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ORIGINAL ARTICLE

Experimental and numerical investigation of the influence of pulsating pressure on hot tube gas forming using oscillating heating

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Abstract

Hot metal gas forming is a modern metal forming process which is generally utilized to manufacture automotive parts with complex shape and light-weight materials such as aluminum-magnesium alloys. One of the critical parameters in this approach is controlling the internal pressure of the tube during the hot forming process. The improvement of formability in tube hydroforming by utilizing pulsating pressure paths has been confirmed in the last few years. In this paper, the effect of the pulsating pressure on the hot tube gas bulging process has been investigated by experimental and numerical methods. In addition, an oscillating heating mechanism was used to provide a uniform temperature distribution along the tube. A novel, simple pneumatic system was designed and used to provide pressure paths. Moreover, the finite element simulation of hot tube gas bulging was carried out to investigate the effect of different parameters of pulsating pressure on tube formability and thickness distribution. The simulation and experimental results showed that the proposed pulsating pressure path improved formability and thickness distribution along the tube in the hot metal tube gas bulging process. It was also concluded that the axial feeding intensifies the effect of pulsating pressure on formability and it should be applied right after the start of the plastic deformation of the tube.

Keywords Bulging · Pulsating pressure · Hot metal gas forming · Improvement of formability · Flame heating

1 Introduction

Nowadays, decreasing the weight of automotive parts is one of the effective factors in increasing fuel efficiency and prevention of air pollution [1]. Therefore, the procedures of metal forming processes should be improved to meet these requirements. Forming hollow parts from aluminum-magnesium alloys could be a solution to provide the aforementioned requirements in several industries such as automotive [2] and aerospace structures [3]. Hot metal gas forming (HMGF) is a new forming process which is used to form aluminum alloys and high-strength steels [4]. This process is similar with warm hydroforming whereas air or gas pressure is used to form tubes instead of fluid media. Previously, utilizing pulsating pressure paths in tube hydroforming was proposed by Mori et al. which is called the pulsating hydroforming of tubes [5]. Mori et al. [6] studied the improvement mechanism of formability in free bulge pulsating hydroforming of tubes by 2-D finite element method and experimental investigation. Loh-Mousavi et al. studied the improvement of formability of pulsating pressure in T-shape hydroforming via 3-D finite element and experimental methods. The numerical results showed that the pulsating pressure had a negligible effect on friction while it could change the strain path and stress state during the forming process [7, 8]. Ashrafi and Khalili investigated the effects of different process parameters in a pulsating hydroforming process using the Taguchi method [9].

Gang et al. [10] explained that reducing the weight of hollow parts can be obtained by using Al-Mg alloys. Kim et al. [11] studied hydroforming process for Al-Mg alloys and showed the poor formability of these alloys in room temperature, and in order to overcome this limitation, the temperature must be raised. Heating increases formability of aluminum alloys while it reduces the value of required pressure for

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hydroforming process. Therefore, newer methods such as warm hydroforming and hot metal gas forming are getting more attention recently.

Neugebauer et al. [12] studied the hot metal gas forming and inferred that both pressure and temperature during the process are vital parameters while forming. Yuan et al. [13] investigated experimental analysis of formability and mechanical specifications in tube hydroforming of aluminum 5A02 alloys in high temperatures. The results showed an improvement of formability at elevated temperatures. Wu [14] reviewed the HMGF and analyzed the creep behavior of Magnesium Az-31 alloy tubes. Vadillo et al. [15] compared the simulation results with experimental tests of the gas forming technology with 20 mm feeding distance at 500–900 °C for high-strength steel tubes. Yi et al. [16] developed a combined heating system in warm tube hydroforming. They used an induction coil and a heating element simultaneously in order to optimize the temperature. He et al. [17] investigated the microstructure and formability of Al6061 in hot metal gas forming at elevated temperatures. They also investigated the tubes made of extruded TA2 alloy in another study [18]. Maeno et al. [19] studied on hot metal gas forming of steel hollow part using resistance heating method. The effect of feeding length on Ti-3Al-2.5V was also studied and it was proved that this parameter could lead to an improvement in formability of the tubes [20]. Paul and Strano [21] studied the influence of forming conditions on hot tube gas forming and press hardening of two different kinds of steel tubes.

