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ORIGINAL ARTICLE

On the tube hydroforming process using rectangular, trapezoidal, and trapezoid-sectional dies: modeling and experiments

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Abstract It is generally known that the contact between tube and die, in the case of tube hydroforming process, leads to the appearance of friction effects. In this context, there are many different models for representing friction and many different tests to evaluate it. In the present paper, the pin-on-disk test has been used and the theoretical model of Orban-2007 has been chosen and developed to evaluate friction coefficient. The main goal is to prove the capacity of theoretical model to present the friction conditions in comparison with the pin-on-disk test. From the Orban model, values of 0.05 and 0.25 of friction coefficient have been found under lubricated and dry tests, respectively. On the other hand, by the classical pin-on-disk test, other values were experimentally obtained as friction coefficient at the copper/steel interface. In the case of pure expansion hydroforming, based on an internal pressure loading only, a "corner filling" test has been run for tube hydroforming. Both dry and lubricated contacts have been considered. Various configurations and shapes have been studied such as the rectangular, trapezoidal, and trapezoid-sectional dies. Finite element simulations with 3D shell and 3D solid models have been performed with different values of friction coefficients. From the main results, it was found that the critical thinning occurs in the transition zone for the square and rectangular section die and in the sharp angle for the trapezoidal and trapezoid-sectional die. The comparison between numerical data and experimental results shows a good agreement. Moreover, the thickness distribution along the cross section is relatively consistent with those measured for the 3D shell model; however, the 3D solid models do not provide a realistic representation of the thickness distribution in the shaped tube. Finally, the results obtained from the theoretical model were more efficient than the results obtained from the pin-on-disk test.

Keywords Tube hydroforming · FE simulation · Friction coefficient · Thickness distribution · Lubrication

1 Introduction

During the last decades, a lot of efforts have been dedicated to study the tube hydroforming process using various shaped dies under dry and lubricated conditions at the contact tube/die [1–3]. In 2003, Kridli et al. [4] have investigated the thickness variation and the corner filling in a square section die through numerical and experimental investigations. Indeed, the thickness distribution is related to the corner radius and the strain hardening behavior of the material. The experimental results agree well with the FE simulation on the stage of the evolution of the thickness distribution and the prediction of the thinning location. Liu et al. [5] have investigated the stress and strain variations in the corner, as well as the effect of friction conditions through analytical and numerical studies, to explore the reasons of the local thinning and to discuss different possible strategies to avoid this defect. They have concluded that the thinning occurs in the transition zone to satisfy the yield condition for the circumferential stress in this location. In 2007, Orban and Hu [6] have proposed an analytical model for the

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expansion of circular tube into a square section die. They have focused mainly to investigate the stress and strain variation along the tube section when the internal pressure increases. It was reported in their work that the friction coefficient and the material hardening affect the thickness distribution along the transversal section of the shaped tube. So, this model (Orban-2007) could be used for the determination of the process limits. Xu et al. [7] have conducted theoretical works where the thickness distribution along the cross section of a square section-hydroformed part is studied. Numerical studies showed again that critical thinning takes place in the transition zone, while the thickest element is located in the middle of the straight wall. Effects of the friction coefficient, the strain hardening exponent, and the anisotropy coefficient on the thickness distribution are explored in the literature [4, 8, 9]. Both of the numerical and experimental results reported that an increase in the friction coefficient reduces the uniformity of thickness. Commonly, the maximum of thickness reduction appears firstly in the transition zone, then in the corner, and finally in the straight wall [10]. Daly et al. [11] have performed a corner filling test in a square section die; therefore, a localized thinning appears in the transition zone between the corner radius and the straight wall. Kyriakides [12] has studied the tube hydroforming in a square section die through 2D numerical models and experimental test. The effect of the friction on the wall thinning has been investigated. Kokoris and Kyriakides [13] have investigated the 3D shell as well as the 3D solid in a square section die. Indeed, they have concluded that the 3D shell model failed to reproduce correctly the evolution and localization of these thickness depressions; however, the 3D solid permits to show well the different area.

In the literature, several researchers have been developed on the study of rectangular section die. Yuan et al. [14] have studied the load path of hydroforming tube in rectangular cross section. The result shows that the bursting occurs in the transition zone and the maximum thickness is at the central point of the side of cross section. Xiao et al. [15] have investigated the plastic deformation on hydroforming of aluminum alloy tube in rectangular section, and they have reported that the thinning occurs in the transition zone. The equivalent stress for the transition point tended to increase with increasing the friction coefficient, which leads to the significant thickness thinning, even bursting. Liu et al. [5] have investigated the stress distribution and the deformation in the corner by mechanical analysis and numerical simulation. The results prove that the thinning and the cracking appear in the transition region. Moreover, the transition region leads to satisfy plastic-yielding conditions and produce thickness compressive strain. Therefore, severe thinning deformation is easy to take place at the transition region. Zhang et al. [16] have studied the corner filling in a rectangular section based on analytical model, numerical simulation, and experimental test. The main goal of the analytical model is to study the effect of friction coefficient and to predict fracture. In fact, the increase of friction value leads to an important variation in thickness and corner radius. The thinning is located in the transition zone. The experimental results show a good agreement with the numerical simulations. Yuan et al. [17] have studied the corner filling in a rectangular section through analytical, numerical, and experimental investigations. As usual, the severe thinning takes place in the transition zone. Moreover, the lubrication conditions have an important effect on the transition corner filling and to lead to a small corner.

