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An approach to improve thickness distribution and corner filling of copper tubes during hydro-forming processes

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Abstract. In hydroforming, the general technique employed to overcome the problem of die corner filling consist in increasing the maximum fluid pressure during the forming process. This technique, in other hand, leads to other difficulties such as thinning and rupturing of the final work piece. In this paper, a new technique has been suggested in order to produce a part with complete filled corners. In this approach, two moveable bushes have been used. So, the workpiece moves driven by both bushes simultaneously. In the first stage, system pressure increases until a maximum of 15 MPa, providing aninitial tube bulge. The results showed that the pressure in this stage have to be limited to 17 MPa to avoid fracture. In a second stage, bushes are moved keeping the constant initial pressure. The punches act simultaneously at the die extremities. Results show that the friction between part and die decreases during the forming process significantly. Also, by using this technique it is possible to produce a part with reasonable uniform thickness distribution. Other outcomes of applying this method are the lower pressures required to manufacture a workpiece with complete filled corners with no wrinkling.

Keywords: tube hydro-forming; corner radius; finite element method; rupturing

1. Introduction

Sheet hydroforming has been developing since before World War II. The early sheet hydroforming technology was a forming technology mainly using a rubber diaphragm and a rubber bag being applied in small batch production of automotive panels and aircraft skins in the 1980s. In two researches which performed by Ziaei Poor *et al*. (2013) they showed that one of the most important defects in hydroforming are wrinkling, rupturing and thinning. These defects are mainly due to insufficient control during the forming process and excessive plastic deformation. Maki (2013, 2003) showed in his researches that sheet hydroforming is a technology which has been used for deep drawing for nearly fifty years.

This process has fewer restrictions when forming complicated parts, which allows styling

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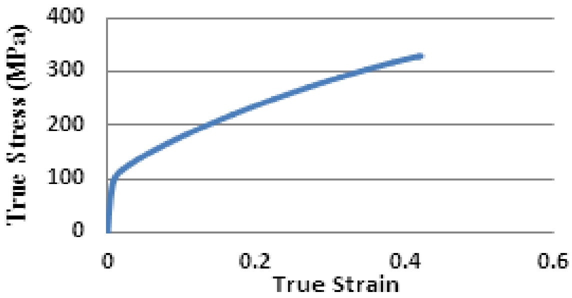
designers and manufacturing engineers more flexibility during the design process. Altan and Tekkaya (2012) have investigated that tube Hydroforming is a material forming process that uses a pressurized fluid in place of a hard tool to plastically deform a given tubular material into a desired shape. Lei *et al*. (2001), Woo *et al*. (1973) showed that in a tube hydro-formed part, the major concern regarding dimensional accuracy is the formation of the corners to a desired radius. If the corner has a smaller radius, it may not be completely filled due to insufficient internal hydraulic pressure. This problem is also related to the tube material formability. It is well known that the hydraulic pressure required in a tube hydroforming process, in order to manufacture a structural part depends on the minimum corner radius in the part shape. The formability analysis of THF process may include the relationship between maximum pressures, minimum corner radius, tube thickness and tube yield stress. Hwang and Altan (2002) have performed the two-dimensional hydroforming of circular tubes into rectangular sections by using FEA. In this study, two processes were compared. In the first, a smaller tube was expanded in a closed rectangular die. In the second, a larger tube was crushed into the die before the application of internal pressure. It was found that in the second case a much lower pressure was required to achieve corner filling. The thickness distribution after forming was more uniform for the crushed tube.

Some researchers focused on die corner filling in THF process. For example, Kridli *et al*. (2003) have studied the effects of some material and die parameters on corner filling and wall thickness distribution of the hydro-formed parts. They concluded that wall thickness distribution is function of die corner radius and strain-hardening behavior of material. They also stated that the thickness distribution could be reduced if a larger die corner radius was used. Hwang and Chen (2005) examined the corner filling in a square cross-sectional die by analytical, numerical and experimental methods. They concluded that higher pressure was required to fill the die corner if the corner radius was decreased, and that increasing the internal pressure to a critical value caused tearing of the tube. Xu *et al*. (2009) studied the effect of friction coefficient, strain-hardening exponent and anisotropic coefficient on thickness distribution of the tube in a square cross-sectional die by analytical, numerical and experimental methods. They finally concluded that the increment of friction coefficient increases tube thickness variation, and as a result, the uniformity of the part is reduced.

