- Yield criterion of Tresca's is applied.

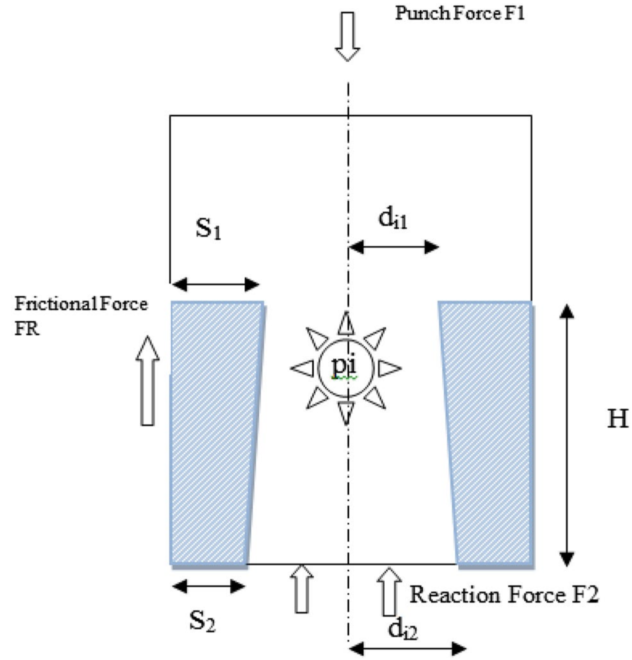

Fig. 3 Forces in tube upsetting hydroforming [10]

Coefficient of friction can be determined as follows. Force balance in longitudinal direction is,

$F1 = F2 + FR$

$F1$ force by punch, $F2$ reaction force from die end, FR force due to friction between wall and tube, S_0 thickness of tube before deformation, d_a outer diameter of the tube before deformation, d_{i} inner diameter of the tube before deformation, H_0 height of tube before deformation, S_1 thickness of wall on the side of movable punch, S_2 thickness of wall on the side of fixed punch, and H height of tube after deformation, $d_{\mathrm{i}1}$ punch-side inner diameter after deformation, $d_{\mathrm{i}2}$ inner diameter of tube at the side of fixed punch after deformation.

If the contact stress between the tube and the die is equal to the inner pressure p_{i}, then according to Plancak et al. [10] analytical model for coefficient of friction is

$$\mu = \frac{1.15C\left\{\left(d_a^2 - d_{\mathrm{i}1}^2\right)\left[\ln \frac{S_1\left(d_a - S_1\right)}{S_0\left(d_a - S_0\right)}\right]^n - \left(d_a^2 - d_{\mathrm{i}2}^2\right)\left[\ln \frac{S_2\left(d_a - S_2\right)}{S_0\left(d_a - S_0\right)}\right]^n\right\} + p_{\mathrm{i}} \times \left(d_{\mathrm{i}2}^2 - d_{\mathrm{i}1}^2\right)}{4 \times p_{\mathrm{i}} \times d_a \times h} \quad (1)$$

As hydroforming pressure and wall thickness of tube are main parameters in tube hydroforming, the current paper illuminates the mathematical model to optimize these process parameters of Eq. (1), i.e., pressure p_{i} and initial wall thickness of the tube S_0. According to Eq. (1), the parameters which influence the COF can be represented as,

$\mu = f\left(S_0, S_1, S_2, H, d_a, p_i, C, n\right).$

where (S_1, S_2, H, d_a) are output parameters which are constant. (H, d_a) are geometrical parameters for particular tube considered. (S_1, S_2) are constant for particular pressure. As hydroforming pressure p_i will change, S_1 and S_2 will change. (C, n) are material properties which are constant for particular material; hence, μ is the function of S_0 and p_i. We will get optimum value of COF (μ) by differentiating μ w.r.t. S_0 and p_i.

3 Mathematical Analysis

In this section, we are considering partial derivative of COF (μ) w.r.t. S_0, S_1, S_2, H, d_a, p_i, C, n to find optimized value of S_0 and p_i and COF (μ).

$$\mu = f\left(S_0, S_1, S_2, H, d_a, p_\mathrm{i}, C, n\right), \tag{2}$$

i.e., μ is dependent on eight parameters. So to take total derivative, i.e., dμ can be written as

$$\mathrm{d}\mu = \frac{\delta\mu}{\delta S_0}\times \mathrm{d}S_0 + \frac{\delta\mu}{\delta S_1}\times \mathrm{d}S_1 + \frac{\delta\mu}{\delta S_2}\times \mathrm{d}S_2 + \frac{\delta\mu}{\delta h}\times \mathrm{d}h + \frac{\delta\mu}{\delta d_a}\times \mathrm{d}\left(d_a\right) + \frac{\delta\mu}{\delta pi}\times \mathrm{d}p_i + \frac{\delta\mu}{\delta C}\times \mathrm{d}C + \frac{\delta\mu}{\delta n}\times \mathrm{d}n \tag{3}$$