Some researchers have investigated the tube hydroforming process using shaped dies, particularly trapezoid-sectional die [18, 19]. Xu et al. [18] have studied the effects of friction coefficient and the thickness distribution via numerical and experimental approaches. It was found that the fracture occurs in the sharp angle and wrinkle takes place in the obtuse corner. Moreover, the increase of the friction coefficient decreases the bursting pressure and the uniformity of the tube wall. Li et al. [19] have studied the crushing and hydroforming process in a trapezoid-sectional die. Their results reveal that three parameters affect the uniformity of thickness distribution which are the die closing seam, the tube diameter, and the performing load path. Moreover, two kinds of defects can occur in the loading part: bursting is most liable to occur at the sharp angle, while wrinkling is most liable to take place at the blunt angle.

Concerning the friction effect, which is always in conjunction with the lubrication conditions, many researchers have been developed in this context. In 2004, Ngaile et al. [2] have investigated the lubrication mechanisms and their effect on the interface friction. They have equally focused on the lubricant performance in the transition and expansion zones for various geometries. In the second study, Ngaile et al. [3] have concluded that the lubrication reduces frictional stresses of the tool/tube wall interface and helps to enhance the product quality. A good lubrication leads to reduce any risk of buckling and wrinkling. In other case, various tests have been used to identify friction coefficient such as the “pin-on-disk” test [1, 20] or tube hydroforming test [21]. Other kinds of tests have been used to investigate friction conditions in cold rolling process such the incremental compression test (IRCT). Indeed, the results prove that this test is more efficient than the classical ring compression test to establish friction coefficient [22]. Other researchers have investigated different measurement methods of friction coefficient for various procedures such the tube hydroforming process. In fact, they have presented an apparatus of friction coefficient test in tube hydroforming which permits to achieve friction value between tube/die interfaces. Consequently, the friction coefficient is found to be uniform at the interface throughout the hole tube length [23, 24].

Several researches have investigated the tube hydroforming process with numerical simulation. Indeed, majority of FE simulation models are performed by 2D geometry and 3D shell

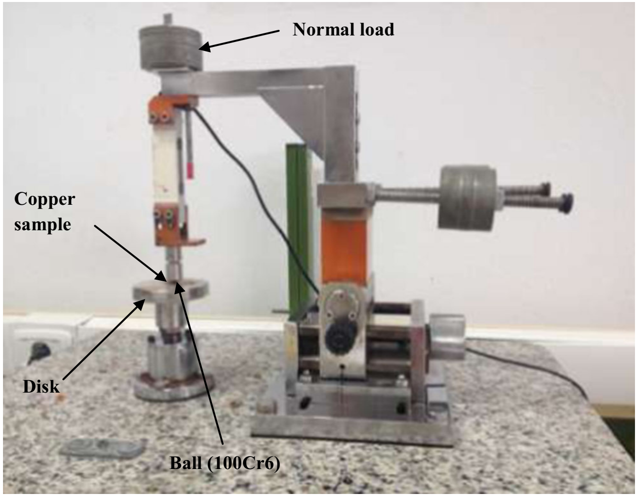

Fig. 1 Schematic representation of the pin-on-disk apparatus at the LGME laboratory

elements in order to simplify the calculations. As for hydroforming, applications of mainly two models, with shell elements [7, 18, 25] and solid elements [13, 26], have been reported in most of the recent papers. It is rather difficult to say which model would be good enough for a specific application. Hence, a comparison of calculated results obtained by means of different numerical models could be very helpful in finding some indications for using those models.

In early studies, the friction coefficient in tube hydroforming has been successfully evaluated with the "corner filling test" in a square section die. The programming of the theoretical Orban-Hu model has been validated through the use of FE simulations. As a logical follow-up to our previous contributions, the main goal of the current work is to show the validity of the characterized friction coefficient by performing both experiments and numerical simulations for other tool

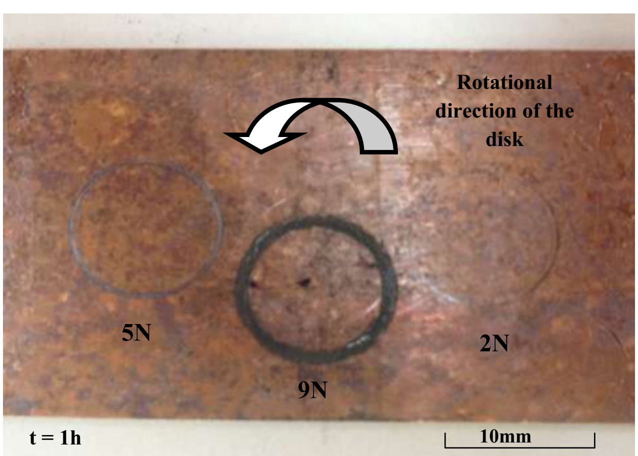

Fig. 2 Effect of normal load on the wear track performed on the copper sample under dry conditions

Table 1 The obtained coefficients of friction (COFs) for different experimental conditions

	Normal applied load	
	2 N	5 N
COF in dry test	0.1	0.37
COF in lubricated test	≈0	0.13

geometries namely rectangular section, trapezoidal, and trapezoid-sectional die.

The main innovation of this paper in conjunction with our previous papers [27, 28] is (i) to prove, in the first case, the capacity of theoretical model to evaluate well the friction conditions in the classical square section die and (ii) to show, in the second case, the validity of the obtained friction values for other shaped dies.

