The Impact of Die Corner Radius and Friction Coefficient on Bulge Forming of T-Shaped Copper Tubes using Finite-Element Method and Experimental Analysis

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Abstract: In this paper, the effects of various parameters on the process of T-shaped copper tube bulge forming have been investigated. This evaluation is based on the properties of the copper tubes, properties of polyurethane rod and practical conditions of a bulge forming process such as the friction coefficient between die and tube, between tube and rod, boundary conditions and their constraints. The effect of each condition on a T-shaped copper tube has been explicitly simulated using the Abaqus software. The experimental results have been validated by conducting a series of experiments. After simulating the process, the effect of other parameters such as die corner radius, friction coefficient, thickness of the tube and counterpoise can be evaluated and used in practical experiments. Then, the simulation results have been compared with the obtained results from the experiments. Once the accuracy of the simulation results has been endorsed, the optimal values of different parameters have been determined using simulations. The optimal values for die corner radius, friction coefficient and counterpoise are 5 mm, 0.05 and 200 N, respectively. The findings shows the positive effect of utilization of optimal value for die corner radius, optimal value for counterpoise and lubricate on optimize forming process properties.

Keywords: Bulge forming, Copper tube, Die corner radius, Friction coefficient, Polyurethane

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1 INTRODUCTION

Bulge forming is a cost-effective method to form ductile metals such as aluminum or brass and lightweight–rigid structured metals. According to the forming conditions for industrial connectors and thin-walled products which are produced from ductile materials, this method is suitable. In recent years, several researches have been performed in this area such as investigating the effect of laser energy on the deformation behavior of materials in bulge forming [1], the simulation of Mg alloy bulge forming [2] and the effect of bulge forming on wrinkle and strength of thin sheets of stainless steel [3].In this method, the forming medium is placed inside the tube. Then, both medium and the subject are put into a die and the die is closed. Afterward, two hydraulic cylinders exert force on both sides of the tube and the medium. By applying the force of cylinders, the medium is then directed to the forming area which results in deformation of the tube. After accomplishing the deformation, cylinders are returned to their initial state and the medium gains its original shape so that it can be easily removed from the deformed tube. It should be noted that the medium need to have a large elasticity property so that it resists against permanent deformation when forces are applied. The compressibility of the medium is also an important parameter. In this regard, the medium should be made of a material which has the lowest compressibility. For this reason, a rod made of polyurethane is used.

Hartl and Dohman mentioned the liquid bulge forming as a flexible production method in their study [4]. They evaluated the mentioned technique in internal forming of metals in high pressure. The results of their study showed the effectiveness of this system. Hashemi and colleagues investigated the effects of different failure criteria on the forming limit curve of aluminum tube during a hydro-forming process [5]. One of the important parameters required for finite element analysis of a hydro-forming process is the mechanical properties of the tube. There is two ways to extract the mechanical properties of the tube, the uniaxial tension test on planar (flat) samples extracted from the tube which the maximum strain before failure is 30% in this test, and hydraulic bulge test in which this value is 70% [6-8]. Researchers have utilized a hybrid method in which they combined analytical and experimental methods to obtain the relationship between effective stress and effective strain in deformed area of the tube. Sokolowski and his colleagues employed a simple hydraulic system along with analytical and finite element methods to obtain the flow stress in the material used in the tube [9-11]. The forming limit curve presents a combination of planar strains which result in creation of a guttural and can be used as a criterion for measuring the ductility of tube before failure and burst. Two common methods used to obtain the forming limit curve assuming homogeneous material structure are Hill’s model and Swift’s model. In various studies, the obtained forming limit curves in a hydro-forming process using Hill’s and Swift’s methods have been compared with those of obtained using the experimental results of bulge forming tests using different load paths [12], [13].