In this paper, the influence of pulsating pressure on hot metal gas forming of Al6063-T5 tube is investigated numerically and experimentally. To examine the effects of different pressure paths on formability and bulge height, a rotary heating system using an oscillating flame heating method was employed. Furthermore, the oscillation of pressure has been implemented by a new pneumatic pulsating pressure apparatus. The goal of this study is to evaluate the effects of pulsating pressure on the formability of tubes by comparing pulsating and non-pulsating pressure paths. In addition, the effect of some process parameters such as axial feeding, preheating time, frequency, and amplitude of pulsating pressure has been investigated by numerical and experimental methods.

2 Pulsating hot gas forming of the tube

2.1 Experimentation

As an innovative method that is shown in Fig. 1, by changing the arrangement of lathe carriage and tail stock in a lathe machine layout, the tube is compressed from one side. The other side of the tube is placed in a three-jaw chuck of lathe machine while the rate of axial feeding was set at 0.36 mm/rev. All dimensions and chemical composition of aluminum 6063-T5 alloy tube used in this study are illustrated in Table 1. The tube was sealed by utilizing brass housings, nuts, and bushes for both sides of the tube in which a schematic of the sealing components is shown

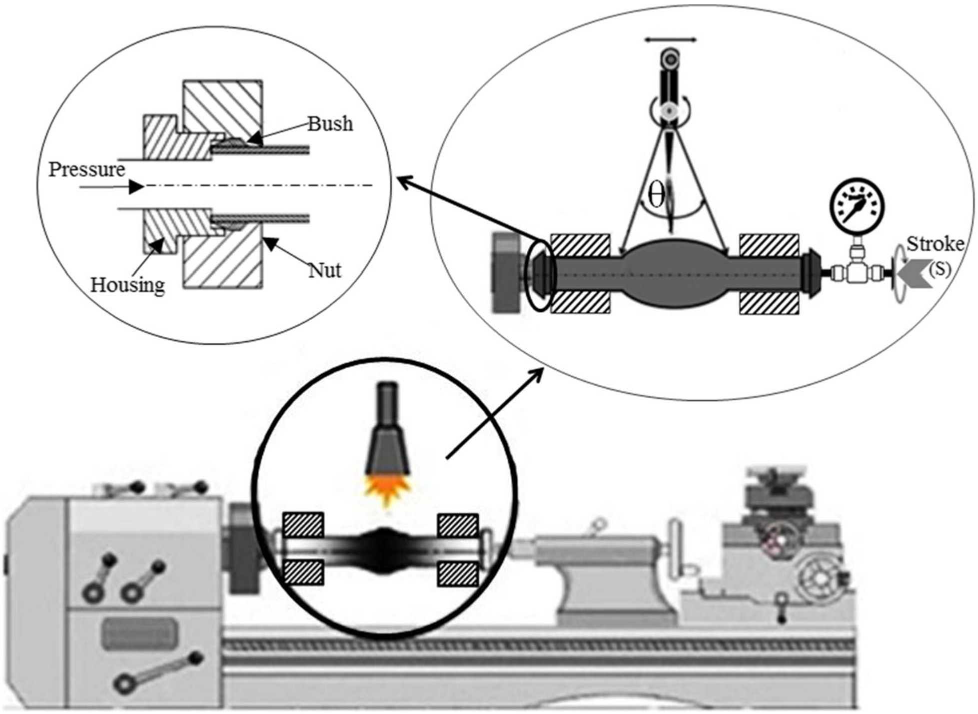


Fig. 1 Schematic of the experimental apparatus for gas forming process using sealed tube and flame

Table 1 Dimensions and chemical composition of aluminum 6063 tube

Tube dimensions (mm)				
Outer diameter			25	
Thickness			1.5	
Length			130	
Chemical composition (wt%)				
Al	Si	Pb	Mg	Fe
98.3	0.388	0439	0.396	0.342

in Fig. 1. In addition, a quick coupling accessory was used to resolve the connection problem between the air hose and rotating tube. Then, the tube and air sealing components were located in the three-jaw chuck of the lathe machine and the rotary velocity of the components was set at 22.4 RPM. These parameters were chosen to achieve a uniform temperature distribution on the surface of the tube using the proposed heating system.

