IJE TRANSACTIONS A: Basics Vol. 32, No. 4, (April 2019) 587-595

International Journal of Engineering

Journal Homepage: www.ije.ir

Improvement of Die Corner Filling of Stepped Tubes Using Warm Hybrid Forming

A. Taheri Ahangar, M. Bakhshi-Jooybari*, S. J. Hosseinipour, H. Gorji

Advanced Material Forming Research Center, Faculty of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran

P A P E R I N F O

Paper history:
Received 31 December 2018
Received in revised form 02 March 2019
Accepted 07 March2019

Keywords:
Aluminum Alloy
Corner Filling
Stepped Tube
Tube Hydroforming
Warm Hydroforming

A B S T R A C T

Aluminum and magnesium alloys are of materials for decreasing vehicle weight and consequently reducing fuel consumption. However, forming limitations regarding their low formability at room temperature are found when being manufactured by conventional forming processes. For this reason, development of new forming techniques, such as warm tube hydroforming, is needed to overcome such limitations. In addition, production of parts with sharp corners is nearly impossible using conventional forming processes. This paper investigates the possibility of forming stepped tubes with high expansion ratio, sharp corner radii and precise geometric shape using a developed hybrid hydroforming and bending method. To assess tube formability, the bulge test was adopted with different forming temperatures and axial feeds. It is shown that using the feed of 35 mm and feed rate of 15 mm/min, a stepped tube with 47.6 % expansion ratio and corner filling ratio of about 100 % (part with sharp corners) could be achieved when adopting the developed hybrid hydroforming and bending method at 150 °C.

doi*: 10.5829/ije.2019.32.04a.17*

NOMENCLATURE

THF	Tube hydroforming	$\bar{\varepsilon}_0^{pl}$	Initial equivalent plastic strain
CFR	Cavity filling ratio	$\dot{\varepsilon}^{pl}$	Denotes the rate of plastic flow
HHB	hybrid hydroforming and bending	ε	Strain
FE	Finite element	$\dot{\varepsilon}$	Strain rate
Greek Symbols		**Latin Symbols**	
$\lambda = 100 \times (D_{die}/D_{tube} - 1)$	Expansion ratio	K	Strength coefficient (MPa)
$\sigma = K\varepsilon^n\dot{\varepsilon}^m$	Flow stress (MPa)	n	Strain hardening coefficient
$\bar{\varepsilon}^{pl} = \bar{\varepsilon}_0^{pl} + \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl}:\dot{\varepsilon}^{pl}}$	Equivalent plastic strain	m	Strain rate

1. INTRODUCTION

Tube hydroforming (THF) is one of the metal forming processes that is used to form tubular components. In this process, the tube in the die is formed into different shapes by simultaneous applying the internal pressure of a fluid and axial force [1]. Compared with conventional manufacturing processes, THF offers several advantages, such as weight reduction, lower manufacturing and tooling costs, fewer secondary operations, and improved structural strength and geometry accuracy of the products [2]. This process depends mainly on the process parameters like internal pressure, axial feeds, material properties, and other processing conditions [3]. The use of aluminum and magnesium alloys is an alternative for carbon steels in the automotive and aerospace industries to reduce the weight and fuel consumption [4]. Today, these alloys are of particular interest to researchers and industrialists due to their higher strength to weight ratio than steels [5]. However, the main problem of these alloys is low formability at room temperature. To overcome this limitation, researchers have suggested forming at higher temperatures. Super-plastic processes that are carried out at temperatures higher than the recrystallization temperature, suffer from problems such as low forming rates (strain rates in the range of 10^{-4} to

---

*Corresponding Author Email: *bakhshi@nit.ac.ir* (M. Bakhshi-Jooybari)

Please cite this article as: A. Taheri Ahangar, M. Bakhshi-Jooybari, S. J. Hosseinipour, H. Gorji, Improvement of Die Corner Filling of Stepped Tubes Using Warm Hybrid Forming, International Journal of Engineering (IJE), IJE TRANSACTIONS A: Basics Vol. 32, No. 4, (April 2019) 587-595

10^{-2}), low workpiece strength, high process time and energy consumption [6]. Additionally, it has been shown that cavitation that proceeds by nucleation, growth, and coalescence of voids is the main drawback of this method [7]. In order to overcome these drawbacks, forming at temperatures ranged from 0.2^*T_m to 0.5^*T_m (T_m is melting temperature in Kelvin), which is called warm forming, is suggested [8]. In the last decade, the warm THF process has attracted more attention because of widely known advantages such as possibility of producing complex components in one step, energy and cost reduction, smaller and less expensive forming equipment, and increasing the rigidity of products due to the removal of joints. Seamless tubular components, such as stepped tubes, conical tubes and box shaped tubes which are difficult to form and require elaborate consideration, are mainly produced by using this process. Hence, in recent years, extensive research has been carried out on the tube hydroforming process at elevated temperatures.