By combining these partial derivatives, the final total derivative of COF (μ) can be obtained. But for particular material, the C and n are constant. Hence,

$$\frac{\delta\mu}{\delta C}\times \mathrm{d}(C) = 0 \quad \frac{\delta\mu}{\delta n}\times \mathrm{d}(n) = 0 \tag{4}$$

S_1, S_2, H and d_a are output parameters, so they are constant. Hence,

$$\frac{\delta\mu}{\delta S_1}\times d(S_1) = 0, \quad \frac{\delta\mu}{\delta S_2}\times \mathrm{d}(S_2) = 0, \quad \frac{\delta\mu}{\delta h}\times \mathrm{d}h = 0 \tag{5}$$

and $\frac{\delta\mu}{\delta d_a}\times \mathrm{d}(d_a) = 0$

Hence, μ is function of S_0 and p_i,

$$\text{i.e. } \mu = f\left(S_0, p_i,\right) \tag{6}$$

Hence, Eq. (3) becomes,

$$d\mu = \frac{\delta\mu}{\delta s_0}\times ds_0 + \cancel{\frac{\delta\mu}{\delta s_1}}\times ds_1 + \cancel{\frac{\delta\mu}{\delta s_2}}\times ds_2 + \cancel{\frac{\delta\mu}{\delta h}}\times dh + \cancel{\frac{\delta\mu}{\delta d_a}}\times d\left(d_a\right) + \frac{\delta\mu}{\delta pi}\times dpi + \cancel{\frac{\delta\mu}{\delta C}}\times dC + \cancel{\frac{\delta\mu}{\delta n}}\times dn \tag{7}$$

$$\mathrm{d}\mu = \frac{\delta\mu}{\delta S_0}\times d(S_0) + \frac{\delta\mu}{\delta p_\mathrm{i}}\times d(p_\mathrm{i}) \tag{8}$$

First, assuming pressure is constant, p_i = constant. Now

$$\mathrm{d}\mu = \frac{\delta\mu}{\delta S_0}\times \mathrm{d}(S_0) \tag{9}$$

Substituting value $\frac{\delta\mu}{\delta S_0}$ in Eq. (9), we get Eq. (10). Substituting the suitable values in Eq. (10), we get the value of S_0. Then, assuming thickness (S_0) is constant, S_0 = constant, then Eq. (8) becomes (11).

$$\mathrm{d}\mu = \frac{1.15\times C}{4\times p_\mathrm{i}\times d_a\times h}\left[\left[\left(d_a^2 - d_{\mathrm{i}1}^2\right)\left[n\times\ln\left\{\frac{S_1\left(d_a - S_1\right)}{S_0\left(d_a - S_0\right)}\right\}\right]^{n-1}\times\frac{S_0\left(d_a - S_0\right)}{S_1\left(d_a - S_1\right)}\times\frac{-S_1\left(d_a - S_1\right)\times\left(d_a - 2S_0\right)}{S_0^2\left(d_a - S_0\right)^2}\right] - \left[\left(d_a^2 - d_{\mathrm{i}2}^2\right)\left[n\times\ln\left\{\frac{S_2\left(d_a - S_2\right)}{S_0\left(d_a - S_0\right)}\right\}\right]^{n-1}\times\frac{S_0\left(d_a - S_0\right)}{S_2\left(d_a - S_2\right)}\times\frac{-S_2\left(d_a - S_2\right)\times\left(d_a - 2S_0\right)}{S_0^2\left(d_a - S_0\right)^2}\right]\right] = 0 \tag{10}$$

$$\mathrm{d}\mu = \frac{\delta\mu}{\delta p_\mathrm{i}}\times \mathrm{d}(p_\mathrm{i}) \tag{11}$$

Substituting value $\frac{\delta\mu}{\delta p_\mathrm{i}}$ in Eq. (11), we get

$$\mathrm{d}\mu = \frac{-1.15C\left\{\left(d_a^2 - d_{\mathrm{i}1}^2\right)\left[\ln\frac{S_1(d_a - S_1)}{S_0(d_a - S_0)}\right]^n - \left(d_a^2 - d_{\mathrm{i}2}^2\right)\left[\ln\frac{S_2(d_a - S_2)}{S_0(d_a - S_0)}\right]^n\right\}}{4\times p_\mathrm{i}\times d_a\times h} = 0 \tag{12}$$

Substituting the suitable values in Eq. (12), we get the value of p_i. Then substituting the optimized values of S_0 and p_i in Eq. (1), optimized value of COF (μ) can be obtained.