Increasing fluid pressure during tube hydro forming process to achieve a lesser amount of corner radius becomes the cause of excessive decrease of thickness in the corner areas of the tube. So, having complete die corners is inaccessible using simple dies. So, in this paper, it is introduced and presented a new technique to improve control in forming and filling of the die corners for single-step work pieces manufacturing.

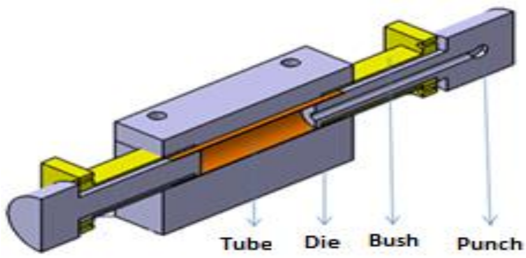
2. Experimental procedure and tooling

To perform the experimental tests, a multipurpose hydraulics press machine of Denison Mayes Group was employed, with 600 KN capacity and computer control. To provide an adequate maximum pressure, a 45 MPa pump has been applied. In this study, several seamless copper tubes have been used. To determine the mechanical properties of the copper, tube samples were provided according to ASTM-A370 standard. Also, an INSTRON universal test machine of 250 KN was used for tubes tensile test. Furthermore, an ultrasonic thickness gauge with the accuracy of 0.001 millimeters was used for measurement of thickness distribution. In Fig. 1, the tensile test machine, as well as true stress - true strain graph is shown.



(a) (b)

Fig. 1 Universal test machine and experimental stress-strain graph.



(a) (b)

Fig. 2 (a) The collection of single-step tube hydro-forming die of box shape (b) Cross-sectional diagram of the proposed mechanism

3. The mechanism of the new die

Fig. 2 illustrates, in the new presented mechanism, two punches for the axial feeding of the tube into the die cavity, as well as two moveable bushes that have been put in the die structure. In this process, the tube is initially put inside the die and the installed “O”-rings at the punches’ end seal them in two directions. After that, the high pressure oil is accomplished inside the tube from the hydraulic unit and via the central hole of the upper punch. After increasing the pressure, and at the onset of tube bulge, the upper punch gets close to the lower punch driven by press machine. Because of this kind of movement, the two bushes which have been placed at the tube sides get close to each other simultaneously. In this phase, fluid pressure must be fixed when the punches are forming the tube. Cross-sectional diagrams of the designed die are shown in Fig. 2.

When comparing to current dies, this proposed method improves the thickness distribution at the tube corners using a lower pressure. In addition, allow for complete filled corners without any rupturing or wrinkling in the formed tube. Moreover, by means of this technique, materials with high yield stress can be formed and it’s not necessary to increase the maximum fluid pressure to filling the corners of tube. In contrast, this technique just can be used for manufacturing stepped tubes with a simple shape, and it is not suitable to form complex shapes.

Table 1 (a) Data and material properties for copper tubular blank, (b) Chemical composition (wt, %) of the Copper tube

(a)		(b)	
Parameter	Value	Percentage	Element
Tube diameter (mm)	35	0.15	Sn
Tube length (mm)	180	0.15	Zn
Sheet wall thickness (mm)	1.35	0.3	Pb
Yield stress (MPa)	109	0.03	Cr
Density, ρ (kg/m^3)	8900	0.15	Fe
Young modulus, E (GPa)	110	0.03	Ni
Poisson coefficient, v	0.343	0.0812	Al
Friction coefficient, μ	0.06	0.003	Mg
		0.2	Si
		0.03	Mn
		0.05	As
		Base	Cu