Lee et al. [5] investigated the effect of forming temperature (between room temperature and 300 °C) on hydroformability of 7075 aluminum tubes. They showed that with respect to room temperature, the formability increases at elevated temperatures. The same result was obtained by Yuan et al. [9] in uniaxial tension and hydrobulge tests for 5A02 aluminum tubes. Kim et al. [10] investigated the free bulge test of AA6061 alloy tube using experiment and finite element simulation by DEFORM-2D software. They showed that by increasing the axial feed at 320 °C, the bulge height increases. They also studied the effect of temperature (room temperature up to 300 °C) on friction condition of aluminum alloy using the pin on disk test and showed that the friction coefficient increases with elevating the temperature. Yi et al. [11] used a combined heating system to warm the tube uniformly. The system they developed increased the part formability, and thus, uniformity of bulging. In addition, they successfully optimized the process parameters including internal pressure, axial feed and thermal conditions. To create uniform thickness distribution of the tube, Liu et al. [12] used a non-equal die temperature to reduce friction coefficient at the feeding area. They also executed a combined thermomechanical simulation to investigate the effect of axial feed on thickness distribution. Seyedkashi et al. [13], optimized warm THF process and obtained an optimal pressure path for 6061 aluminum alloy tube with different thicknesses and die corner radii using simulated annealing (SA) algorithm. Hashemi et al. [14] showed that the thickness distribution of 1050 aluminum tubes could be improved with increasing temperature in free bulge test, compared with constrained bulging. They also studied the effect of temperature on forming of 6063 aluminum alloy tubes. To predict tube bursting and resultant height in the warm hydroforming process, they successfully used the modified ductile fracture criterion along with the Zener-Hollomon parameter in the process simulation. Mitsui et al. [15] studied the formability of small diameter A1100 aluminium tube in warm bulge forming. The effects of different temperatures and internal pressures on the tube bulge forming was investigated. It was concluded that internal pressure loading rate affected the deformation characteristics of the tubes.

Producing tubular components with sharp corner radii by hydroforming is a very difficult or even impossible task. A new hybrid hydroforming and bending (HHB) method was recently proposed by Elyasi et al. [16] at Advanced Material Forming Research Center of Babol Nooshirvani University of Technology in order to improve the cavity filling ratio (CFR) of SS316L tubular parts. They proved that by using this method, in comparison with conventional hydroforming, the thickness distribution and CFR of stepped tubes can be improved. The main problem of this method is that forming the low formable aluminum alloy stepped tubes with high expansion ratios is not accessible. In preliminary experiments in this research, it was concluded that the cold HHB is not able to completely form the low formable AA6063-O stepped tubes with expansion ratios higher than 27%. Thus, the HHB die set-up has been further developed to investigate hydroforming of the aluminum alloy tubes at warm condition. To this aim, empirical tests and finite element simulation of warm tube bulging were performed at first to assess the bi-axial tube formability. Then, to improve the CFR of stepped tubes, warm HHB die set-up was designed and constructed. The developed set-up was successfully used to form a stepped tube with high expansion ratio and almost complete cavity filling (or sharp corner radii).

2. EXPERIMENTAL PROCEDURE

2. 1. Tube Material In this study, 6063 annealed aluminum alloy tubes with an outer diameter of 25.4 mm and thickness of 1.1 mm were used. Table 1 illustrates the chemical composition of the tube material acquired by the quantometry test. In order to determine the stress-strain data of the tube, the uniaxial tensile test was adopted according to ASTM-E8. The tests were conducted at temperatures of 25, 150, 200 and 250 °C and the strain rates of 0.001 and 0.01 s^{-1}. The obtained true stress-true strain curves are shown in Figure 1.

2. 2. Hybrid Hydroforming and Bending (HHB) Method Figure 2 depicts the schematic of the die set and forming stages in the HHB method. Compared with the conventional tube hydroforming, there exist

TABLE 1. The chemical composition of AA6063 tube

Element	Al	Mg	Cr	Si	Mn	V	Cu	Zn	Fe
W %	Base	0.479	0.001	0.335	0.002	0.006	0.026	0.012	0. 228

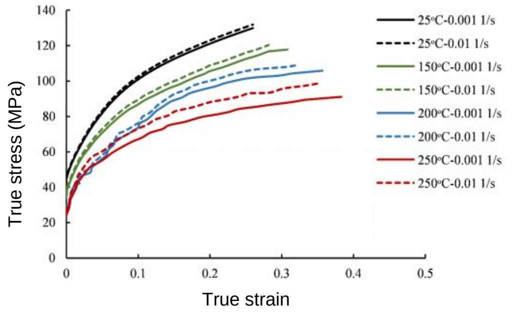


Figure 1. True stress-strain curves of AA6063-O at different temperatures and strain rates

two extra forming elements, namely upper and lower bushes which could axially move inside the fixed die. Figure 2a denotes the positioning of the tube between dies, bushes, and punches. After positioning, the oil is transferred into the tube through a channel located in the upper punch and causes the tube to be somewhat bulged. At the same time, the punches along with the tube ends move axially (Figure 2b) (the die is somehow is maintained fixed). The resultant axial feeding together with the internal pressure are applied continuously throughout the process. Once the tube touches the die wall, the internal pressure increases to help in final bending operation in which the whole die comes in contact with the tube wall and a stepped tube with sharp corner is produced (Figure 2c).