The work is organized basically into three parts. First of all, Sect. 2 pays attention to experimental studies by introducing the retained material, the corner filling in various shaped dies, the pin-on-disk test as well as the various measurements. Second, in Sect. 3, the theoretical model is briefly presented, the evaluation of friction coefficient for dry and lubricated test has been investigated, and both FE models (3D shell and 3D solid) for various shaped dies are illustrated. The comparative study between FE simulations and experimental measurement for various shaped dies is the subject of Sect. 4. Finally, the main retained points of the current work are summarized in the conclusion.

2 Experiments

2.1 Materials

The material used in the current study consists of the deoxidized copper (Cu-DHP) which is previously described in ref. [27].

2.2 Corner filling in various shaped dies

During this work, tube hydroforming experiments have been performed using different shaped dies such as square, rectangular, trapezoidal, and trapezoid-sectional die. Indeed, these values have been determined from crack level. At the beginning of the tests, some parameters need to be adjusted such as the maximal internal pressure, the compression force that realizes the tube end clamping and the sealing, and the position of the displacement sensors. Two different experimental

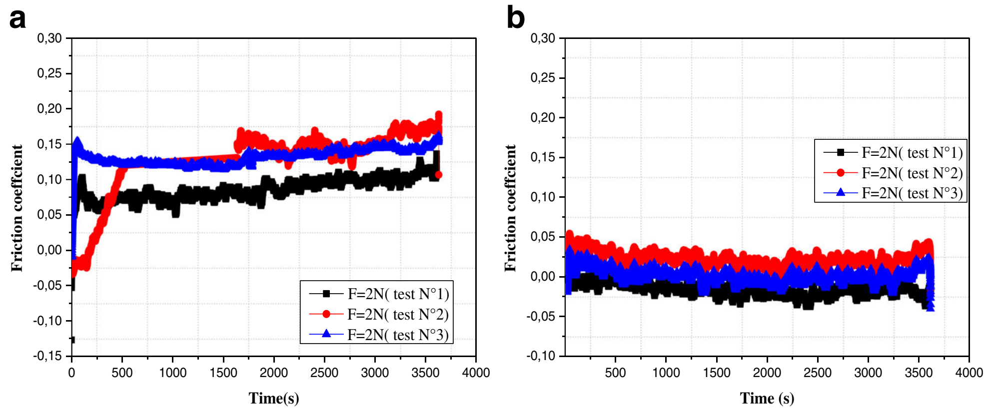

Fig. 3 Variation of the friction coefficient with testing time: under dry conditions (a) and lubricated conditions (b). (Test conditions: 2 N, v=78.5mm/s)

investigations were carried out in this study. The first one was performed to study the effects of the lubrication on the process, and the tests were conducted for tube hydroforming under different lubrication conditions. The second one was used to identify the friction value from the experimental results in conjunction with the analytical model [6]. Finally, it was compared the friction coefficients obtained from the tube hydroforming with the one estimated using a pin-on-disk test under the different lubrication conditions.

2.3 Pin-on-disk test

The pin-on-disk test was performed to investigate the friction coefficient such as many previous researches [1, 20]. The schematic illustration of this apparatus at the LGME laboratory is given in Fig. 1. A hardened steel (carbon chromium steel 100Cr6) ball with 10 mm of diameter is used as the counter body. This material permits to simulate the real contact between the copper tube and the steel die. Samples have been degreased and cleaned prior to the experiment using acetone and ethanol. Typically, flat samples in deoxidized copper (Cu-DHP), with dimensions of 70 mm × 25 mm × 0.9 mm, were fixed horizontally on a rotary disk. Tests were carried out using various normal loads (F_n) of 2, 5, and 9 N and at a velocity of 150 rpm. A friction/load sensor allows measuring the tangential force (F_t) in the contact between sample and ball. Experiments are carried out in ambient air (22 °C and 40% relative humidity). For a good repeatability of the results, all tests have been triplicated and averages are considered. The data is saved in a text file which is then analyzed using a MATLAB program for the evolution of the friction coefficient with time. The apparent friction coefficient (μ) is therefore determined as the ratio between the two forces

$$\mu = F_t / F_n$$

The results obtained with the load of 9 N were eventually discarded because high wear was observed as shown in Fig. 2. The friction coefficients thus measured are provided in Table 1, and the results obtained are shown in Figs. 3 and 4. Therefore, we retain a friction coefficient of 0.1 and 0 for the test without lubrication and with lubrication, respectively.

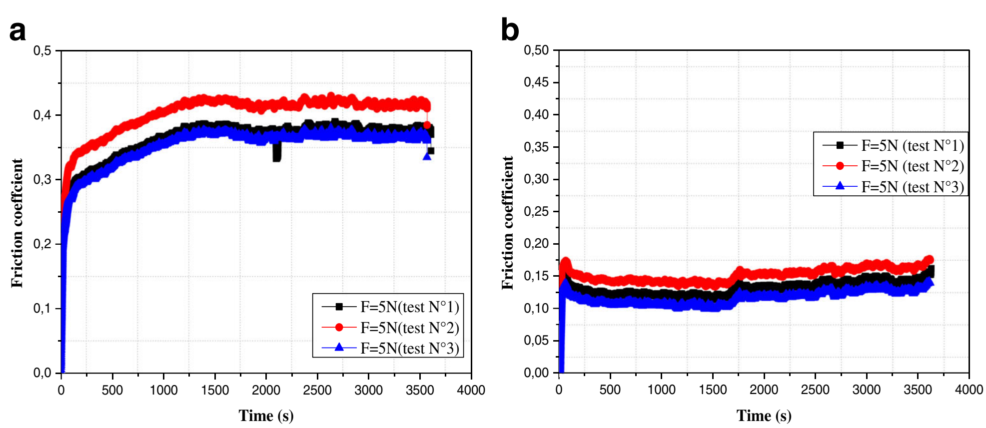

Fig. 4 Variation of the friction coefficient with testing time : under dry conditions (a) and lubricated conditions (b). (Test conditions: 5 N, v=78.5mm/s)

