Impact of Loading Rate in Hot Tube Gas Forming of AA6063

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Received: 11 July 2018, Revised: 6 October 2018, Accepted: 10 January 2019

Abstract: In this paper, the manufacturing of a cylindrical AA6063 step tube via hot metal gas forming (HMGF) process is studied both experimentally and numerically. The goal is to investigate the effect of loading rate on the specimen profile and thickness distribution. ABAQUS finite element software is used for the numerical simulation. Experiments were carried out at 580°C in two conditions; first, without axial feeding and then with an axial feeding of 14 mm at a maximum pressure of 0.5 MPa. The studied parameters are the pressure rate and the axial feeding rate. The results show that in the non-axial feeding mode, the thickness distribution in the die cavity region was non-uniform and a rupture occurred at a pressure of 0.6 MPa. The reduction of the pressure rate has no significant effect on the rupture pressure. In the case of axial feeding, by choosing the pressure rate of 0.001 MPa/s and the axial feeding rate of 0.1 mm/s, wrinkling has been created in the specimens. However, at a pressure rate of 0.005 MPa/s and an axial feeding rate of 0.02 mm/s, the specimens are raptured. Under low pressure rate of 0.001 MPa/s and low axial feeding rate of 0.02 mm/s, the thickness in the die cavity area has decreased. A suitable die filling and thickness distribution are obtained at a pressure rate of 0.005 MPa/s and axial feeding rate of 0.1 mm/s.

Keywords: AA6063, Hot Metal Gas Forming, Loading Rate, Tubular Parts

Reference: Rajaee, M., Hosseinipour, S.J., and Jamshidi Aval, H., "Impact of Loading Rate in Hot Tube Gas Forming of AA6063", Int J of Advanced Design and Manufacturing Technology, Vol. 12/No. 1, 2019, pp. 59–66.

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1 INTRODUCTION

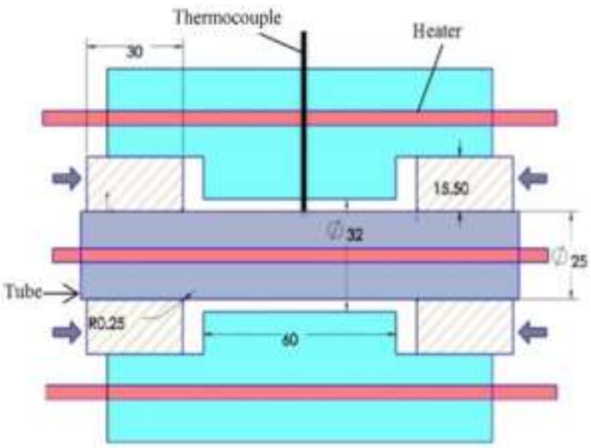
In recent years, the use of tubular parts from aluminium alloys has been considered to increase the strength-to-weight ratio of structures and in particular to reduce fuel consumption in vehicles. Due to the low ductility of aluminium alloys at ambient temperature, the research usually focuses on high-temperature forming. Warm tube hydroforming process is one of the solutions provided for this purpose and there is a lot of research in this regard [1-3]. The maximum operating temperature of the warm hydroforming process is limited to 300 °C because of using oil fluid and high pressure requirement. In this regard, a new solution is to use the gas blowing process known as hot metal gas forming (HMGF) [4]. It enables forming large parts with high expansion ratio since it decreases material flow stress and increases material formability at high temperatures.