2. 3. Forming Procedure and Apparatus There are two types of experiments. At first experiments, the tubes are hydroformed in a bulge die with different forming temperatures in order to determine the formability of tubes by measuring the bulge height at the bursting point. In the second type, the warm HHB method is adopted to make initial tubes into stepped tubes with high expansion ratios by using appropriate feeding and pressure regime. Figure 3 depicts the schematic, the dimensions and the actual die set-up for the HHB experiment mounted on the test machine. The bulge test has the same die set configuration except that the die is not used. In the HHB, the die is machined so that its inner diameter (D_{die}) matches the expected expansion ratio at the specified temperature. For instance, at the temperature of 150 °C, the diameter of the die is 37.5 mm. The tube formability could be defined in the form of expansion ratio (λ) as follows:

$$\lambda=100\times(D_{die}/D_{tube}-1) \tag{1}$$

in which D_{tube} is the external diameter of the tube. Therefore, if possible, a tubular part with expansion ratio of 47.6 % could be achieved at 150 °C. A 560 W cartridge heater inside a copper casing has been placed in the lower punch to warm the oil to a specific temperature. There is a digital thermocouple used for measuring the forming temperature. As soon as the probe of the thermocouple over the tube center reaches the target temperature, the heater is unplugged and the forming process begins. Due to the high heat transfer coefficient and low thickness of aluminum tube, the heated oil could warm the tube uniformly. All the experiments were conducted using a DMG hydraulic universal testing machine with 600 kN capacity. This machine is connected to a computer unit which controls ram speed, up to 200 mm/min, and measures reaction force by using a load cell. The machine, holds the die set-up, provides sealing force and in the case of HHB, it also applies axial feeding.

A hydraulic pump with a maximum pressure of 120 MPa, a one-way valve, and a relief valve were used to apply fluid pressure inside the tube. The relief valve prevents further pressure increase within the tube by evacuating excess oil. A digital manometer connected to the computer unit was used in order to capture pressure data. The fluid used is SF 350 silicon based oil which is able to withstand temperatures of up to 320 °C. The pressure and axial feed paths are illustrated in Figure 4. Except for the first 10 seconds of the process, the axial feed on both the bush and the tube is applied continuously with a constant speed of 15 mm/min. In the primitive bulging step, the fluid pressure increases to a specified level in which the tube could be bulged monotonically at

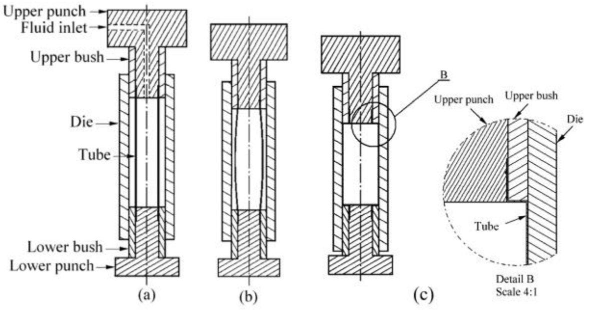


Figure 2. Schematic illustration of stepped tube forming using HHB method: (a) positioning the tube, (b) bulging with axial feeding, and (c) final forming [16]

that pressure level. Amongst the process, a large wrinkle is formed in the tube due to the feeding which disappears when the calibration step applied. At this step, the fluid pressure increases along with the feeding that pushes the tube against the die wall and fills the die corners completely. After the tests, the parts were cut by the wire cut machine and the height of the bulge and the thickness values were measured using a digital caliper vernier and a thickness gauge.

To understand better the HHB process, the formability and forming characteristics of the final part were also assessed with conventional tube hydroforming in which the bushes are fixed and feeding are just applied on the tube ends. The final distance between the bushes determines the bulge length of the stepped tube. Therefore, the initial bulge length (W), as shown in Figure 3, should be adjusted so that the final bulge length reaches the desired value. As an example, for the final bulge length of 65 mm, W should be adjusted to 100 mm if 35 mm feeding is to be applied. Also, for the conventional forming where the bushes are fixed, W is 65 mm. The remaining die set dimensions are the same as the HHB.

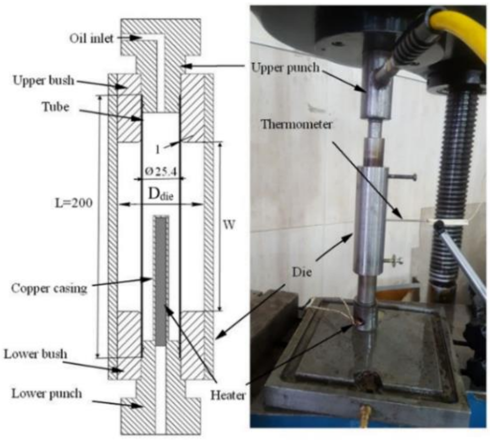


Figure 3. Schematic and actual experimental set up of the HHB test, dimensions in mm