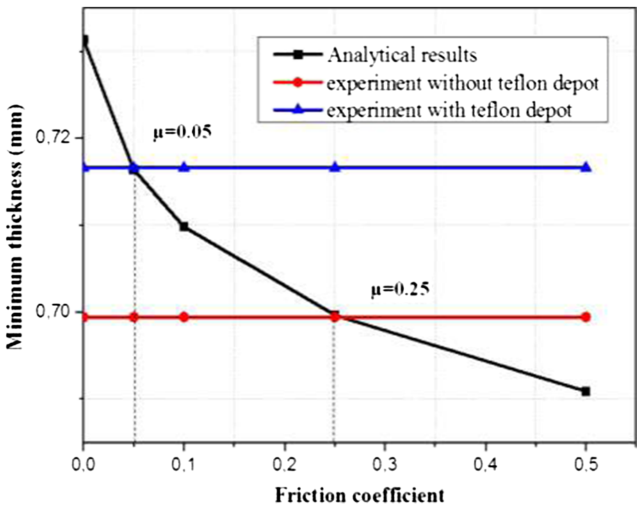

Fig. 5 Evaluation of the friction coefficient with the minimum thickness – friction coefficient curve

In the following section, the choice of the friction values for the lower load was justified as follows: in our case, it is not easy to specify the contact pressure between the tube and the die. In addition, it is certain that at the end of the hydroforming test, any sign or track of wear can be observed on the tube surface. For this reason, we choose to work with the lower normal load (2 N) to avoid any risk of critical wear. As can be seen in Fig. 4, the signs of wear for the load charges of 5 and 9 N are very important, nevertheless for the normal load of 2 N is less severe. For that, a normal load of 2 N effort appears to be nearest to reproduce the real case for identifying the coefficient of friction between the copper/steel either dry or in the presence of lubricant.

3 Models

3.1 Theoretical model: friction coefficient evaluation and process simulation

As described in our previous works [29, 30], the model of Orban-Hu [6] has been investigated. Indeed, this model consists of studying the corner filling in a square section die considering two parts named corner and the wall. The stick and slip zone has been also studied. With the use of mathematical assimilation, the evolution of corner radius, corner thickness, wall length, and wall thickness has been evaluated. The swift hardening law has been considered. The theoretical model has been programmed with MATLAB using experimental material parameters (strength coefficient k, strain hardening coefficient n, and initial strain ε_0) and geometric parameters (corner radius, tube thickness, die width). In our study [28], our programming of the Orban-2007 model has been successfully validated. Moreover, the capacity of this model to well represent the friction condition effect on the material flow in a corner filling test has been equally validated. In addition, the study of this model leads to select the most appropriate FE models which is the 3D model based on shell or solid finite elements. Finally, this model helps to define approximately the value of the most discriminatory parameters which is the friction coefficient instead of spending much time to try different values. Indeed, the leader factor which affects friction in tube hydroforming process was the lubricant. Selecting the appropriate lubricant depends on the internal pressure, the sliding velocity, and the distance involved for a particular part.

In the present study, our reference model is the square section. So, the friction value reached from the analytical model will be applied for the other sections. The studied tube

Table 2 Conditions used for FE simulations

Material	Cu-DHP Hardening law: $\overline{\sigma} = 441.97(0.0075 + \overline{\varepsilon})^{0.349}$
Friction conditions	▪ Case of dry test: μ = 0.1 obtained from the “pin-on-disk” test μ = 0.25 obtained from the pure expansion test in a square section. ▪ Case of lubricated test: μ = 0 obtained from the pin-on-disk test μ = 0.05 obtained from the pure expansion test in a square section.
3D shell model	FE shell Belytschko-Tsay 13,423 elements 13,530 nodes
3 D solid model	Fully integrated quadratic 8-node element with nodal rotations 4 elements in the thickness 52,000 elements 65,520 nodes