4 Results and Discussion

Estimation of optimized initial thickness S_0 of tube in tube hydroforming for steel (Steel35NBK): Using Eq. (9), we can find the value of optimized initial thickness of tube in tube hydroforming. General parameters of case study are shown in Table 1.

For the case I: First assume that pressure is constant, p_i = constant. Using Eq. (10) and substituting the geometrical parameters of tube considered for case study of steel (Steel35NBK) as per [10], we get, Table 2.

Table 1 Geometrical parameters of tube considered for case study

S. no.	Symbol	Description	Value	Unit
1	d_a	Outer diameter of the tube before deformation	70	mm
2	d_{i1}	Punch-side inner diameter of the tube after deformation	66	mm
3	d_{i2}	Punch-side outer diameter of the tube after deformation	68	mm
4	n	Strain hardening coefficient	0.180	–
5	S_1	Thickness of wall on the side of movable punch	6	mm
6	S_2	Thickness of on the side of fixed punch	4	mm

Table 2 Geometric and optimized parameters of tube considered for case study

S. no.	Symbol	Description	Value	Unit
1	d_a	Outer diameter of the tube before deformation	70	mm
2	d_{i1}	Punch-side inner diameter of the tube after deformation	66	mm
3	d_{i2}	Punch-side outer diameter of the tube after deformation	67	mm
4	n	Strain hardening coefficient	0.180	
5	S_1	Thickness of wall on the side of movable punch	6	mm
6	S_2	Thickness of wall on the side of fixed punch	4	mm
7	S_0	Thickness of the tube before deformation	3.5	mm
8	H	Height of the tube after deformation	145	mm

Table 3 Optimized geometrical parameters of tube considered for case study for Steel35NBK

S. no.	Symbol	Description	Value	Unit
1	d_a	Outer diameter of the tube before deformation	70	mm
2	d_{i1}	Punch-side inner diameter of the tube after deformation	66	mm
3	d_{i2}	Punch-side outer diameter of the tube after deformation	67	mm
4	n	Strain hardening coefficient	0.180	–
5	S_1	Thickness of wall on the side of movable punch	6	mm
6	S_2	Thickness of wall on the side of fixed punch	4	
7	S_0	Thickness of tube before deformation	3.5	mm
8	H	Height of the tube after deformation	145	mm
9	C	Strength factor	656	mm

Table 4 Optimized geometrical parameters of tube considered for case study for AlMgSi

S. no	Symbol	Description	Value	Unit
1	d_a	Outer diameter of the tube before deformation	70	mm
2	d_{i1}	Punch-side inner diameter of the tube after deformation	66	mm
3	d_{i2}	Punch-side outer diameter of the tube after deformation	67	mm
4	n	Strain hardening coefficient	0.197	
5	S_1	Thickness of wall on the side of movable punch	6	mm
6	S_2	Thickness of wall on the side of fixed punch	4	mm
7	S_0	Thickness of tube before deformation	3.5	mm
8	H	Height of the tube after deformation	145	mm
9	C	Strength factor	260	MPa

Putting these values in Eq. (10), we get, $S_0 = 3.50$ mm. Hence from the value of $S_{0,}$ it is clear that the thickness of tube should be 3.5 mm.

Estimation of optimized pressure p_i of tube in tube hydroforming for steel (Steel35NBK): Using the Eq. (12), we can find the value of optimized pressure of tube in tube hydroforming. The required parameters of case study for steel (Steel35NBK) as per [10] are shown in Table 2.

For the case II: Assume that initial thickness (S_0) is constant, S_0 = constant. Using Eq. (12) and substituting