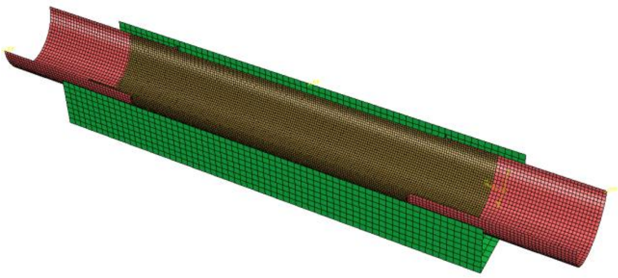


Fig. 3 FE model of single-step THF process by movable punch method

4. Finite element analysis

Modeling of THF process was developed using Abaqus/CAE. In the simulation, the tools including punch and bushes and die were considered as rigid, while the sheet was deformable. The S4R (4-node shell, reduced integrated) element was chosen for the sheet model and R3D4 for rigid parts. To validate the accuracy of the model in predicting the behavior of the tube, especially when a local neck forms, almost, the number of 3500 shell elements has been used. Coulomb friction was assumed for contact conditions and tubes material assumed as homogeneous. Fig. 3 shows the finite element model of the current dies. According to the symmetry of the model only half of the model has been modeled. A uniform pressure profile is used over the sheet surface at each stage of the forming process.

The path of the counter-pressure was defined using “Amplitude” which employs forming-time as a variable. Regarding the THF process conditions, the explicit solver has been selected for FEM analysis. The material and geometrical properties of copper are provided in the below table.

The final FE model of Tube hydroforming process is shown in Fig. 3.

Viorel *et al* (2003) showed that during THF process, only a limited length of tube can be pushed into the die cavity. There are some relations between maximum compressive force (F_a); the frictional force (F_f); the coefficient of friction between the tube and die surface (μ) and the length of the tube (L).

These equations could be obtained by the followings relations

$$F_a=\pi(D-t_i)t_i\sigma_u \tag{1}$$

Where: D is the tube diameter; t_i is the initial wall thickness; σ_u the ultimate tensile strength of material. The frictional force (F_f); from internal feed pressure could be obtained by the followings

$$F_f= \pi(D-2t_i)L\mu P_a \tag{2}$$

Where: P_a is the internal pressure. By manipulating these equations, the value for tube length (L) would be

$$L = t_i\sigma_u(1-\frac{t_i}{D})/(1-\frac{2t_i}{D})\mu P_a \tag{3}$$

During the axial feeding stage, the internal pressure for round sections is approximated by the following equation

$$P_a=2t_i(0.85\sigma_u)/(D-2t_i) \tag{4}$$

For large D/t_i ratios, ($D-2t_i$) approximates to D; and $(1-\frac{t_i}{D})/(1-\frac{2t_i}{D})$ approximates to 1; so Eqs. (3) and (4) can be simplified to the below relation

$$L=D/1.7\mu \tag{5}$$

The amount of feed is approximated by equating the material volume of the hydroformed component to the material volume of the tubular blank. Also, component material volume (V_c), and the axial feed length (F) can be calculated as follows

$$V_c=\pi Dt_iL \tag{6}$$

$$F=L-C \tag{7}$$

Path diagram of pressure loading is estimated by relating three different parameters which are; yield pressure (P_{Yield}); bursting pressure ($P_{Bursting}$) and calibration pressure ($P_{Calibration}$). These parameters are shown by the followings relations

$$P_{Yield}=\sigma_y(\frac{2t_i}{D-t_i}) \tag{8}$$

$$P_{Bursting}=\sigma_u(\frac{4t_i}{D_p-t_i}) \tag{9}$$

$$P_{Calibration}=\frac{2}{\sqrt{3}}\sigma_f \; Ln(\frac{r_b}{r_b-t}) \tag{10}$$

As Aue-U-Lan *et al.* (2004) showed in the above relations, σ_y is the yield strength, r_b is the smallest die corner radius, σ_f is the flow stress of the material and D_p is the protrusion diameter. According to the presented theoretical method, the values of the below table was obtained for determining of significant parameters in forming of copper tubes by THF process.