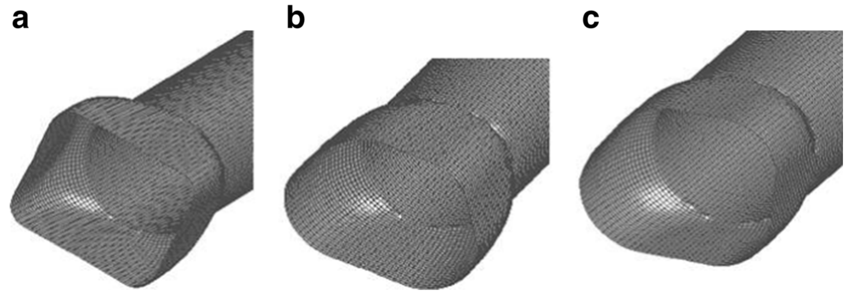

Fig. 6 Deformed tube obtained by 3D shell simulations for different configurations

presents a mean thickness of 0.9 mm. The minimal thickness at the end of the process corresponding to an internal pressure of 28 MPa has been measured; its value is 0.69941 mm. In Fig. 5, the friction evaluation is described; it is found that μ = 0.25. In fact, it is important to keep in mind that the friction coefficient determined with the tube expansion in a square die is not comparable to the physical friction coefficient characterized by the pin-on-disk test. This friction coefficient includes a number of parameters linked to the process such as the surfaces in contact and the type of the mechanical load. The results obtained from the tube hydroforming with the Teflon depot lead to a minimal thickness of 0.71659 mm. Again, in Fig. 5, the friction evaluation is described and value of 0.05 is found.

It is worth noting that the theoretical model exhibits the same conditions with the experimental expansion test in the case of geometric parameters, material parameters, and maximal internal pressure. For this reason, friction values achieved from theoretical model are more appropriate to the experimental hydroforming test. However, for the pin-on-disk test, to conduct a friction test, the choice of suitable applied loads depends on pressure contact. Although, it is not easy to optimize the pressure contact of cooper/steel suitable to the real expansion test since the experiment conditions are not similar in the both cases. Therefore, the measured values are not accurate and have an improper physical significance.

3.2 Finite element simulation

In this part, various configurations are simulated using explicit FE code LS-DYNA software for different friction conditions in relation with the experimental results reported in ref. [28].

Due to the symmetry of the geometry, only a half of tube is considered to simulate the forming process. The post-processing of the numerical results consists of analyzing the evolution of the thickness distribution, thickness spatial repartition, and die radius evolution in relation with the different friction conditions. The main conditions used for simulation are illustrated in Table 2. Figures 6 and 7 illustrate the 3D model based on shell and solid finite elements, respectively, for different shaped dies.

4 Results and discussion

4.1 Square section

Numerical simulations of the corner filling test were conducted with 3D solid and 3D shell models, using both friction values (μ = 0.1, μ = 0.25) achieved from the pin-on-disk test and from the Orban-Hu model, respectively, in the field of dry test (Fig. 8a). As shown in Fig. 8a that, with an internal pressure of 28 MPa, the resulting thickness along the section of the tube obtained at the end of the process has been illustrated. First of all, it can be noticed that the experimental measurements exhibit a thinning location in the transition zone. Consequently, this result leads to reach a good agreement with the results obtained from several studies [5, 7, 10, 11, 14]. For the 3D solid finite element model, only critical points are plotted introducing the right wall, transition zone, and the corner zone. Indeed, the 3D solid model gives the best agreement with the experimental results especially in the transition zone where the coefficient of friction becomes important (μ = 0.25). However, it has a steady thickness in the corner

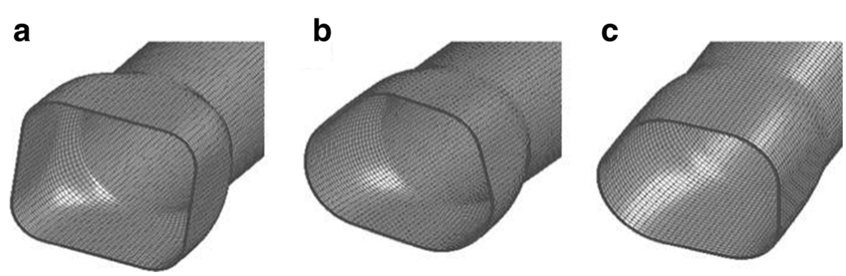

Fig. 7 Deformed tube obtained by 3D solid simulations for different configurations

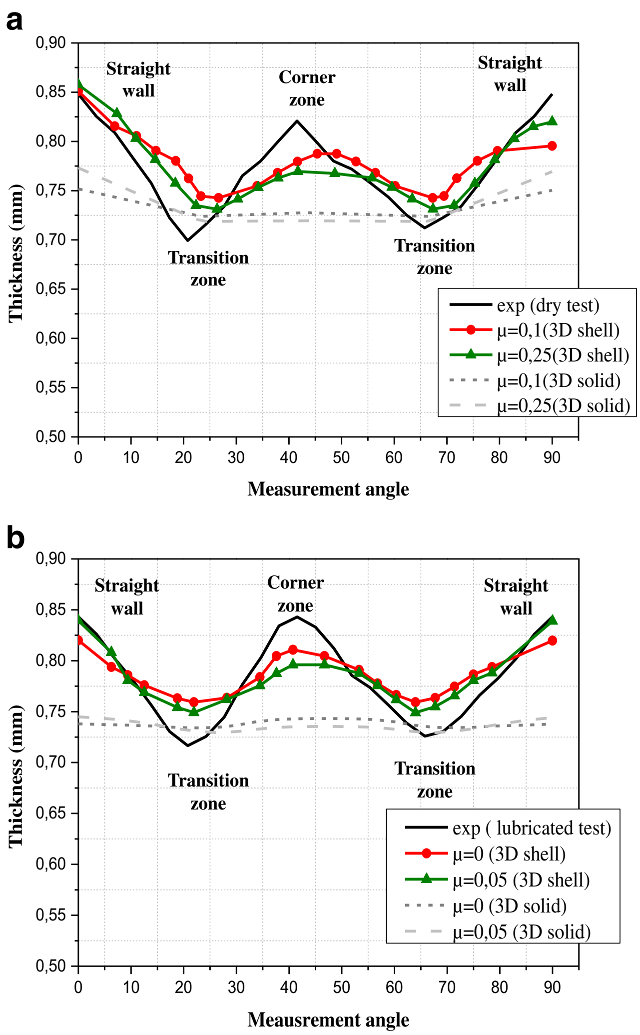

Fig. 8 (a) Thickness distribution against measurement angle using dry test for square section die and (b) Thickness distribution against measurement angle for lubricated test using square section die