According to the published works, there are a few researches considering the HMGF of the ferrous and non-ferrous tube. For instance, Kigler et al. [5] simulated the gas forming process of 5182 aluminium alloy tube by the LS-DYNA software and compared it with experimental results. Experiments were carried out using nitrogen gas at 450 °C. Nazzal et al. [6] analysed the superplastic tube forming of AZ31 alloy by finite element simulations at 400 °C. They demonstrated that the pressure path of tube gas forming was different from sheet metal gas forming. Lin et al. [7] studied the formability of AZ31B alloy tube up to 480 °C by nitrogen gas blowing process. Their results showed that both the total elongation along hoop direction and the maximum expansion ratio value increase to a peak value at about 160 °C. After that, they begin to decrease quickly until a certain rebounding temperature is reached. From the rebounding temperature, they begin to increase rapidly again. Damours and Beland [8] developed a thermo-mechanical model using LS-DYNA to predict the necessary temperature and pressure to optimum formability of 7075 aluminium alloy tubes. He et al. [9] carried out a free bulging test by HMGF process at different temperatures to examine the formability of AA6061 tube. They showed that with increasing temperature, the burst pressure dropped sharply and the expansion ratio increases to 65% at 500 °C. He et al. [10] investigated the formability of titanium tube TA2 by tube bulging test up to 950 °C. They concluded that the expansion ratio reaches the maximum value of about 70% at 890 °C. Also, the bursting pressure decreases from 6.5 MPa to 1.2 MPa as temperature increases. They reported that the ideal temperature range for TA2 tube forming is from 860 °C to 920 °C in HMGF process. Maeno et al. [11] performed hot free bulging of an aluminium alloy tube at 560°C using rapid heat by electrifying the tube. They found that the hot free bulging is impressive in increasing the expansion ratio of the aluminium tube. Maeno et al. [12] developed a resistance heating set for hot bulging of an aluminium alloy tube into a die. They reported that the decrease in wall thickness of the whole forming area was prevented by axial feeding with the optimised condition before the contact with the die. Maeno et al. [13] performed HMGF without and with axial feeding of the sealed aluminium alloy tube. They found that the amount of expansion can be controlled by heating during forming without adjusting the internal pressure. Pavel and Strano [14] combined the process of HMGF and hot press hardening to produce tubular components using two different kinds of steel. They show that the minimum achievable radii depend on the maximum pressure. Also, they reported that as for the other process parameters, when they have a positive effect on the final tube hardness, at the same time they have a negative effect on calibration, i.e. on the chances of obtaining small radii.

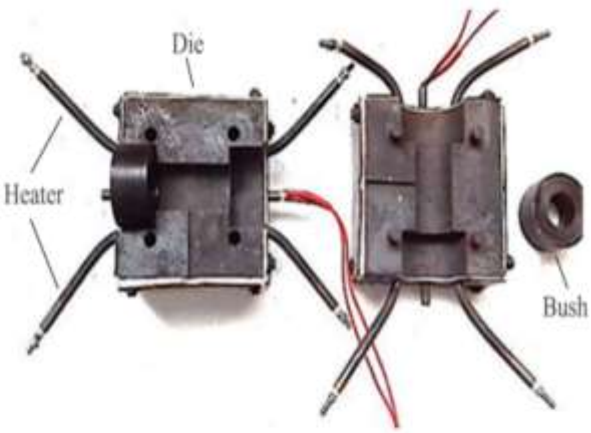
Aluminum alloy 6063 due to corrosion resistance, good mechanical strength, and welding ability has a lot of applications in various industries such as construction, and transportation. With the help of HMGF process, components with complex geometry can be produced at a lower cost and time than other production methods. According to the literature, the research on the hot tube forming with gas blowing is often limited to the examination of the formability through a free bulging test. Limited research has been conducted to produce tubular parts with various sections in the die. Therefore, the need for more knowledge in this regard is felt, especially for different alloys. In the current research the effect of loading rate in hot metal gas forming process with axial feeding to make cylindrical step tubes from aluminum alloy 6063 was investigated both experimentally and numerically. Accordingly, a three-dimensional model is performed to determine forming behavior during HMGF as well as experimental tests are conducted to evaluate the effect of loading rate on formed specimens.