Table 2 The calculated parameters based on the theoretical method in THF process

Parameter	Value
Component material volume, V_c, mm^3	26719.2
The axial feed length, F, mm	112
Maximum compressive force, F_a, KN	48.522
Yield pressure, P_{Yield}, MPa	10.2
Internal pressure, Ps, MPa	28.4
Clibration pressure, PCalibration, MPa	39.1
Bursting pressure, $P_{Bursting}$, MPa	42.4

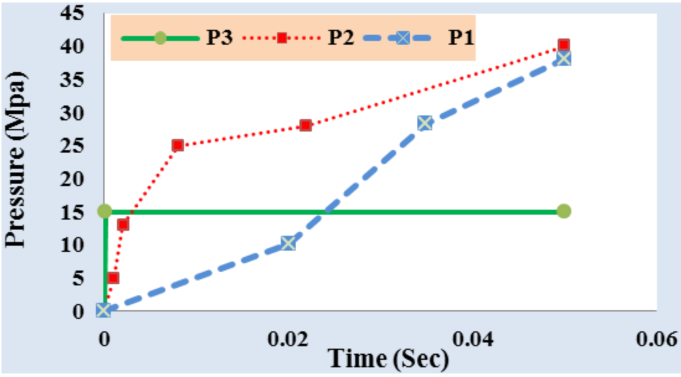


Fig. 4 Fluid pressure profile used in common THF (P_1, P_2) and fluid pressure profile used in proposed method (P_3)

Different fluid pressure profiles (Fig. 4) have been used in order to compare the results of common THF process the proposed method. Fluid pressure profile of P1 has been obtained from the theoretical methods that proposed by Viorel *et al*. (2003), Aue-U-Lan *et al.* (2004). Fluid pressure profile of P_2 is the result of fluid pressure profile which has been presented by Imaninejad *et al* (2005), Al-Qureshi *et al*. (2001). In this profile, multi stage fluid pressure has been used for achieving more uniform thickness distribution as well as for obtaining better bulge. In order to achieve the initial bulge an increasing pressure has been used in the initial stage of this profile. After that, fluid pressure has been increased linearly to reach its maximum value.

In this research the minimum amount of fluid pressure which is necessary in bulge stage, as well as to control wrinkling, has been obtained via different simulations for determining of fluid pressure profile of P_2. The maximum fluid pressure has been determined via finite element method when corners thickness is less than 20 percent of the initial thickness. The fluid pressure profile P_2 has been obtained in the way that has been shown in Fig. 4 regarding these parameters. Fluid pressure profile of P_3 has been used in the proposed method, and obtained through different simulations regarding the two parameters of thickness distribution and wrinkling.

Fig. 5 shows the achieved results of common THF process and the presented method for single-step forming using the pressure profiles P_1, P_2 and P_3.

As can be seen in the results of Fig. 5, most of thinning has been occurred at the die corners. The results also show that the better results have been achieved by applying pressure profile P_3, filling die corners with minimum pressure. The profile of corners done by different pressure profiles are shown in Fig. 6.