zone. However, the 3D shell model provides a better depiction of the thickness variation, even if it is not perfect. In fact, thinning in the transition zone is underestimated with $\mu = 0$ and $\mu = 0.05$. These comparisons are summarized in Table 3.

Figure 8b also shows the thickness distribution along the tube section. Indeed, two friction coefficients are considered: $\mu = 0$ and $\mu = 0.05$ obtained from the pin-on-disk test and the theoretical model, respectively, under lubricated test. In Fig. 8b, the results are very similar to those given in Fig. 8a. In fact, the maximum thinning occurs in the transition zone. The 3D shell model reveals the best configuration compared to 3D solid model. The raise in the friction coefficient from 0

Table 3 Comparison between numerical results and experimental measurements (square section)

	Error in t_{min}	Error in Δt
μ = 0.1 (3D shell)	−6.2%	+2.8%
μ = 0.25 (3D shell)	−4.6%	+1.5%
μ = 0.1 (3D solid)	−3.5%	+8.4%
μ = 0.25 (3D solid)	−2.8%	+6.3%

Table 4 Comparison between numerical results and experimental measurements (square section)

	Error in t_{min}	Error in Δt
μ = 0 (3D shell)	−5.9%	+5.2%
μ = 0.05 (3D shell)	−4.5%	+2.8%
μ = 0 (3D solid)	−2.4%	+9.6%
μ = 0.05 (3D solid)	−1.8%	+8.7%

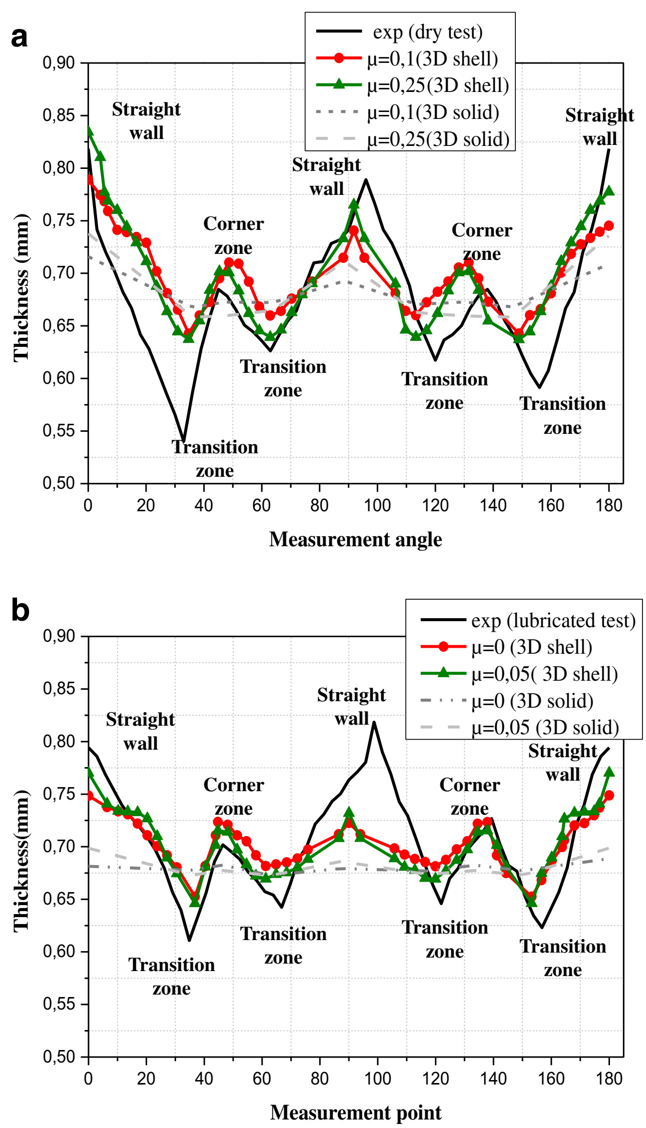

Fig. 9 (a) Thickness distribution against measurement angle using dry test for rectangular section die and (b) Thickness distribution against measurement angle using lubricated test for rectangular section die

Table 5 Comparison between numerical results and experimental measurements (rectangular section)

	Error in t_{wall}	Error in $t_{transition}$	Error in t_{corner}
μ = 0.05 (3D coque)	+3%	−5.7%	−1.9%
μ = 0.25 (3D coque)	+3.6%	−9.7%	−2.4%

to 0.05 with both FE models leads to increase the thinning. Nevertheless, the lubrication leads firstly to decrease the friction coefficient (from 0.25 to 0.05, for example) and then to reduce the thinning. For instance, for friction values of $\mu = 0.25$ and $\mu = 0.05$, the distinguishing among the measures achieved by 3D solid model and experimental results has been declined from 2.8 to 1.8%. These comparisons are summarized in Table 4.