2 RESEARCH METHOD

In this study, AA6063 tubes with 1.3 mm thickness and 25 mm in diameter were employed. To produce a step tube, a die set was designed as shown in “Fig. 1”. The die diameter is 32 mm (expansion ratio 28%), and the length of the deformation is 60 mm. The tube was fed axially by displacing two bushes from both sides. In order to create heat uniformly, resistance heaters are used inside the die and the tubes. The set of equipment for hot metal gas forming process with axial feeding is presented in “Fig. 2”. The axial feeding was adjusted by a step motor controller board. An air compressor system with a maximum capacity of 1 MPa was used to supply gas pressure. The pressure applied during the process was controlled by a manometer. The temperature was controlled by a temperature controller connected to the tube surface by a thermocouple. No lubricants were applied during the tests.



(a)



(b)

Fig. 1 (a): Schematic of die set designed and (b): the die set made for experimental tests.

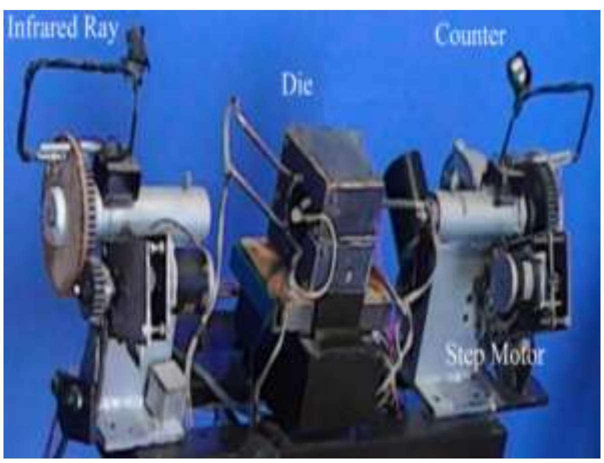


Fig. 2 Equipment set for the hot metal gas forming process with axial feeding.

Simulations were performed by ABAQUS/Implicit finite element software based on the actual conditions exhibited in experiments. Due to the symmetry of the die assembly, the quarter model was used for simulation ("Fig. 3"). The effect of heat transfer during deformation is neglected and isotherm conditions are considered for the process. The tube is modelled as 3-D deformable and the die is modelled as discrete rigid. The pressure applied gradually increases over time both in simulations and the experiments. The C3D8R axisymmetric element was used with three elements through the thickness of the tube. The dimensions of the elements are 43×1×1 mm. Friction behaviour of the tube and die surfaces is modelled using the Coulomb friction model with 0.5 as the coefficient of friction [15-16]. The time-dependent material law is implemented in the simulation using the data presented as in [17].

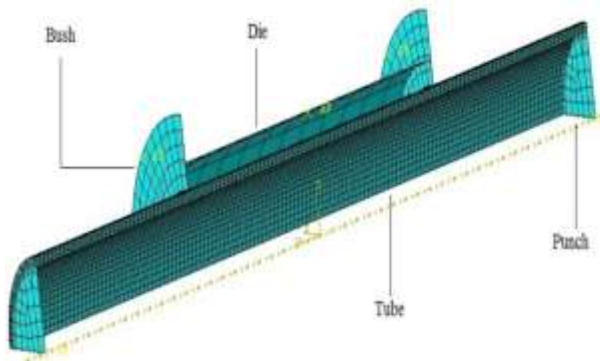


Fig. 3 A quarter model for tube and the die components used in the simulation.

Due to the high deformation temperature, the anisotropy effect is neglected and the von Mises criterion is used. All experiments were performed at 580 °C due to the high elongation of the material at this temperature [17]. The values of the experiment parameters are presented in "Table 1".

Table 1 The values of the parameters

Path No.	Pressure, MPa	Pressure Rate, MPa/s	Feeding, mm	Feeding Rate, mm/s
P1	0.6	0.001	0	0
P2	0.6	0.005	0	0
P3	0.5	0.005	14	0.02
P4	0.5	0.001	14	0.1
P5	0.5	0.005	14	0.1
P6	0.5	0.001	14	0.02

As shown in "Fig. 4", experiments were designed in two conditions; without axial feeding (P1 and P2) and with an axial feeding (P3-P6). Since in the without axial feeding condition the burst pressure was about 0.6 MPa, a maximum pressure of 0.5 MPa was selected in the condition of with an axial feeding. Assuming a uniform thickness distribution for the final piece, the required axial feed was calculated to be about 14 mm due to the fact that the material volume is constant in plastic deformation.