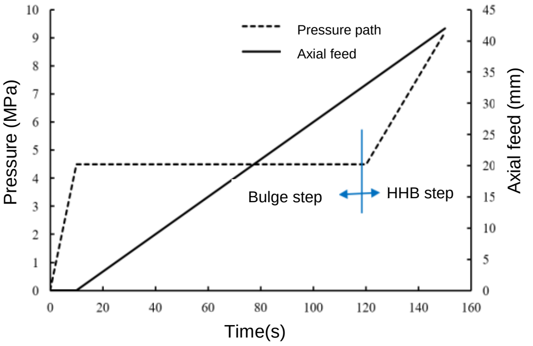


Figure 4. The pressure and axial feed paths versus time

3. FINITE ELEMENT SIMULATION

The hydrobulge, conventional stepped tube hydroforming, and HHB experiments were simulated using Abaqus 6.14 commercial FE package. Due to the axial symmetry of the die set-up geometry, loadings, boundary conditions and material (isotropic assumption due to the tube material annealing), an axisymmetric simulation was built. Additionally, because of the symmetry, only a half of the die set-up cross-section was modelled. All the parts were discretized by deformable CAX4RT elements which have both displacement and temperature degrees of freedom. To restrain the die and bush elements from being deformed, rigid body constraint was assigned to them. The tube was meshed with 4 elements along the thickness and 100 elements in the longitudinal direction (505 nodes) (Figure 5). Unlike the HHB process, the die is not part of the simulation in the hydrobulging FE model. Defining the mechanical behavior of the material, especially in the plastic region, is the main part of the simulation. The Ramberg–Osgood equation [17] was adopted to fit the stress-strain data in the plastic region according to Equation (2):

$$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m} \tag{2}$$

in which σ, ε, and $\dot{\varepsilon}$ are stress, strain and strain rate, respectively, and K, n and m are constant coefficients, derived from the regression fit which are shown in Table 2. The remaining simulation conditions are listed in Table 3.

TABLE 2. Work hardening model coefficient at different temperatures

Temp °C	K (MPa)	n	m
25	190	0.28	0
150	176.1	0.276	0.01
200	170.2	0.25	0.016
250	165	0.2	0.03

TABLE 3. FE simulation conditions [14]

Al 6063-O tube properties (mechanical and thermal)	
Density	2700 kg/m^3
Young's modulus	70 GPa
Poisson ratio	0.33
Conductivity	220 W/mK
Heat capacity	904 J/kgK
Interfacial conditions	
Die-tube friction coefficient	0.06 (25 °C), 0.1 (250 °C)
Contact heat transfer coefficient	1400 W/m^{2}K
Oil convection	30 W/m^{2}K

For numerical prediction of the failure, the second derivative of equivalent plastic strain criterion was employed, as Afshar et al. [18] successfully used to predict the failure onset of the 7020-T6 aluminum tube in hydroforming process. In this method, it is assumed that failure occurs when the second derivative of the plastic strain reaches its maximum value. The equivalent plastic strain ($\bar{\varepsilon}^{pl}$) can be defined as follows:

$$\bar{\varepsilon}^{pl} = \bar{\varepsilon}_0^{pl} + \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl}:\dot{\varepsilon}^{pl}} \tag{3}$$

where $\bar{\varepsilon}_0^{pl}$ is the initial equivalent plastic strain and $\dot{\varepsilon}^{pl}$ denotes the rate of plastic flow. A sample history diagram of equivalent plastic strain and its second derivative is illustrated in Figure 6.

4. RESULTS AND DISCUSSION

4. 1. Hydrobulge Experiments Based upon the forming temperature which affects the bulge diameter, different shape geometries for the final tubular part could be considered. Figure 7a presents the effect of forming temperature on the maximum height of the bulged tubes together with the required pressure in the free bulge experiments.

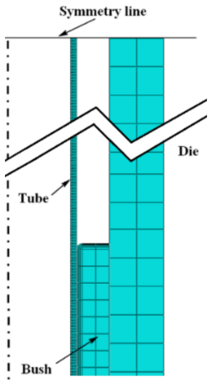


Figure 5. Meshed parts for the axisymmetric FE simulation of HHB process

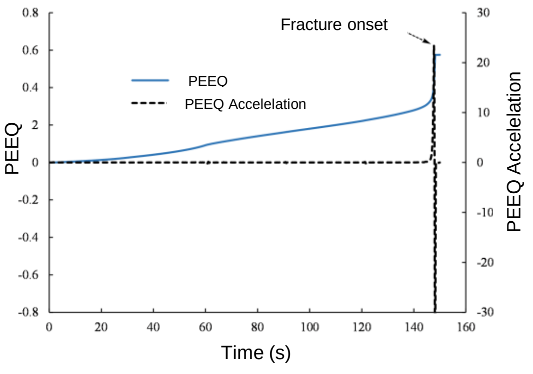


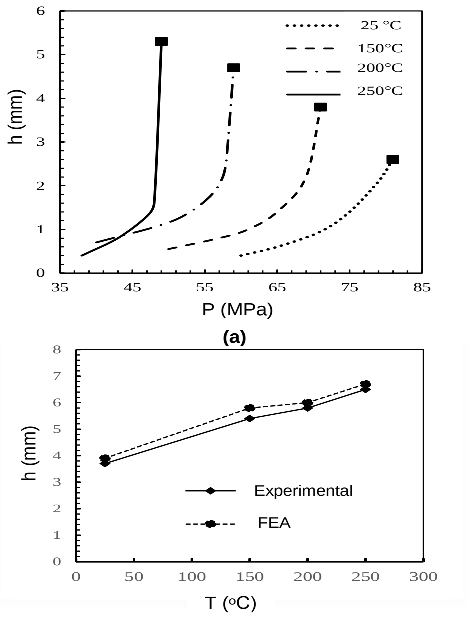
Figure 6. Equivalent plastic strain and its second derivative versus time

Increasing forming temperature obviously improves the bulge height before the occurrence of fracture. This is because of material softening at elevated temperatures (Figure 1) which enables the tube material to carry higher strains compared with cold hydroforming. It implies that a part with high expansion ratio is the consequence of using elevated temperatures. In addition, lower pressure value is required before the tube bursts. In other words, compared with room temperature, higher bulge height is obtained with lower pressure level at warm tube forming process.