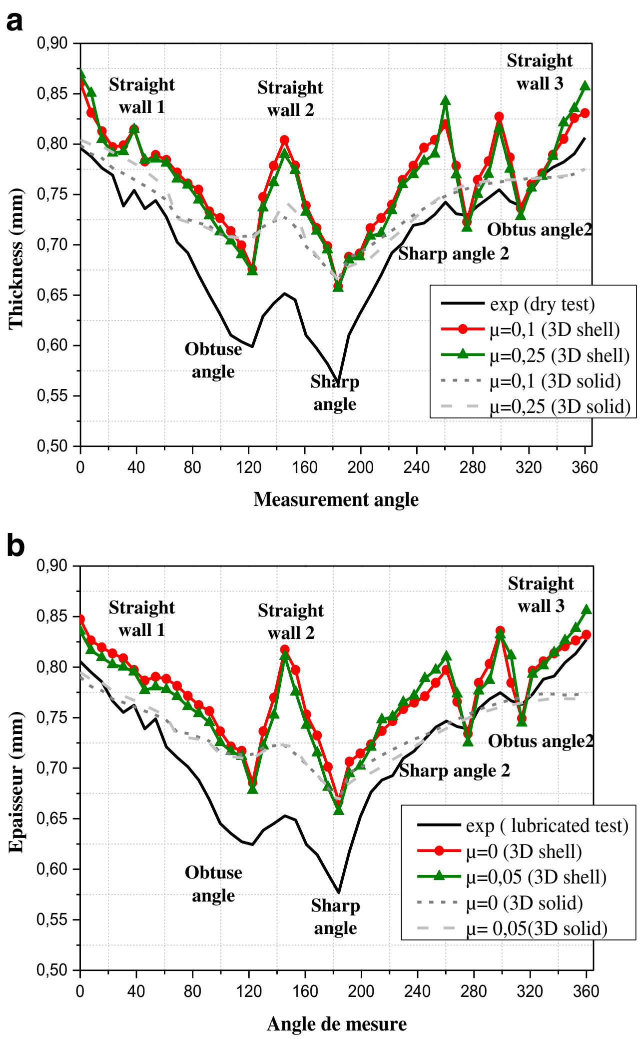

Fig. 10 (a) Thickness distribution against measurement angle using dry test for trapezoidal section die and (b) Thickness distribution against measurement angle using lubricated test for trapezoidal section die

4.2 Rectangular section

The tube expansion test in rectangular section has been simulated using a 3D shell model and 3D solid model, for different contact conditions (with or without lubrication). Only the half of the tube has been considered due to the symmetry conditions; for this reason, the thickness distribution is illustrated for an angular sector ranging from 0° to 180°. Indeed, thickness profiles were obtained quite similar to those obtained from the square section (Fig. 9a, b). If the thinning at the straight wall is in the same order of magnitude, it is more pronounced at the "corner" area in the case of the rectangular section. This is due to the fact that the tube is free to deform in the direction corresponding to the long side of the rectangular section, in the beginning of process; the deformation in the corner is very significant, and it leads to an important thinning.

In general, the thickness distribution of the cross section at the end of the process is very similar to the one acquired experimentally. The critical thinning areas are well predicted. However, the obtained numerical results are relatively away from the experimental measurements; the critical thinning in the transition areas is underestimated. However, the one achieved in corner area is overestimated. For the results obtained with 3D solid model (gray in Fig. 9a, b), they poorly represent the thickness distribution, but ultimately provide a critical thinning value closer to the experimental results.

The friction coefficients for the lubricated test obtained by the pin-on-disk and expansion tests are very close (0 and 0.05, respectively). It is found in Fig. 9 that the LS Dyna software does not allow a clear distinction of the results obtained with either of these coefficients, in particular in the angular positions 0° and 180° (initial contact) where the results obtained with the friction coefficient achieved from expansion test are closer to the experimental measurements.

Figure 9b shows the thickness distribution obtained by FE simulations of expansion test in rectangular section for dry test. Therefore, two friction coefficients acquired from pin-on-disk test (μ = 0.1) and the expansion test (μ = 0.25) were used to carry out FE simulations. The results obtained are compared with experimental measurements. We see once again the difficulty of reproducing faithfully the distribution of thicknesses in the hydroformed part, even if the general profile is found. Strong localization at the transition zones is not reproduced. However, the predicted thickness at the contact areas (marked with the name "right wall" in the figure) is close enough to the measured thicknesses in these areas, and the results are much better in the case of simulations conducted using the friction coefficient resulting from the expansion test.

Nevertheless, the analysis in Table 5 puts into perspective the differences on the curves. In this table, errors in percent were recorded on the thicknesses obtained in the three areas (wall, corner, transition zone) for dry and lubricated tests. It is

Table 6 Comparison between numerical results and experimental measurements (trapezoidal section)

	Error in t_{wall1}	Error in t_{obtus1}	Error in t_{sharp1}	Error in t_{sharp2}	Error in t_{obtus2}
μ = 0.05 (3D shell)	−3.7%	−5.4%	−8.1%	+1.3%	+1.5%
μ = 0.25 (3D shell)	−7.1%	−7.4%	−9.4%	+1.9%	+2.3%

to notice that only the results obtained with the friction coefficients in the expansion test are shown here. The main results are

– Firstly, the errors in thicknesses predicted by numerical simulations are in fact all less than 10% compared with experimental measurements.
– Secondly, errors are more important in the case of dry hydroforming.
– Finally, the lowest thicknesses reproduced by the simulations are those at the transition zone wall corner.