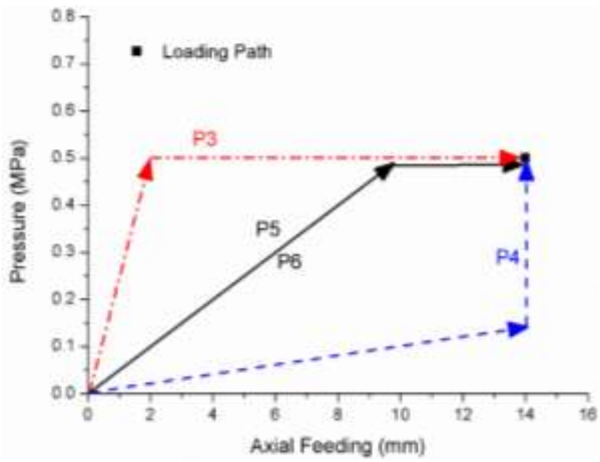


Fig. 4 The loading paths of P3-P6 with an axial feeding condition.

After the experiments, the specimens were cut in the longitudinal direction of the tube and the thickness of the specimens was measured. Figure 5 shows a cut specimen in which “A”, “B”, and “C” represent the flange region, the corner area of the die, and the die cavity area respectively.

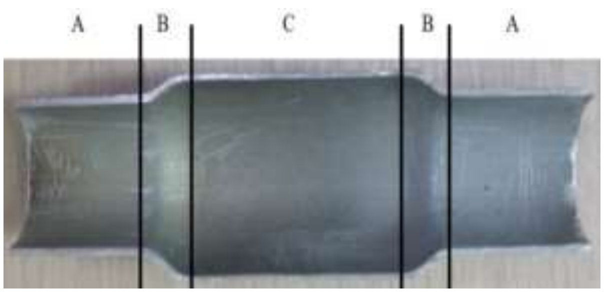


Fig. 5 A cut specimen after forming.

3 RESULTS AND DISCUSSION

3.1. Without Axial Feeding Condition

Figure 6 shows the pressure rate in time for the without axial feeding condition. P1 is at a pressure rate of 0.001 MPa/s and P2 is at a pressure rate of 0.0005 MPa/s. The specimens after experimental tests are shown in “Fig. 7”. It is observed that with increasing pressure, a rupture occurred at a pressure of 0.6 MPa. The crack length is greater in P2 which may be due to the higher pressure rate. It is noteworthy that the amount of deformation in specimen P1 is higher than that in P2.

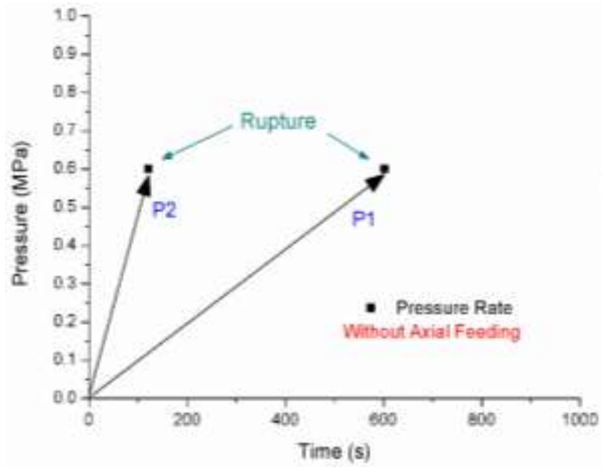


Fig. 6 The pressure rate for the loading paths of P1 and P2.