As an alternative way to calculate the forming limit curve which is based on the existence of defects in the structure of the material, is the method of Marciniak–Kuczynski. Hashemi and colleagues employed this model using a numerical Newton-Raphson method to obtain the forming limit curve in a hydro-forming process and finding proper load paths. They examined this model by using a finite element simulation [14], [15]. In a study performed by Gheisari and Javanroodi, the experimental results of forming stainless steel 304 in different pressures using double-bulge hydro-forming have been presented. After measuring the maximum change in height (maximum outer diameter) in the forming curves given by the coordinate measuring machine, thickness profile has been measured using ultrasonic thickness measurements. The results show the direct effect of pressure on the maximum change in height and changes in the thickness. It can also be seen that the changes in thickness using this method is very small compared to those of other methods of forming the same components [16].

In this paper, to evaluate the effect of the die corner radius and the friction coefficient in bulge forming, the experimental results of forming the copper tubes with bulge forming method applying various pressures is presented. The results show the direct effect of the maximum pressure on the height and thickness. It can be seen that the changes in thickness in this method is very low compared to those of other forming methods. In other section, the process of forming has been simulated by Abaqus software and the impact of effective forming parameters has been discussed.

2 METHODOLOGY

2.1. Finite Element Simulation of the Process

Simulation can prevent errors, optimize parameters of a process and enhance tools. Forming is a process in which simulation plays an important role, because during the forming process, several parameters such as geometry, material and the contact conditions of the subject with different surfaces are continuously changing. Finite element simulation is a common method to predict the geometry and dimension of the parts and can prevent the potential errors. To perform a finite element simulation, the exact mechanical properties of the tubes are required [10].

2.1.1. Modeling

In Figure 1, a series of assembled model which employed three-dimensional shell model in Abaqus software is shown. Die, punches and rods are modeled as a discrete rigid model since they are not subject of any analysis.

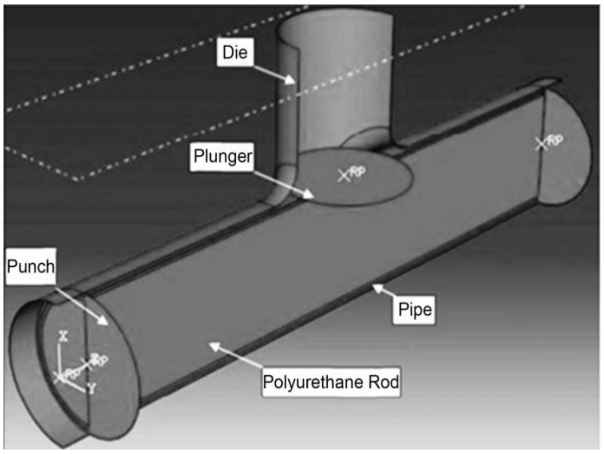

Fig. 1 Assembling software components modeled in Abaqus

2.1.2. Assumptions and Properties of Materials

Annealed C12200 copper tube with ASTM standard which is usually used in air conditioners and refrigerators (Standard Specification for Seamless Copper Tube for Air Conditioning and Refrigeration Field Service) with the nominal size of 7/8 in is employed. It is assumed that displacement of the punches is 16 mm in the simulation.

The surrender strength and the tensile strength of tube are assumed to be 62 MPa and 272 MPa, respectively. The friction coefficient between the die and the tube and between the tube and rods are assumed to be 0.1 and 0.3 respectively. In the simulations, the polyurethane is considered as a forming medium. The property of the polyurethane is that it persists against permanent deformation when it is subject to forming forces. In addition, it keeps its elasticity when it is subjected to a very high strain [17].

Such behavior is called hyper-elastic in software. The plot of vertical stress-strain of such hyper-elastic materials is according to Figure 2.

As it can be seen from the Figure 2, they exhibit a completely non-linear behavior. In the case of the polyurethane, strain potential energy model of Mooney-Rivlin is selected.

One of the most important issues in simulation of a bulge forming process is to determine the incompressibility of the polyurethane. The incompressibility has a direct relation with the ratio of the initial bulk modulus and the initial shear modulus (K_0/μ_0).