Applying axial feeding from the two ends of the tube is another way to improve the bulge height even more (Figure 7b). Also, using a high amount of axial feed leads to wrinkling [19], buckling and/or folding back in the tube, as Yuan et al. [20] showed for the conventional hydroforming of aluminum alloy tubes.

4. 2. FE model Verification To validate the FE simulation, thickness distribution from the center to the outer region of the bulged tube, the resultant bulging height and the pressure level at the bursting moment correspond to the temperature of 150 °C obtained from the simulation were compared with the experimental results. The bulge height (h) is calculated from Equation (4), in which D_0 and D are the diameters of initial tube and the deformed tube at the bulging zone, respectively.

$$h = \frac{D-D_0}{2} \tag{4}$$



(a)

(b)

Figure 7. Effect of forming pressure, process temperature and axial feed on the obtained bulge height from the simulation: (a) free bulge process and (b) bulge process with axial feed=10 mm

According to Figure 8, an acceptable agreement with less than 3 % maximum deviation exists between the thickness data of the FE model and that of the experiment. Additionally, as Table 4 shows, the differences between the experimental and numerical bulge height and bursting pressure results are less than 5.2 %.

4. 3. Warm Hybrid Hydroforming and Bending (HHB) Experiments

4. 3. 1. Feasibility of the Warm HHB Process The stepped tube in the present work has a maximum diameter of 37.5 mm. By looking at the material property at different temperatures and performing some preliminary experiments, it was concluded that the temperature of 150 °C is a suitable temperature. At this temperature, the formability of the tube is increased significantly, while the required temperature for working oil is not high. It is notable that below 150 °C, the tube bursts under the internal pressure before the bulge diameter reaches 37.5 mm. For instance, the HHB process fails in forming a complete stepped tube with λ=47.6 % at room temperature as Figure 9 depicts. Due to poor formability at room temperature, the tube bursts far below this expansion value (λ=26 %). In order to guarantee the perfect formation of a stepped tube, selection of appropriate axial feed is a critical issue. The part formed using low feeding has unfilled corners as shown in Figure 10a. High feeding, on the other hand, leads to wrinkling (Figure 10b). The successfully formed tube at 150 °C is shown in Figure 11 in which the axial feed and axial feed rate were set as 35 mm and 15 mm/min, respectively. It can be seen that using the warm HHB method, a stepped tube with high expansion ratio (λ=47.6 %) and almost full cavity filling (or sharp corner) could be produced. Figure 12 has compared the final part in both experimental and numerical methods and shows how equivalent plastic strain is distributed in the part. In order to capture the tube shape during the process in detail, it is beneficial to make use of FE simulation. According to Figure 13b, due to axial feeding, a useful wrinkle is formed in the proximity of the die-bush corner in the 120th second. As the axial feeding proceeds, a double-dome shape emerges in the tube, which signifies the axial pressure state in this region (Figure 13c). In the latter forming step shown in Figure 13d in which the wrinkles disappear, all the tube walls, except the corner area, come in contact with the die wall. The negative axial strains and the feeding help the corner area of the tube to withstand thinning when pressure increases sharply in the last seconds. Forming continues up to the point where the tube wall almost fills the die-bush corner (Figure 13d).

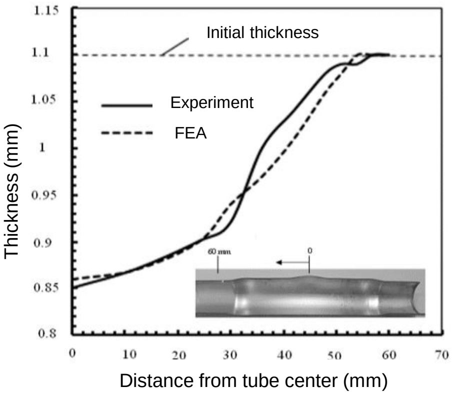


Figure 8. Experimental and FE results of the thickness distribution of the bulged tube at 150 °C

TABLE 4. Comparison of experimental and simulation bursting pressure and bulge height at 150°C

	Bursting pressure (MPa)	Bulge height (mm)
Exp.	6.94	3.7
FEA	7.2	3.9
Error (%)	3.6	5.1

4. 3. 2. Cavity Filling Filling the die cavity and achieving the desired part shape without failure is an important issue in forming processes, particularly for tubular components. The major task is mostly filling the corner areas of the part. In cases in which the part has sharp corners, achieving the final shape is hard or even impossible. For this reason, the ratio of filled area to the total cavity area (or simply Cavity Filling Ratio-CFR) is defined to evaluate the sufficiency of the process.