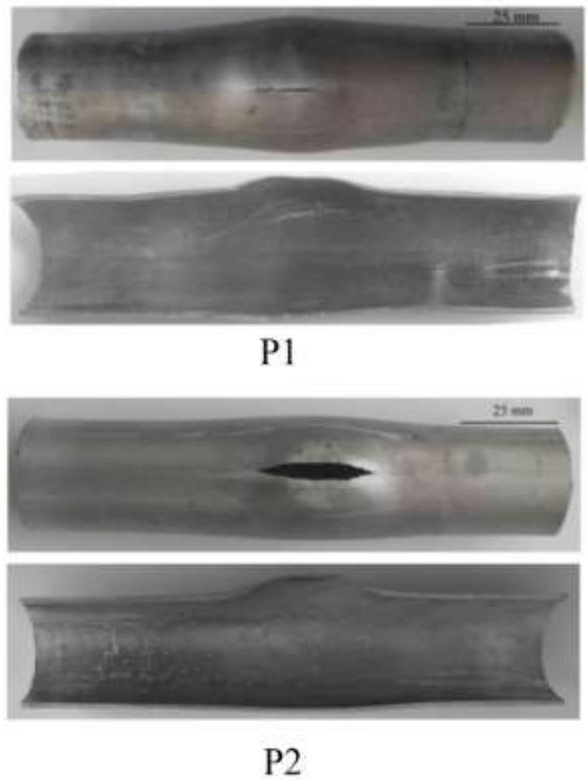


Fig. 7 Specimens P1 and P2 from experiments in without axial feeding condition.

Figure 8 shows the simulation results of radial displacement for specimens P1 and P2. The filling percentage is going down with pressure rate, and the expansion ratio in specimens P1 and P2 was 13 and 11%, respectively. It is due to the time-dependent deformation behaviour of the material at high temperatures. In the path P1 the deformation time was increased, due to the low pressure rate, therefore deformation of the material took longer.

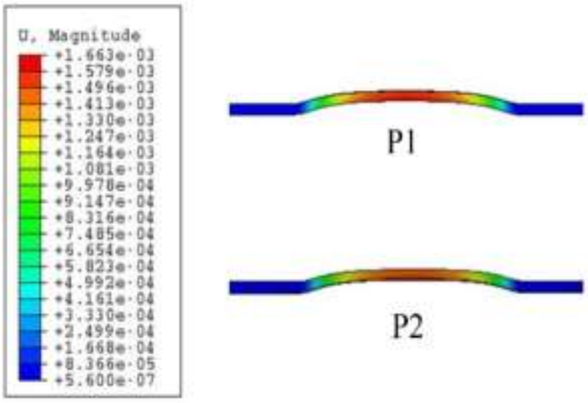


Fig. 8 The radial displacement of specimens P1 and P2 based on simulation results.

Figure 9 shows the thickness variations in specimens P1 and P2. As can be seen, there is fairly good compatibility between the experimental results and simulations. The maximum error is about 5% for the rupture region. The local thinning occurred in the corners of the die (B) due to the bending effect, and the thickness reduction in the die cavity area (C) is non-uniform. The minimum thickness of the tube in the rupture area is about 1.1 mm. According to the experimental results, a minimum allowable thickness of 1.1 mm is considered in the simulation.

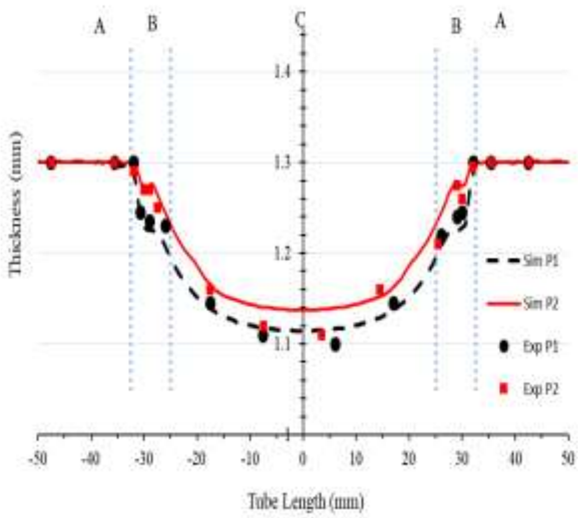


Fig. 9 Thickness distribution in specimens P1 and P2 from experiments and simulation.