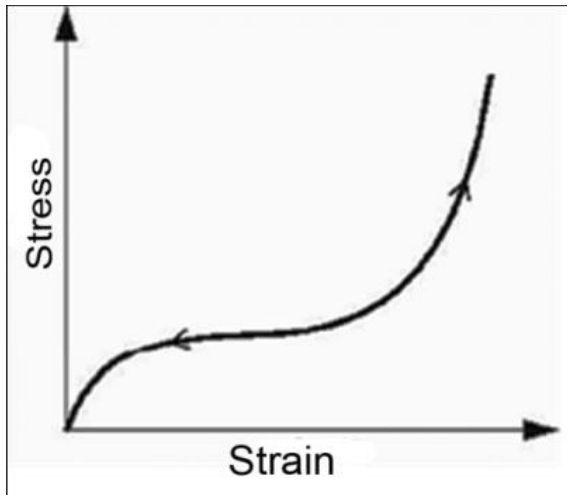

Fig. 2 Diagram of vertical stress - strain of hyper elastic material [18]

From Eq. (1) it can be concluded that whatever Poisson's ratio is closer to 0.5, the material is more incompressible.

$$\nu = \frac{3K_0/-2}{6K_0/\mu_0+2} \quad (1)$$

In the selected model for strain potential energy, there are three factors $C_{10}D_1, C_{01}$ which their relations with μ_0 and K_0 are given in Eq. (2) and (3).

$$\mu_0 = 2(C_{10} + C_{01}) \quad (2)$$

$$K_0 = \frac{2}{D_1} \quad (3)$$

By combining Eqs. (1), (2), (3), then (4) is obtained which indicates that the Poisson's ratio reaches to 0.5 when D_1 decreases, and thus the material become more incompressible [19].

$$\nu = \frac{3-2(C_{10}+C_{01})}{6+2(C_{10}+C_{01})} \quad (4)$$

The default value of ν in software is 0.475 which corresponds to K_0/μ_0=20. Selecting values larger than 0.495 as Poisson's ratio is not recommended since it results in degradation in accuracy of the obtained results. That's why D_1 can not be selected too small.

Thus, for D_1, a variety of values were tested. Hence, D_1= 5e-8 was chosen as the smallest amount which yielded the best results. To perform a forming process, both sides of the tube and the rod were displaced such that the same boundary conditions of displacement were applied on the nodes of both sides of the tube and the rod. This displacement was slowly changed over the time. Tube and rod were symmetrically bounded and all degrees of freedom of the frame were controlled. No boundary condition for the plunger was considered, except for evaluation of the effect of counterpoise on which there is a concentrated force. A linear brick element with 8 nodes (C3D8R) was utilized for polyurethane rod, an S4R was selected for tube and an R3D4 was employed for rigid components. Due to large produced strains and large deformations, ALE technique was used for polyurethane.

2.2. Experimental Evaluation

After designing the mold, it was built and the required materials were provided. Figure 3 shows the mold and die sets along with punches, tube and rod prior to forming process. Die with 5mm corner radius and hydraulic punch for supplying power to shape were prepared and set using information obtained from the simulation process, with measuring instruments for force, displacement and branch height (Figure 3). Then the effects of changing discussed parameters were studied by repeating the test and the obtained products were investigated.

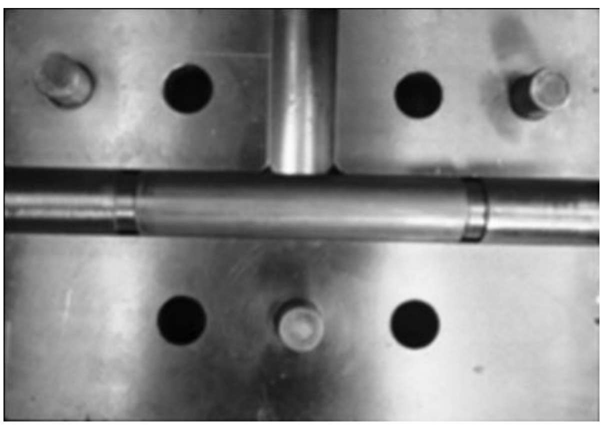

Fig. 3 Mold and die sets, punches, tube and rod, prior to forming process

3 RESULTS AND DISCUSSION

When the simulation and experimental evaluations of the process were accomplished, the impact of various parameters can be expressed as follows.