Figure 9. Incomplete stepped tube in the HHB process at room temperature (λ=26 %)

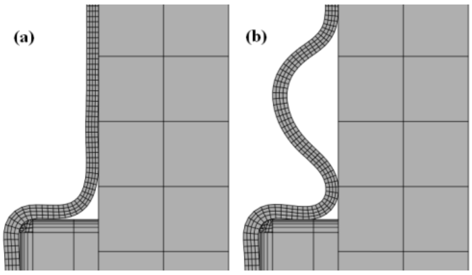


Figure 10. The effect of different axial feed on the shape of the stepped tube at 150 °C: (a) insufficient feed of 30 mm (unfilled corner area), and (b) high feed of 40 mm (wrinkling)

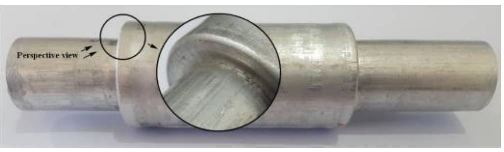


Figure 11. Perfect stepped tube formed under the appropriate axial feed and pressure attained with warm HHB at 150 °C

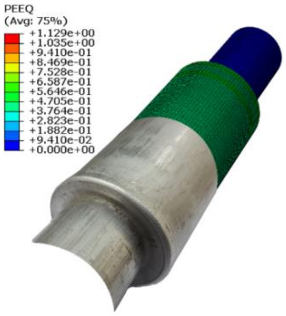


Figure 12. Experimental and FE simulation of the final part at 150 °C

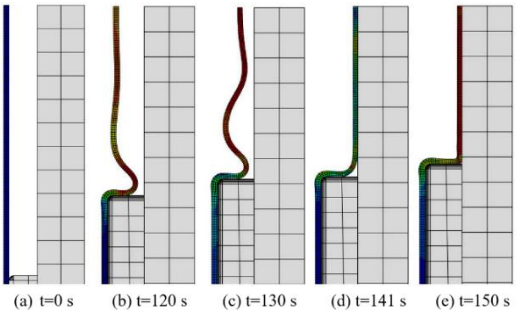


Figure 13. Tube shape in HHB process at 150 °C

Figure 14 compares the conventional and the HHB processes from the cavity filling capability point of view. In both the processes, the axial feeding is the same (35 mm) but three pressure levels are used. Figure 14a indicates the condition in which insufficient oil pressure is applied. By doubling the pressure level from 9.2 to 18.4 MPa (Figure 14b), the wrinkles disappear but the die-bush corner area is still unfilled (CFR=98.27 %). On the other hand, applying a high pressure amount (50 MPa) seems not to improve the CFR significantly (Figure 14c). When using HHB process, as Figure 14d shows, the initial tube turns into the complete stepped tube with almost filled corner area (CFR=99.85 %) and precise geometric shape with just one half of the applied pressure in the conventional hydroforming process. The complete formation of the concave corner is in direct relevance to the internal pressure value, specifically for the parts with sharp corner radii (Figure 14c) whereas the convex corner is mainly influenced by the amount of axial feeding of the tube and the bending operation caused by the bush movement (Figure 14d).

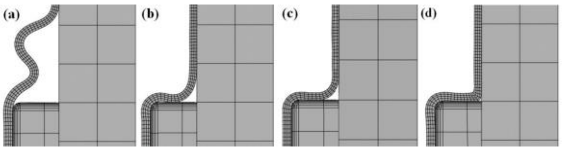


Figure 14. Comparison of the part shape in conventional hydroforming when (a) P=9.2 MPa, (b) P=18.4 MPa and (c) P=50 MPa with (d) HHB process (P=9.2 MPa)

4. 3. 3. Thickness Distribution The longitudinal thickness distribution of the stepped tube using HHB is shown in Figure 15. It is seen that the thickness variation is well predicted by the FE simulation. At the initial state, the ending sites of the tube are the only parts that are in contact with the tooling. The thickness of these regions remain unchanged throughout the process due to the absence of material flow. Hence, the axial movement of the bushes apply compressive strain just to the central zone of the tube. At the beginning, the tube is bent over the bush corner which causes negative strain on the regions indicated by No. 1. The thickness of this area steadily increases up to the point when bending is ended and do not vary significantly until the end of the process. The bulge zone that has greater distance from the tube axis has the lowest thickness values because of considerable tensile hoop strain. There is a pick in the thickness curve located at the convex corner zone (No. 2). The local thickening at a narrow area of this zone that has regions with the highest thickness values, appears in the last stage of forming in which the axial feeding pushes the tube into the die-bush corner (see Figure 13.e). Additionally, as Figure 13c depicted, a large wrinkle is formed near the die-bush corner area during the process and then disappears when forming proceeds (Figure 13d). This bending and unbending effect causes in a slight drop in the tube wall thickness (No. 3).To comprehend the HHB, the thickness distribution of the final part formed in this process is compared with that formed by the conventional hydroforming at 150 °C by using FE simulation. In the central areas of the bulge region, the thickness in both processes is mostly uniform, as is illustrated in Figure 16. These regions, encounter the lowest thickness values, especially the ones near the convex corner. The part thickness in this particular area drops drastically by varying the operating pressure level from 18.4 to 50 MPa due to the increasing tension force and lack of contact between the tube and the die/bush surfaces. Further increase in the pressure value may lead to bursting in the tube because of excessive thinning. Such pressure limitation is not present in the case of HHB method.