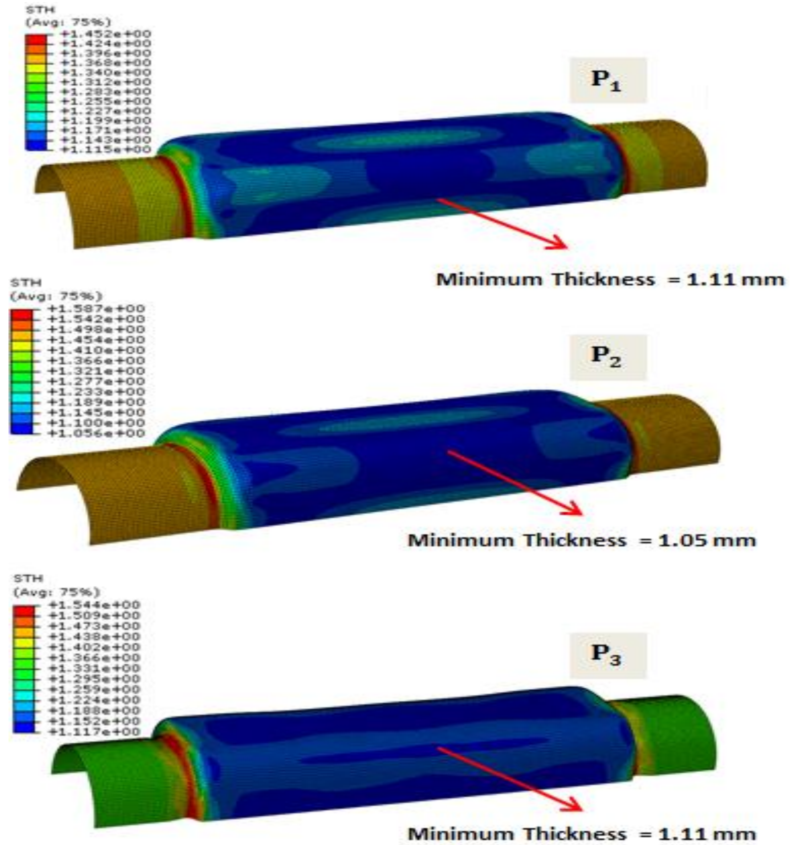


Fig. 5 Thickness distribution of FEM analysis by using pressure profiles P_1, P_2 and P_3

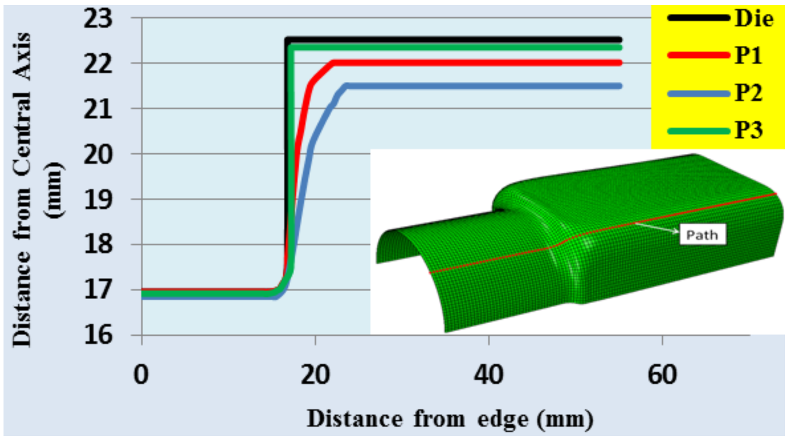


Fig. 6 Tube filling profile under different shaping path pressures

A criterion for the filling percentage of the die corners has been used. It is based on the outer radius of formed work piece (R) and the die radius (R_0). Fig. 7 shows the bar chart related to the filling percentage of the die corners.