The heating system applied to the hot gas bulging process is shown in Fig. 1. In addition, to prevent heating concentration to apply various pressure paths, the flame was oscillated by a simple mechanical mechanism. This method provides a uniform heating on the surface of the tube. A digital thermometer is utilized to measure temperature in this experiment. The tube was preheated for 90 s before bulging by pulsating pressure to increase the tube temperature up to 500 °C. Set-up and tools used in the experiments are shown in Fig. 2.

As shown in Fig. 3, a simple pneumatic circuit is designed and fabricated to generate the pulsating air pressure. A compressor with a big air tank (accumulator) was used as a pressure source to prevent the thermal effect and volume change in the tube internal pressure. Two 2/2 way solenoid valves with a digital timer are used to control the frequency of pulsating pressure while the pressure amplitudes are adjustable via two pressure control valves to provide a range of pressure paths by this configuration.

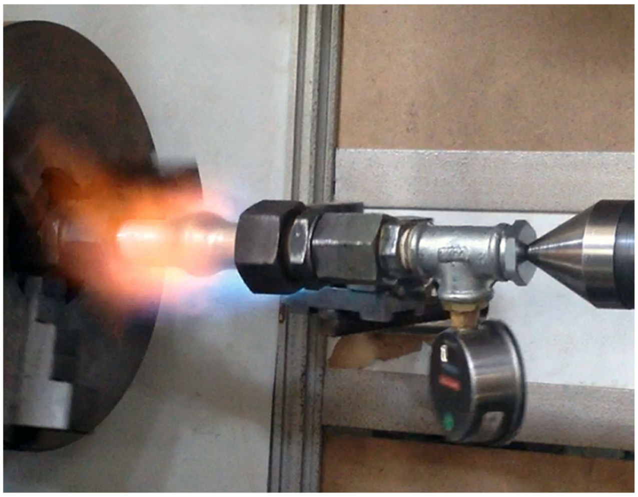


Fig. 2 Set-up and tools used in the experiments

The designed pulsating pressure path in the aforementioned pneumatic system is shown in Fig. 4. The average pressure is 0.55 MPa with a frequency of 0.25 Hz and an amplitude of 0.15 MPa used to examine the effect of pulsating pressure in the hot metal gas bulging process. In order to evaluate the effect of the oscillation of the internal pressure, a non-pulsating peak pressure of 0.7 MPa and a mean pressure of 0.55 MPa equal to pulsating pressure path were also studied by finite element and experimental methods.

2.2 Finite element simulation

The pulsating hot gas bulging process was simulated by ABAQUS/Explicit software and a Dynamic, Temperature-Displacement analysis was used. An axisymmetric model was used in the simulation due to the symmetric shape of the forming process (Fig. 5). The tube was meshed with 374 elements and the sealing components were considered as rigid elements. As it is shown in Fig. 5, the boundary condition of the tube ends was defined the same as the experimental procedure. Therefore, one side of the tube was fixed and the axial feeding was applied from the other side as a linear displacement with the speed of 0.08 mm/s.

The mechanical and thermal properties [22] of aluminum 6063 alloy used in the finite element simulation were obtained from previous studies which are given in Table 2.

Aluminum 6063 tensile strength and elongation curves at different temperatures used for the simulations were extracted by Maeno et al. [23].

As it is shown in Fig. 6, the temperature distribution on the heated area was measured along the tube right at the start of the deformation using a precise digital infrared thermometer. This temperature distribution was defined in the simulation as the following equation. T is temperature and Y is the vertical coordinate along the tube axis.

$$T = -0.0166Y^2 + 540(^\circ C) \tag{1}$$

It should be noted that the surface between the tube and rigid parts was assumed to be at a constant temperature (about 200 °C).