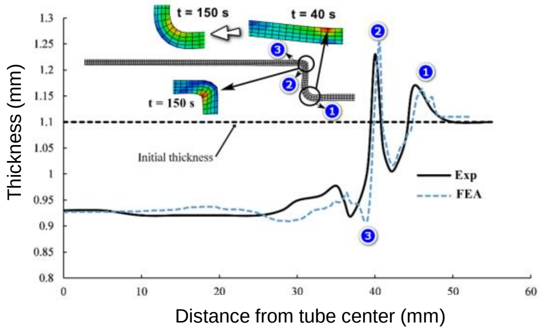


Figure 15. The thickness distribution of the stepped tube formed at 150 °C together with the detailed thickness strain contours for the tube corners at the first and the last stages of the process

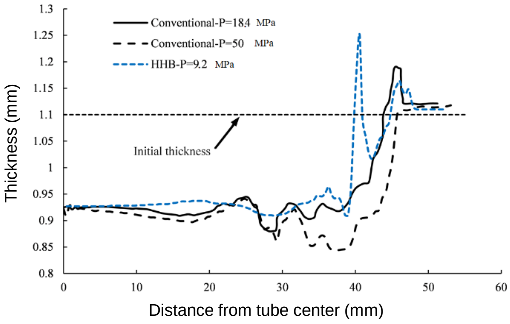


Figure 16. Comparison of thickness distribution of the stepped tube in the two processes (T=150 °C)

5. CONCLUSION

The present work investigated the possibility of forming 6063 aluminum alloy stepped tubes with high expansion ratio and sharp corners using warm hybrid hydroforming and bending (HHB) forming method. Experimental tests along with FE simulation were used in order to compare the final parts produced by the conventional hydroforming and the HHB forming. The formability of the tube material was tested through hydrobulge experiments at different temperatures. At the condition in which the tube was ruptured before touching the die walls in the cold HHB process, by allocating appropriate pressure and axial feed values, a stepped tube with the expansion ratio of 47.6 % and sharp corners (nearly complete cavity filling with CFR of 99.85 %) was formed at temperature of 150 °C. Based on the experimental results, the FE simulation in conjunction with the second derivative of equivalent plastic strain failure criterion was then validated and used to broaden the finding. The results show that the conventional and HHB processes are both able to produce the final part with the specified expansion ratio. Although, the conventional forming requires twice as much pressure as the HHB method, produces a part with unfilled corners (CFR=98.27 %) and do not result in sharp corner radii. Increasing the pressure value leads to sever thinning in the convex corner region of the stepped tube where no remarkable difference was observed in the amount of CFR.

6. REFERENCES

1. Lang, L., Wang, Z., Kang, D., Yuan, S., Zhang, S.-H., Danckert, J. and Nielsen, K.B.J.J.o.M.P.T., "Hydroforming highlights: Sheet hydroforming and tube hydroforming", ***Journal of Materials Processing Technology***, Vol. 151, No. 1-3, (2004), 165-177.
2. Salahshoor, M., Gorji, A. and Bakhshi-Jooybari, M.J.I.J.o.E.-T.A.B., "Investigation of the effects of pressure path and tool parameters in hydrodynamic deep drawing", ***International Journal of Engineering, Transactions A: Basics***, Vol. 27, No. 7, (2014), 1155-1166.
3. Reddy, P.V., Reddy, B.V. and Rao, P.S.J.M.T.P., "A numerical study on tube hydroforming process to optimize the process parameters by taguchi method", ***Materials Today: Proceedings***, Vol. 5, No. 11, (2018), 25376-25381.
4. Khosrojerdi, E., Bakhshi-Jooybari, M., Gorji, A. and Hosseinipour, S.J., "Experimental and numerical analysis of hydrodynamic deep drawing assisted by radial pressure at elevated temperatures", ***The International Journal of Advanced Manufacturing Technology***, Vol. 88, No. 104, (2016), 185-195.
5. Lee, M.-Y., Sohn, S.-M., Kang, C.-Y., Suh, D.-W. and Lee, S.-Y., "Effects of pre-treatment conditions on warm hydroformability of 7075 aluminum tubes", ***Journal of Materials Processing Technology***, Vol. 155, (2004), 1337-1343.
6. Yadav, A.D., "Process analysis and design in stamping and sheet hydroforming", The Ohio State University, (2008),
7. Varloteaux, A., Blandin, J. and Suery, M., "Control of cavitation during superplastic forming of high strength aluminium alloys", ***Materials Science and Technology***, Vol. 5, No. 11, (1989), 1109-1117.
8. Hosford, W.F. and Caddell, R.M., "Metal forming: Mechanics and metallurgy, Cambridge University Press, (2011).
9. Yuan, S., Qi, J. and He, Z., "An experimental investigation into the formability of hydroforming 5a02 al-tubes at elevated temperature", ***Journal of Materials Processing Technology***, Vol. 177, No. 1-3, (2006), 680-683.
10. Kim, B., Van Tyne, C., Lee, M. and Moon, Y., "Finite element analysis and experimental confirmation of warm hydroforming process for aluminum alloy", ***Journal of Materials Processing Technology***, Vol. 187, (2007), 296-299.
11. Yi, H., Pavlina, E., Van Tyne, C. and Moon, Y., "Application of a combined heating system for the warm hydroforming of lightweight alloy tubes", ***Journal of Materials Processing Technology***, Vol. 203, No. 1-3, (2008), 532-536.
12. Gang, L., ZHANG, W.-d., HE, Z.-b., YUAN, S.-j. and Zhe, L., "Warm hydroforming of magnesium alloy tube with large expansion ratio within non-uniform temperature field", ***Transactions of Nonferrous Metals Society of China***, Vol. 22, (2012), s408-s415.
13. Seyedkashi, S.H., Moslemi Naeini, H., Liaghat, G., Mosavi Mashadi, M., Shojaee G, K., Mirzaali, M. and Moon, Y.H., "Experimental and numerical investigation of an adaptive simulated annealing technique in optimization of warm tube hydroforming", ***Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture***, Vol. 226, No. 11, (2012), 1869-1879.