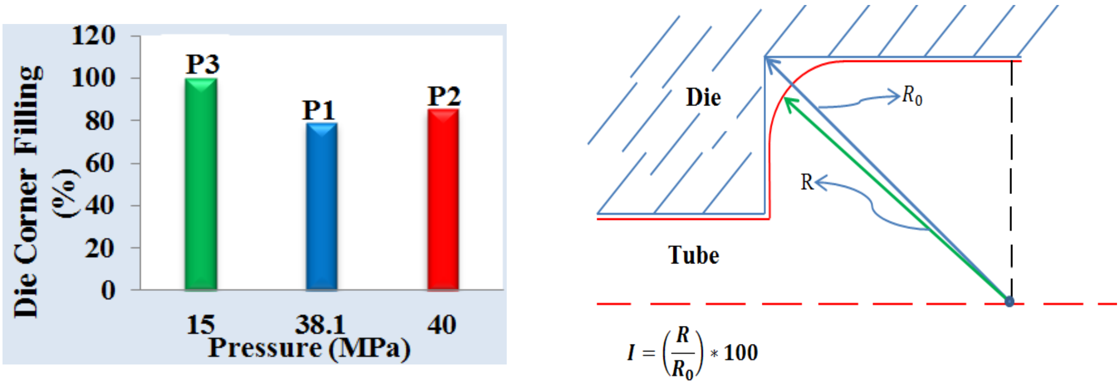


Fig. 7 The chart of the filling percentage for different pressure profiles

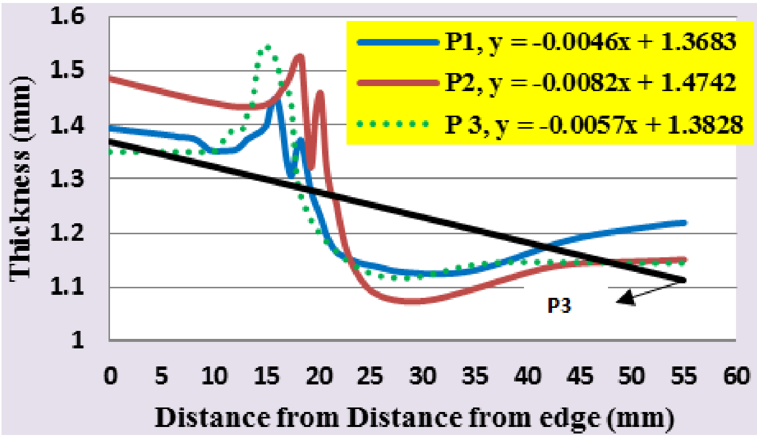


Fig. 8 Thickness distribution chart in longitudinal direction of the tube for pressure profiles of P_1, P_2 and P_3

Fig. 8 shows the chart of thickness distribution at the tube longitudinal direction for pressures profiles P_1, P_2 and P_3. Regarding the tube symmetry, and for better comparison of the results, only half of the model has been analyzed. As it's shown in Fig. 10, the pressure profile P_1 yields a better thickness distribution (less slope of line while the filling percentage of the die corner is less than the other cases. In the pressure profile P_2, the filling percentage of the die corner has been improved (Fig. 9) but the slope of the interpolated line is more than the two other cases. In P_3 pressure profile, the filling percentage of the die corners is close to 100. In addition, the slope of the interpolated line which is shown with black color in Fig. 8 is acceptable.

The results show that P_3 pressure profile shows acceptable results. So, it has been used for performing the experimental tests and validation. Fig. 9(a) shows that rupturing occurred in the middle region of the tube if pressure of 17 MPa is used for initial shaping of the tube in bulge stage. In addition, a safe and sound work piece is manufactured if P_3 pressure profile is used for doing the process by the proposed methods of moveable bushes.

In order to compare experimental and simulation results, three sections of the tube have been selected. Fig. 9(b) shows these sections and the thickness distribution has been considered in these regions. Fig. 10 shows the thickness distribution in three areas of A, B and C for FE model and experimental tests. As seen in Fig. 10, in this work piece, some corners of the work piece near the

(a)

(b)

Fig. 9 (a) The ruptured tube in initial bulge phase because of improper pressure in 17 MPa pressure, (b) the formed tube by using P_3 pressure profile