3 Results and discussion

3.1 Effect of heating method on deformation behavior

The part deformed by the oscillating flame mechanism is compared with tubes deformed by the fixed flame heating method

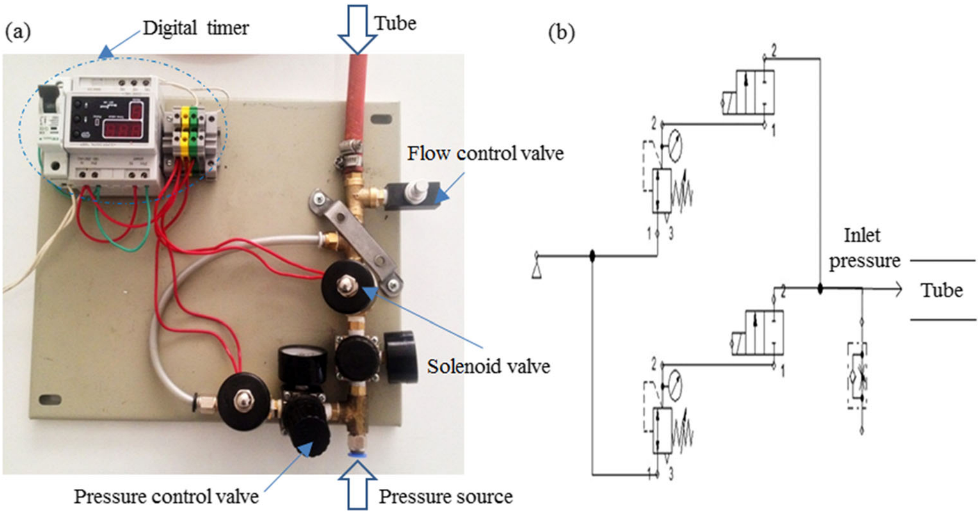


Fig. 3 The pneumatic apparatus (**a**) and circuit (**b**) to generate pulsating pressure during the experiment

in Fig. 7. A heat concentration on the center of the tube occurred when the fixed heating flame was used and this phenomenon led to local thinning and rapid bursting of the tube without sufficient bulging. The oscillating flame mechanism postponed bursting by providing a uniform heating on the surface of the tube.

The comparison between the maximum bulge heights for two pressure paths and heating conditions are shown in Table 3. The obtained results for these two heating methods show that utilizing the oscillating flame method in both pulsating and non-pulsating pressure increases the maximum bulge height up to 8.6 mm. The expansion ratio for this bulge height is about 69%. It can also be concluded that the formability of the tubes is improved by using both pulsating pressure and oscillating flame heating methods.

By comparing the tubes formed by pulsating pressure that are shown in Fig. 7, (b) and (c), it is inferred that using the oscillating heating system accompanied with inner pressure oscillations generated a larger and more uniform bulging.

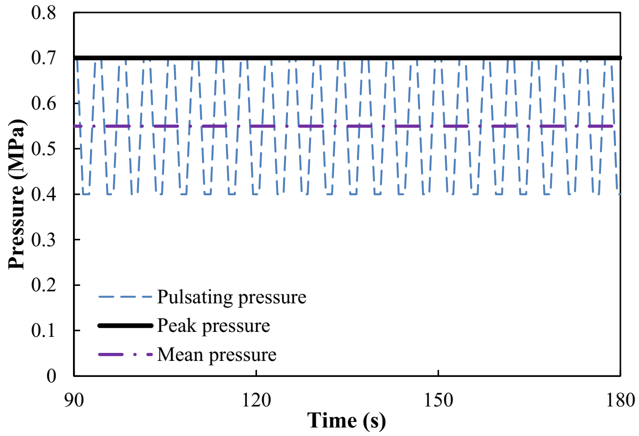


Fig. 4 Pulsating pressure path used in the experiment and finite element simulation

3.2 Effect of pulsating pressure on deformation behavior

Figure 8 illustrates the formed parts using pulsating pressure and non-pulsating pressure. The oscillating heating system was used to form these parts. The pulsating hot gas bulging was performed by frequency of 0.25 Hz, amplitude of 0.15 MPa, and an average pressure of 0.55 MPa as it was shown in Fig. 4. The pressure of non-pulsating peak pressure path that equaled to the maximum value of the examined pulsating pressure was