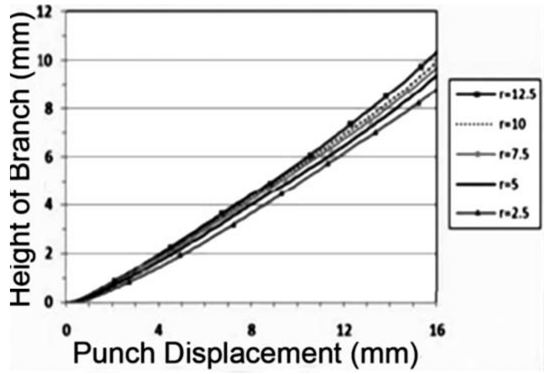

Fig. 4 The changes in the height of produced branch in terms of punch displacement in various die corner radius

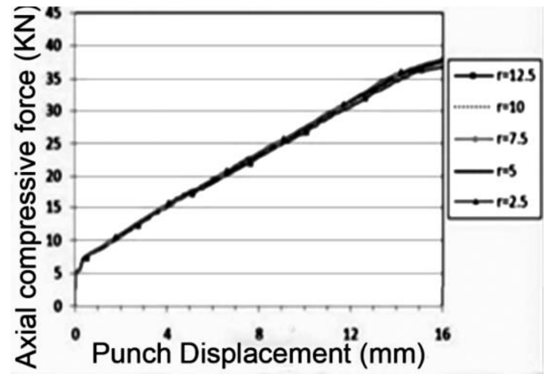

Fig. 5 The axial compressive reaction force based on the displacement of the punch for various die corner radius

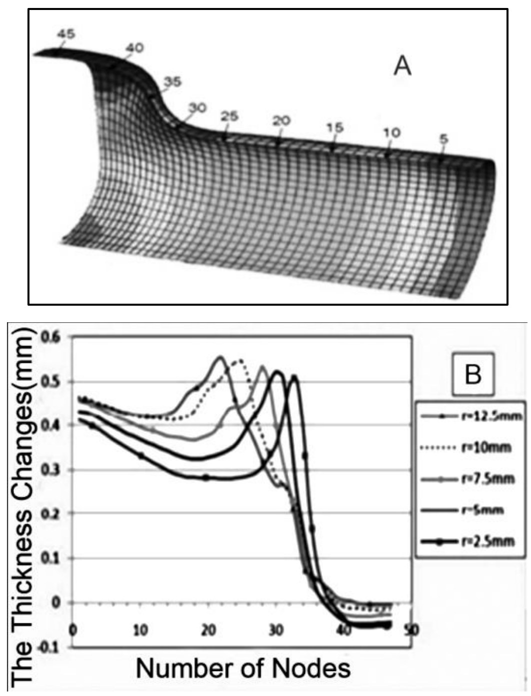

Fig. 6 The changes in the thickness of the tube for different die corner radius

3.1. The Impact of the Die Corner Radius

During the simulation, the die of different corner radius (2.5 mm, 5 mm, 7.5 mm, 10 mm and 12.5 mm) have been chosen. Figures 4, 5 and 6 show the effect of choosing different die corner radius on the height of the produced branch, the reaction pressure and the changes in thickness of the tube, respectively.

The results of mentioned diagrams show that the greatest impact of die corner radius is on the height of the branch. Due to the fact that if the corner radius is too large, machining capability is reduced after forming, so the preferred value of this parameter was 5 mm.