3.2. With Axial Feeding Condition

Figure 10 shows the pressure and the axial feeding rates for the loading paths of P3-P6. P3 is at high pressure rate and low axial feeding rate, P4 is at low pressure rate and high axial feeding rate, P5 is at high pressure and axial feeding rates, and P6 is at low pressure and axial feeding rates.

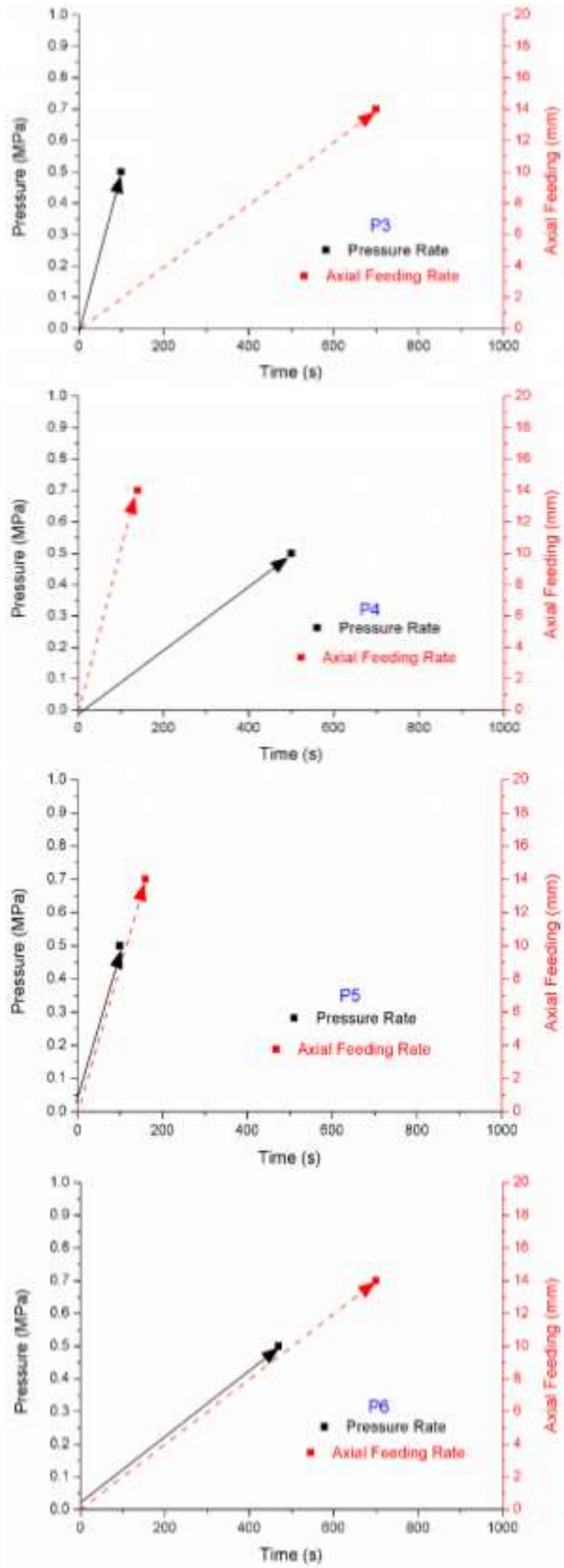


Fig. 10 The pressure and the axial feeding rates for the loading paths of P3-P6.

The simulation of specimens P3-P6 at different times of forming is shown in "Fig. 11".