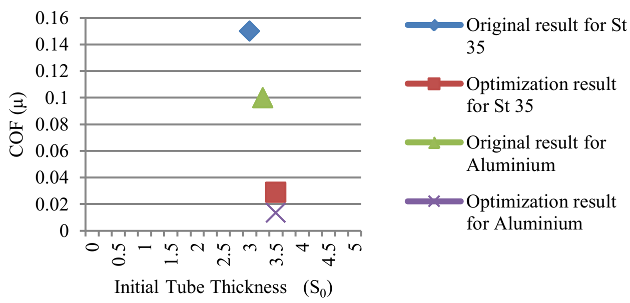

Fig. 4 Variation of COF (μ) with initial tube thickness S_0

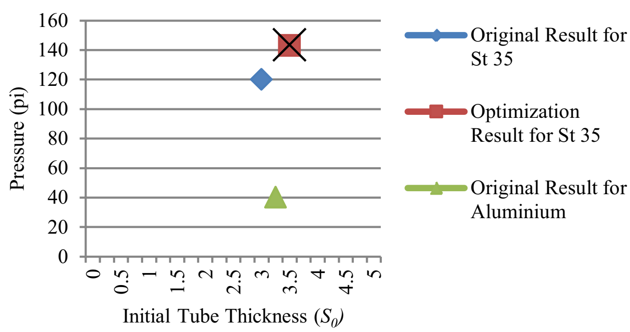

Fig. 5 Variation of pressure with initial tube thickness

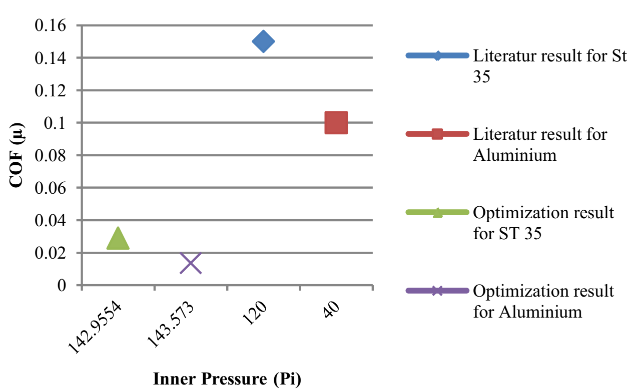

Fig. 6 Variation of coefficient of friction with inner pressure

the geometrical parameters of tube considered for case study from Plancak et al. [10], we get, $p_i = 142.9554$ MPa for Steel35NBK.

Combination of cases I and II: Substituting the values of S_0 and p_i in Eq. (1), we obtain the output value of COF (μ), i.e., $\mu = 0.0289$ for Steel35NBK. For different materials, values of C and n will be different; hence, COF will be different (Tables 3, 4).

Figure 4 shows the COF (μ) as the function of initial thickness of tube (S_0). It is seen that COF (μ) decreases from 0.15 to 0.0289 for Steel35NBK and 0.1 to 0.0136 for AlMgSi. As compared with original values, after optimization of initial tube thickness to 3.5 mm, Fig. 5 shows the inner pressure (p_i) as a function of initial thickness of tube (S_0). After optimization of initial tube thickness to 3.5 mm, it is seen that optimized pressure for Steel35NBK increases from 120 to 142.9554 MPa and for AlMgSi, it increases from 40 to 143.5730 MPa. Figure 6 shows COF (μ) as a function of inner pressure (p_i). It is seen that for optimized pressure of 142.9554 MPa for Steel35NBK, COF (μ) decreases from 0.15 to 0.0289 and for optimized pressure of 143.5730 MPa for AlMgSi, COE (μ) decreases from 0.1 to 0.0136. COF values are lower than those obtained by Plancak et al. [10] for this particular pressure. Hence, there is decrease in wall thickness inhomogeneity which will increase the quality of the component. As pressure p_i will change, values of S_1, S_2 will change, and for new pressure, we will get new optimized hydroforming pressure and new optimized COF as shown in Table 5. Hence, for different optimized pressures, we will get different optimized COF.

Table 5 Comparison of original and optimized values of COF (μ), pressure (p_i), and initial tube thickness (S_0)

S. no.	1	2
Material used	Steel35NBK	AlMgSi
C	656	260
N	0.180	0.197
Original (Plancak et al. model)		
μ	0.15	0.1
p_i (MPa)	120	40
S_0 (mm)	3	3.25
After optimization		
μ	0.0289	0.0136
p_i (MPa)	142.9554	143.5730
S_0 (mm)	3.5	3.5

5 Conclusions

- The tube upsetting method is easy for experimentation as compared to other methods, as it does not require measurement of applied force.
- The COF depends on two main factors, i.e., initial thickness of tube S_0 and internal pressure p_i.
- COF (μ) decreases from 0.15 to 0.0289 for Steel35NBK and from 0.1 to 0.0136 for AlMgSi after optimization of initial tube thickness $S_0 = 3.5$ mm and pressure $p_i = 142.9554$ MPa and pressure $p_i = 143.5730$ MPa.

- Without consideration of lubrication, the optimized values of COF, $\mu = 0.0289$ and $\mu = 0.0136$ between die and materials (Steel35NBK and AlMgSi). If lubrication effect is considered between die and material, COF (μ) will further decrease. Hence, new correlation can be obtained by considering the effect of lubrication during hydroforming process.

6 Future Scope

This mathematical model can be used for any suitable material and geometrical parameters of tube to obtain the optimized hydroforming pressure and optimized initial thickness of tube with minimum coefficient of friction between tube and die in tube hydroforming process.

Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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