3.2. The Effects of Friction Coefficient

In the following diagrams, the effect of the friction coefficient between dies and mold on the height of the produced branch, the reaction pressure and the changes in thickness of the tube are illustrated.

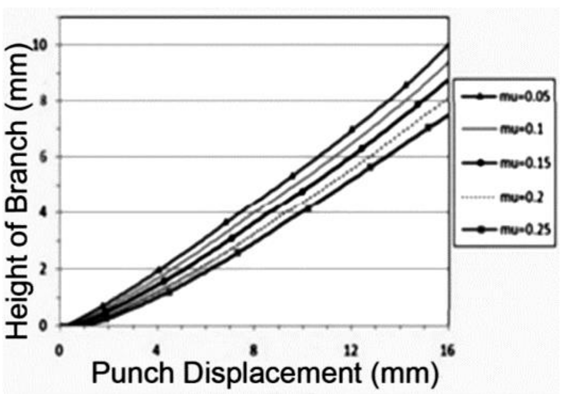

Fig. 7 The changes in the height of the produced branch based on the displacement of the punch for various friction coefficients between mold and tube

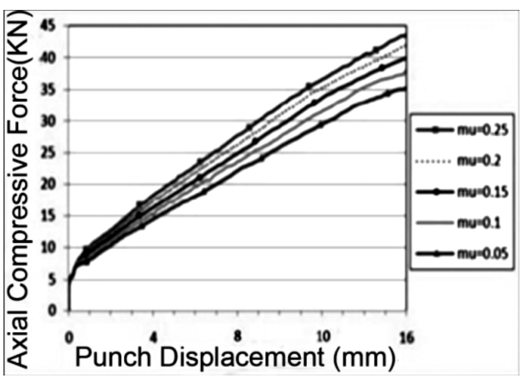

Fig. 8 The axial compressive reaction force based on the displacement of the punch for various friction coefficients between mold and tube

As maintaining a constant friction coefficient is difficult, a lubricant was applied to minimize the amount of friction coefficient. By comparing the obtained results with simulation results, the preferred friction coefficient was obtained as 0.05.

The change in friction coefficient between the polyurethane rod and inside of the tube does not have a significant effect on the height of the produced branch, the axial reaction force and the wall thickness distribution of the tube. Since when the force of the punch is applied, the polyurethane rod and the tube move together and the effect of friction between them will be insignificant.

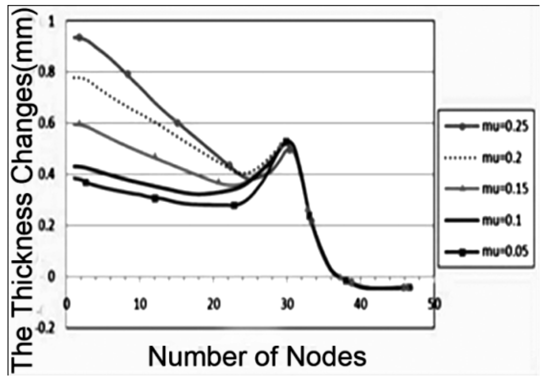

Fig. 9 The rate of change in the thickness of the tube in terms of the number of nodes in different friction coefficients between mold and tube

3.3. Effect of Applying a Counterpoise against the Formation of a Branch

The purpose of determining a proper counterpoise is to produce a minimum change in thickness of the tube after the forming process. To evaluate the effect of counterpoise against the formation of a branch, the plunger which is located on the top of branch is subjected to applying forces of 100 N, 300N and 500 N. The obtained results are shown in Figures 10 and 11. As a result, to minimize the negative effects of the parameter, the average force value of 200 N for this method is given optimal.