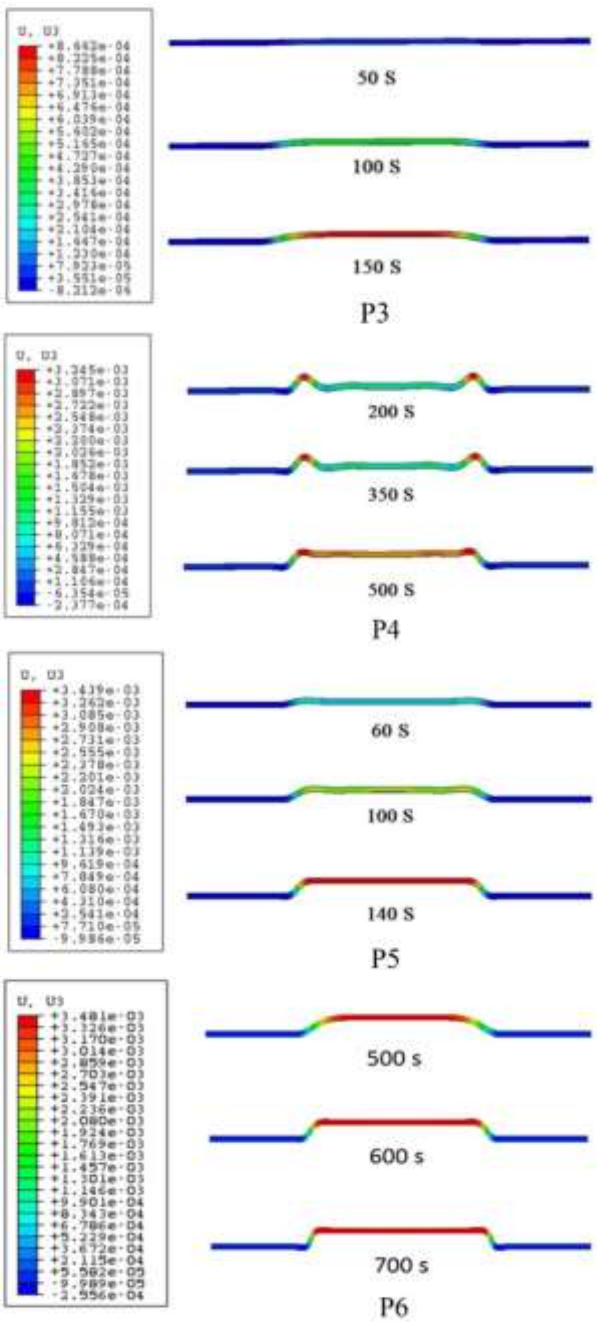


Fig. 11 The deformation of specimens P3-P6 at different times of forming in terms of radial displacement.

As can be seen, for specimen P3 at 50 seconds, the deformation is negligible, and until 100 seconds the specimen has bulged. At 150 seconds failure occurred and the simulation is stopped at a pressure of 0.5 MPa and axial feeding of 3 mm due to the minimum thickness of the specimens were lower than the allowable thickness ("Fig. 12"). It is seen that in comparison with specimens P1 and P2, the deformation was more uniform in the die cavity area (C). For specimen P4 at 200 seconds (14 mm axial feeding and 0.2 MPa pressure) the specimen is wrinkled, and by increasing pressure to 0.5 MPa in 500 seconds, the amount of wrinkling decreased.

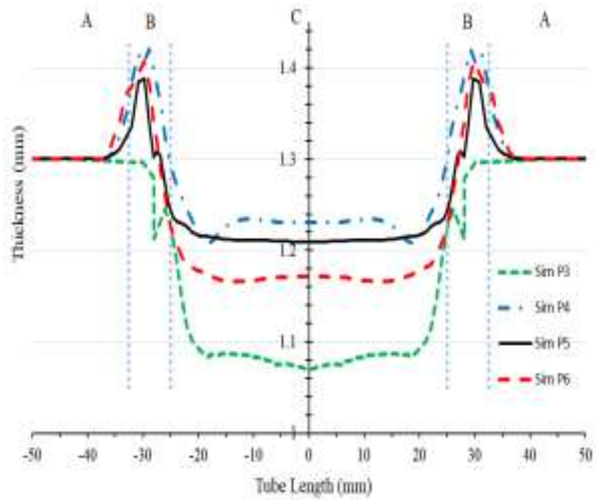


Fig. 12 Thickness distributions of specimens P3-P4.