14. Hashemi, S., Naeini, H.M., Liaghat, G. and Tafti, R.A., "Prediction of bulge height in warm hydroforming of aluminum tubes using ductile fracture criteria", ***Archives of Civil and Mechanical Engineering***, Vol. 15, No. 1, (2015), 19-29.
15. Mitsui, S., Miyagawa, T., Yasui, H. and Yoshihara, S., "Warm bulge forming of small diameter a1100 aluminium tube", in Materials Science Forum, Trans Tech Publications, Vol. 920, (2018), 149-154.
16. Elyasi, M., Bakhshi-Jooybari, M. and Gorji, A., "A new die design for the hydroforming of stepped tubes", ***International Journal of Material Forming***, Vol. 3, No. 1, (2010), 71-75.
17. Ramberg, W. and Osgood, W.R., "Description of stress-strain curves by three parameters", NASA, Scientific and Technical Information Facility (1943).
18. Afshar, A., Hashemi, R., Madoliat, R., Rahmatabadi, D., Hadiyan, B.J.M. and Industry, "Numerical and experimental study of bursting prediction in tube hydroforming of al 7020-t6", ***Mechanics and Industry***, Vol. 18, No. 4, (2017), 411.
19. Yang, L., Tao, Z. and He, Y., "Prediction of loading path for tube hydroforming with radial crushing by combining genetic algorithm and bisection method", ***Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture***, Vol. 229, No. 1, (2015), 110-121.
20. Yuan, S., Wang, X., Liu, G. and Wang, Z., "Control and use of wrinkles in tube hydroforming", ***Journal of Materials Processing Technology***, Vol. 182, No. 1-3, (2007), 6-11.

Improvement of Die Corner Filling of Stepped Tubes Using Warm Hybrid Forming

A. Taheri Ahangar, M. Bakhshi-Jooybari, S. J. Hosseinipour, H. Gorji

Advanced Material Forming Research Center, Faculty of Mechanical Engineering, Babol Noshirvani University of Technology, Babol, Iran

PAPER INFO

Paper history:
Received 31 December 2018
Received in revised form 02 March 2019
Accepted 07 March2019

Keywords:
Aluminum Alloy
Corner Filling
Stepped Tube
Tube Hydroforming
Warm Hydroforming

چکیده

آلیاژهای آلومینیوم و منیزیم از موادی هستند که باعث کاهش وزن خودرو و در نتیجه کاهش مصرف سوخت می‌شوند. با این حال، محدودیت هایی در ارتباط با شکل پذیری پایین آنها در دمای اتاق، زمانی که توسط فرایندهای تولید متعارف تولید می شود، پیدا می شود. به همین دلیل، برای غلبه بر چنین محدودیت هایی، نیاز به توسعه تکنیک های شکل‌دهی جدید، از جمله هیدروفرمینگ گرم لوله است. علاوه بر این، تولید قطعات با گوشه های تیز با استفاده از فرایندهای شکل گیری معمول تقریبا غیرممکن است. در این مقاله قصد داریم تا با استفاده ازیک روش ترکیبی هیدروفرمینگ و خم‌کاری، امکان تشکیل لوله های پله‌ای با نسبت انبساط بالا، شعاع گوشه تیز و شکل هندسی دقیق را بررسی کنیم. برای بررسی شکل پذیری لوله، آزمون بالج در دماها و تغذیه محوری مختلف انجام شد. نشان داده شده است که با استفاده از تغذیه ۳۵ میلیمتر و سرعت تغذیه ۱۵ میلی متر بر دقیقه ، یک لوله پله با نسبت انبساط ٤٧/٦ درصد و نسبت پرشدگی حدود ۱۰۰ درصد (قطعه کار با شعاع گوشه های تیز) ، در هنگام اتخاذ هیدروفرمینگ ترکیبی توسعه یافته با خم‌کاری در دمای۱۵۰°C قابل دستیابی است.

doi*: 10.5829/ije.2019.32.04a.17*