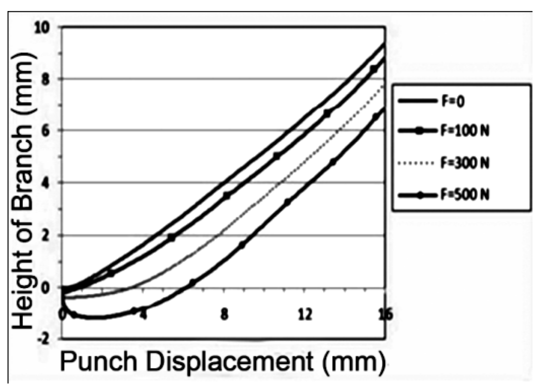

Fig. 10 The change in the height of the produced branch based on punch displacement in different counterpoises

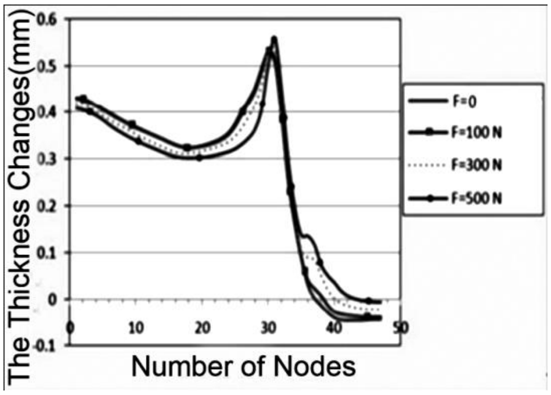

Fig. 11 The rate of change in the thickness of the tube in terms of the number of nodes in the various resistance forces

3.4. The Results of Experimental Study

At first, in order to perform the initial tests, the HD tubes (hard) were used. The maximum height of the produced branch was 3.2 mm. This amount is not enough to be able to cut the head of branch. For this reason, by applying some modifications, the maximum attainable height of branch was increased.

With the same objective, the tube was annealed so that the height of the branch reached 10.6 mm. Then, the OL tube along with a lubricant was examined. To this aim, grease was applied between the mold and tube. Consequently, a maximum height of the produced branch for the above mentioned tube, reached 11 mm, which is shown in Figure 12.

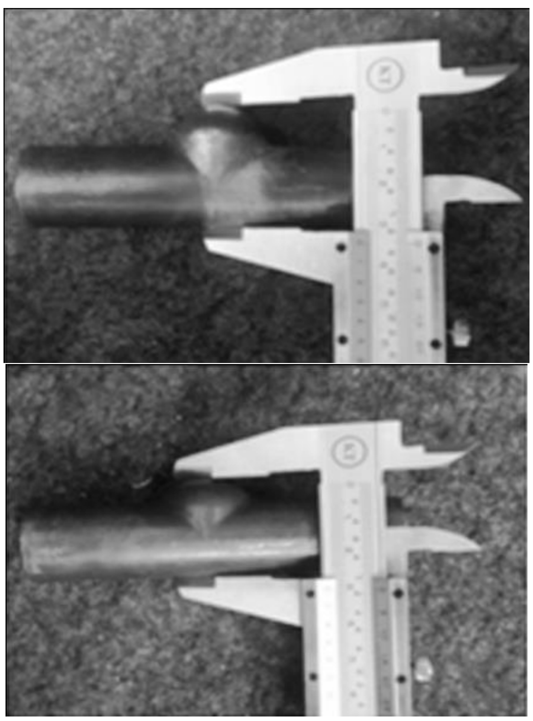

Fig. 12 Forming an annealed tube before and after using lubricant

In order to overcome the produced dent under the branch and to prevent rupture at the top of the produced branch, it is suggested to perform this process in several steps and with detention of the tube if one needs to increase the height of branch. The samples produced by this method are shown in Figure 13.