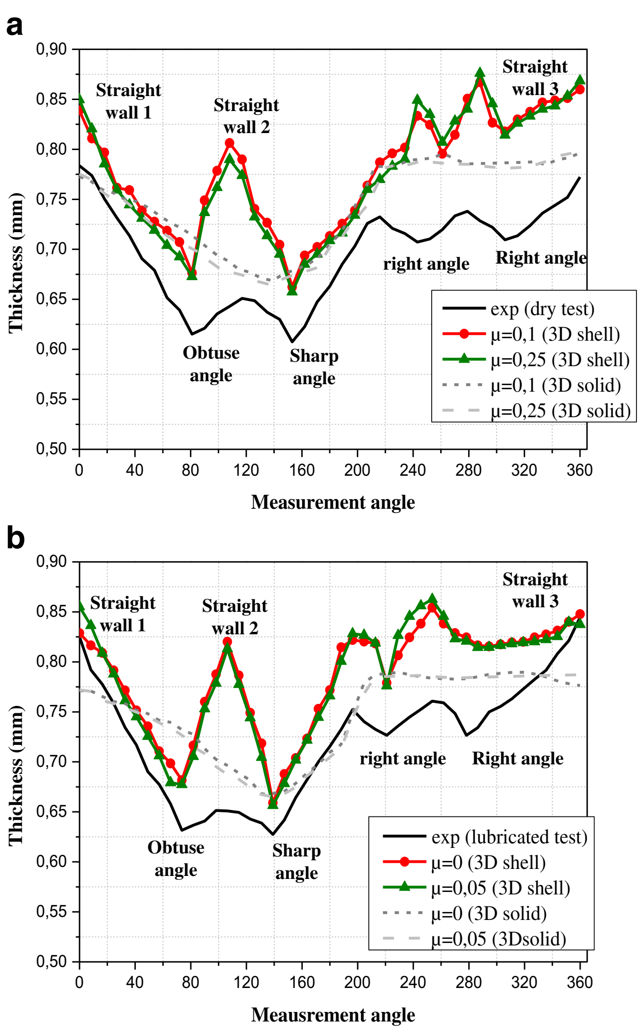

Figure 11 (a) Thickness distribution against measurement angle using dry test for trapezoid-sectional die and (b) Thickness distribution against measurement angle using lubricated test for trapezoid-sectional die

In fact, the little gap among the experimental measurement and FE simulations could be related to the choice of FE parameters such as mesh element, thickness element numbers, number of integration, and mesh geometric order. Indeed, it is not easy to predict the appropriate FE parameters. For this reason, we meet some problems to estimate exactly the experimental thickness distribution and wall thinning.

4.3 Trapezoidal section

Further, the expansion test in trapezoidal section was simulated by FE using a 3D shell model. From the experiments conducted previously [27], both test conditions (dry and lubricated test) have been realized. For FE simulations, the friction values achieved by the pin-on-disk test and by the expansion test were considered.

As indicated in Fig. 10a, b, the thickness distributions acquired numerically have been compared with those measured on the tubes formed. As there is no symmetry, the angular sector concerned varies from 0° to 360° and is shown as grayed results using 3D solid model.

It is shown the difficulty of correctly predicting again the thickness distribution using the 3D shell model. The 3D solid model seems more realistic for the present case. But the thickness levels are generally overestimated. In addition, the 3D shell model does not allow a clear representation of the friction conditions; it is difficult to distinguish the different friction values whatsoever in Fig. 10a, b.

However, in Fig. 10b that represents the thickness distribution obtained in the case of a dry forming, the predicted thickness distribution has a relatively faithful profile with that obtained experimentally, in particular in the left part of the diagram, even if the thickness levels are very different.

A more detailed analysis is provided in Table 6. The conclusions that can be drawn are identical to those set out in the previous section.

4.4 Trapezoid sectional

The same study was conducted for the tube hydroforming in trapezoid-sectional die, and thickness distributions are shown in Fig. 11a, b. Also, the main results are reported in Table 7. Again, we find the same features already mentioned in the previous section, so the same remarks can be made even for the trapezoid-sectional die.

Table 7 Comparison between numerical results and experimental measurements (trapezoid sectional)

	Error in t_{wall}	Error in t_{obtus}	Error in t_{sharp}	Error in t_{right}
μ = 0.05 (3D shell)	−3.7%	−7.2%	−4.6%	−6.8%
μ = 0.25 (3D shell)	−6.5%	−9.3%	−8.2%	−9.5%

5 Conclusion

In the present paper, the tube hydroforming process has been investigated in various shapes: square, rectangular, trapezoidal, and trapezoid-sectional dies. The impact of the friction coefficient and lubrication conditions is considered. The thinning location and the thickness distribution along the cross section were studied. The following conclusions can be drawn:

1. The FE simulations and the experimental tests show a good agreement especially in terms of thinning location.
2. For the different shape section, the friction values obtained with the analytical model show a good accordance with the experimental results than the pin-on-disk test.
3. The raise of friction coefficient reduces the uniformity of the tube wall thickness.
4. The thickness distribution along the cross section is relatively consistent with those measured for the 3D shell model.
5. The 3D solid model does not provide a realistic representation of the thickness distribution in the shaped tube.

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