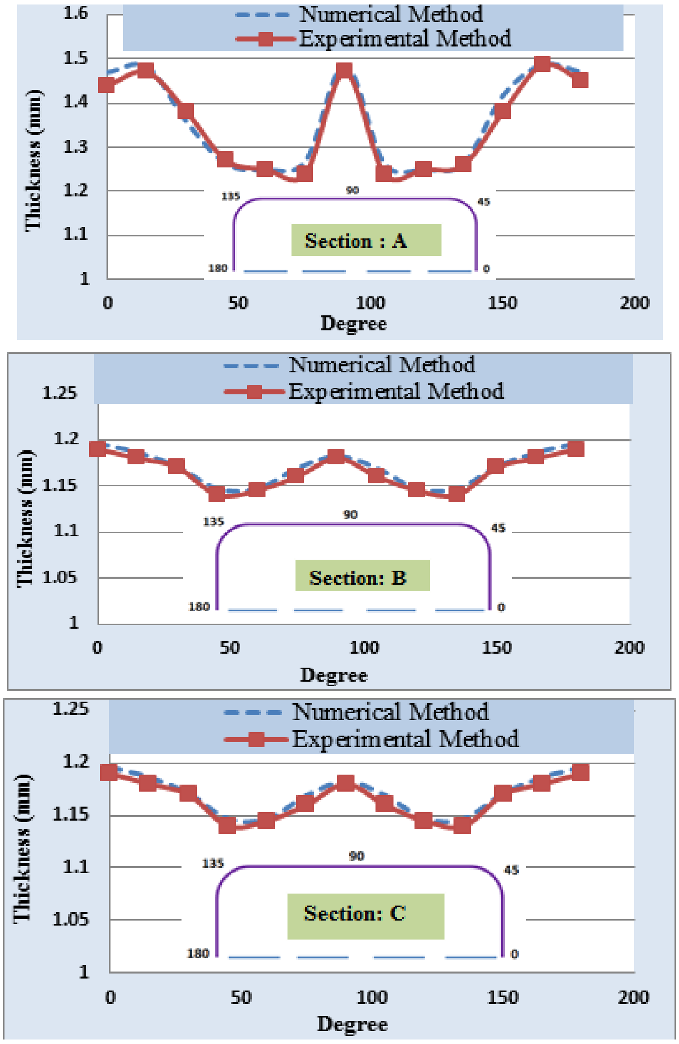


Fig. 10 The comparison of thickness distribution chart in three Sections of A, B and C of the formed tube by movable bush method

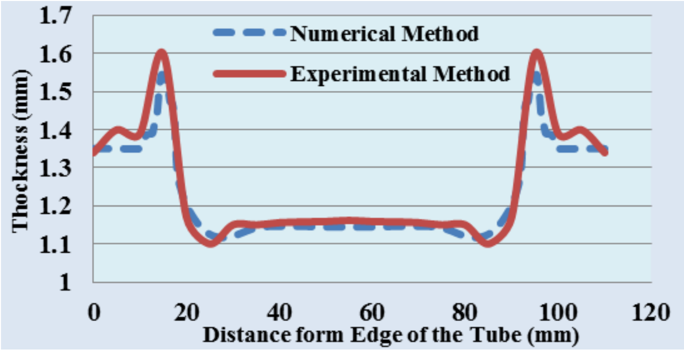


Fig. 11 Alteration curve of minimum thickness of the work piece in proportion to the distance from the border of the box shaped part

bushes have been filled completely, but in some areas (parallel to the tube axis), the corners have not been filled completely. The reason is related to better axial feeding at the areas near to the bushes. However, the fluid has not been able to continue to act at the tube central regions.

According to Fig. 10, the amount of thickness distribution at the selected section in different angles increases gradually from section A to section C, which has been placed in the central part of the tube. The reason is that axial feeding of the bushes causes the flowing of the material in axial direction, in the sections which are near to two heads of the tube. Friction force increases according to the process flow, so the amount of axial flowing which has been created by the bushes decreases from the end of the tube to the middle part of the tube gradually. Therefore, there will be less materials flow in the central areas of the tube. Fig. 11 illustrates the thickness distribution of FE model and experiments in a formed tube by using the movable bush method.

As it's shown in Fig. 11, the minimum thickness of the tube has been increased from the two ends of the tube till the distance of 15mm from both ends of tube. As it can be seen, the thickness distribution in the area of 30 to 80 mm was constant. The main reason of this non-uniform thickness distribution is related to fractional force, which is maximum in these areas. So, a non-uniform feeding will take place in the central regions of the tube.

5. Conclusions

In this paper, a new die was presented for forming the single-step tubes, in which filling of the die corner has been improved in proportion to common tube hydro framing dies. To predict the results, FE models of common die and the new proposed die have been considered by using three different pressure profiles. The simulation results showed that in the new method, the die corners have been filled completely while the die corners have not been filled completely in the conventional die. For verification, this new die was built and the thickness distribution of tubes was compared numerically and experimentally. The results showed that by using moveable bushes it would be possible to feed the material into the die cavity directly. According to the results, the frictional force that is related to the friction between die and tube was decreased and the thickness distribution was improved. Other advantages of the presented method are, simplicity of the die shapes, manufacturing some tubes with small corner radius and complicated shapes and it would be possible to product a tube without any wrinkling by using lower maximum pressure. One of the limitation of this technique is that can be used just for manufacturing stepped tubes with a simple shape, and it is not suitable to form complex shapes.

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