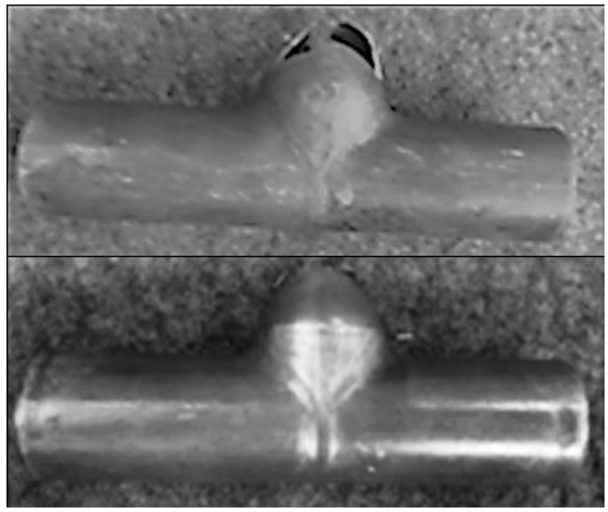

Fig. 13 Increasing the height of the produced branch using a multistage detention process and preventing rupture at the top of the branch and wrinkles in the root of branch

3.5. Validation of Simulation Results

The results show that the hydro-formed part simulated in software is consistent (with acceptable precision) with the hydro-formed part using actual bulge forming process.

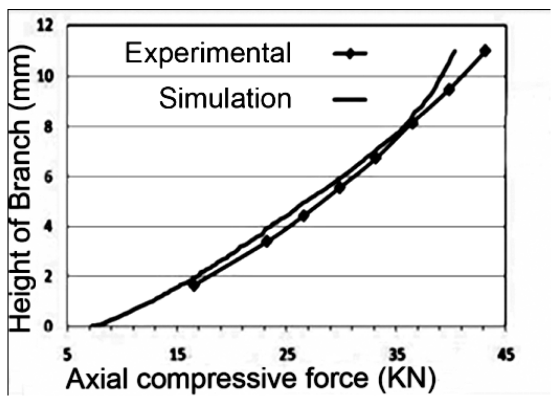

Fig. 14 Comparison of the simulation and experimental results of changes in the height of the produced branch in terms of the axial compressive force

For axial forces less than 38 KN, the accuracy of simulation results are very good. For larger forces, the error rate of 6.5% was experienced. This value of error is acceptable for the behavior analysis of a material such as polyurethane, since in researches, the behavior analysis of the polyurethane is considered as a hard analysis. Simulation of a hyper-elastic material behavior cannot be completely accurate and is difficult to achieve and maintain a constant friction coefficient during the shaping process [20].

4 CONCLUSION

Regarding the die corner radius, as it increases, the longer branch could be formed. This is due to easier flow of the material in the deformation area. The amount of increase in thickness at both sides of the tube and at the die corner has a direct relation with the radius of the mold. In addition, the amount of decrease in thickness of the top of branch as well as the reduction in the length of the tube is inversely related to the radius. The axial force has an insignificant relation with the die corner radius. By increasing the die corner radius, the maximum required axial force is reduced to a very small value.

Regarding the impact of the friction coefficient, it can be stated that when the friction coefficient between the die and the tube decreases by utilizing a proper lubricant, meanwhile the maximum attainable height of branch increases, the axial reaction force decreases. By reducing the friction coefficient between the die and the tube, the thickness of end of the tube is reduced. The medium in the tube can be more easily directed to the formation area in a less friction condition which results in reduction in reposition of the medium at the end of the tube. The change in friction coefficient between the polyurethane rod and the tube has little impact on the attainable height of the branch, axial reaction force and the thickness distribution of the wall of the tube.

The presence of the counterpoise results in reduction in height of the branch so that the greater the force is applied, the more the height of the branch decreases. The counterpoise against the branch has no impact on the reaction forces exerted on the punch, because the counterpoise is negligible with respect to the axial reaction forces. Increasing in the counterpoise results in creating a more uniform thickness distributed throughout the length of the tube, so that by increasing the counterpoise, the thickening at the end of the tube as well as the thinning at the top of branch are declined.

Utilization of the heat treatment in this study indicated that employing an annealed tube results in increasing the height of the branch. In addition, performing a multistage detention process resulted in further increase in the height of the branch.

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