In specimen P5, it is seen that the deformation continues with slight wrinkling until 100 seconds (10 mm axial feeding and 0.5 MPa pressure), indicating the superior effects of the axial feed on the gas pressure under high axial feeding rate. At 140 seconds (14 mm axial feeding and 0.5 MPa pressure), the tube had contact with the die surface and wrinkling disappeared. For specimen P6 at 500 seconds (10 mm axial feeding and 0.5 MPa pressure), unlike the specimen P5, no wrinkling happened and the amount of deformation is increased so that the tube has contact with the die surface. This indicates the superior effects of the gas pressure on the axial feed under low axial feeding rate that lead to more tensile hoop deformation of the tube. The reason for this increase in deformation is the time-dependent deformation behaviour of the material at high temperatures. Until 700 seconds (14 mm axial feeding and 0.5 MPa pressure), the deformation is continued at the corner of the die.

Figure 12 shows the thickness distribution for specimen P3-P6. It is observed that, in specimen P3 similar to the specimens P1 and P2 ("Fig. 9"), a local thinning occurred in the corner of the die (B). Due to the axial feeding effect, the thickness variations in the die cavity area (C) were more uniform than in P1 and P2. In specimens P4, unlike the specimen P3, the thickness at the corner of the die (B) was increased. The reason is the higher axial feeding rate in comparison with the path P3, which led to the compression and the flow of material from the flange region (A). The minimum thickness in the die cavity area (C) has increased compared to the specimen P3, but due to the wrinkling effect, the thickness distribution in this area is not uniform.

For specimen P5, it can be seen that similar to specimen P4, the thickness in the corners of the die (B) increased, but the thickness distribution in the die cavity (C) is quite uniform. The minimum thickness in this area is about 1.2 mm. The thickness variations in specimen P6 are similar to specimen P5, except that the amount of thinning is greater in the die cavity region (C).

According to the simulation results, experimental tests were performed based on the loading paths of P5 and P6. Figure 13 shows the specimens after forming from the experimental tests. As can be observed, there is good compatibility between the experimental tests and the simulation results, and the specimens had contact with the die surface and filled the die.

P5

P6

Fig. 13 Specimens P5 and P6 after deformation from experimental tests.

4 CONCLUSION

In this paper, the effect of the loading rate in the hot metal gas forming process with axial feeding to produce cylindrical step tubes of AA6063 alloy was investigated both experimentally and numerically. The results revealed that:

- In the non-axial feeding mode, the thickness distribution in the die cavity region was non-uniform and a rupture occurred at a pressure of 0.6 MPa. The reduction of the pressure rate has no significant effect on the rupture pressure, but the filling percentage of the die increased, which can be due to the behaviour of the time-dependent deformation of the material.
- In the case of axial feeding, a rupture has been made in specimens with a choice of high pressure rate (0.005 MPa/s) and low axial feeding rate (0.02 mm/s). By choosing a low pressure rate (0.001 MPa/s) and high axial feeding rate (0.1 mm/s), wrinkling occurred in the specimens, and the thickness distribution in the die cavity became non-uniform.
- The suitable loading path with respect to die filling percentage and thickness distribution was obtained under the condition of high pressure rate (0.005 MPa/s) and high axial feeding rate (0.1 mm/s).
- Under loading condition of low pressure rate (0.001 MPa/s) and low axial feeding rate (0.02 mm/s), the thickness in the die cavity area has decreased due to the increase in forming time that led to increasing the time-dependent deformation of the material.

ACKNOWLEDGMENTS

The authors would like to appreciate the office of the Vice President for Research of Babol Noshirvani University of Technology for the financial support.

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