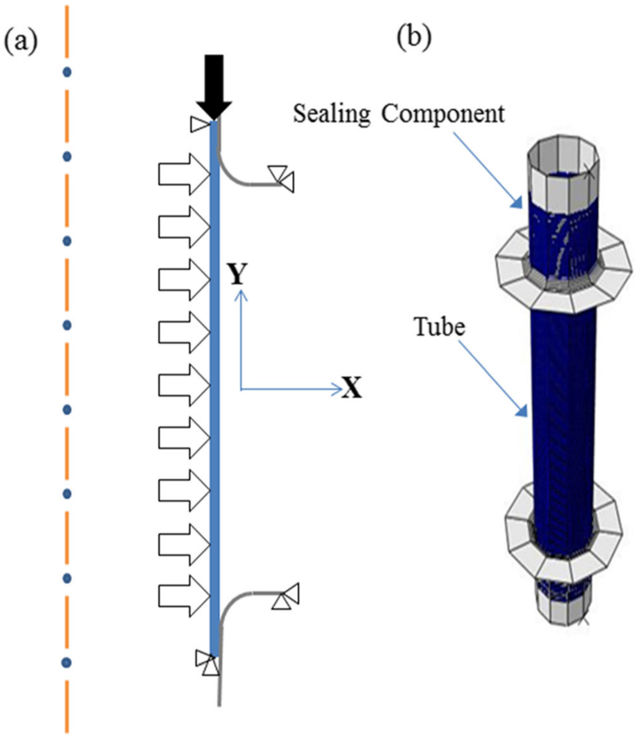


Fig. 5 Finite element model of the pulsating hot gas bulging. **a** Axisymmetric model. **b** Extended model

Table 2 Mechanical and thermal properties of Al6063 alloy

Parameters	Value
Poisson's ratio (−)	0.33
Friction coefficient (−)	0.1
Conductivity (W/mK)	209
Specific heat (J/kg °C)	900

set at 0.7 MPa. The experimental results of mean pressure show that the tube needs more time to reach required bulging due to the less internal pressure which causes the tube to burst and brings about melting. It was found that the bursting and melting could be postponed by pulsating pressure. The obtained distribution of equal plastic strain by the finite element simulation for pulsating hot metal gas bulging is shown in Fig. 9. It can be seen that the equivalent plastic strain (PEEQ) is about 0.6116 around the tube center.

Figure 10 shows the wall thickness reduction through longitudinal direction obtained from the experiments. It can be seen that the results with pulsating pressure have a superior performance on the uniformity of the thickness distribution compared with the non-pulsating pressure path.

Figure 11 demonstrates a comparison between the numerical and experimental results of the wall thickness reduction during the forming process by pulsating pressure. It is shown that the results are in acceptable agreement.

The thinning behaviors at the center of the bulged tubes which formed by pulsating and peak pressure paths obtained by FE simulation are shown in Fig. 12. The results show that formability and thickness reduction are improved compared with the peak pressure. It is observed that the thinning rate for the peak pressure is much faster than that for the pulsating pressure and thus bursting occurred quickly for the peak pressure.

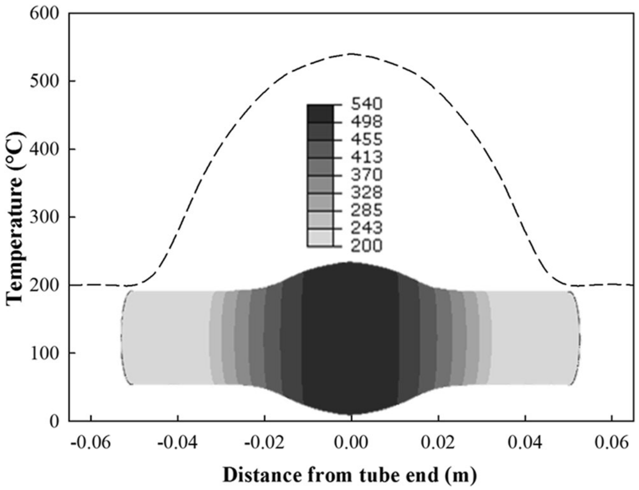
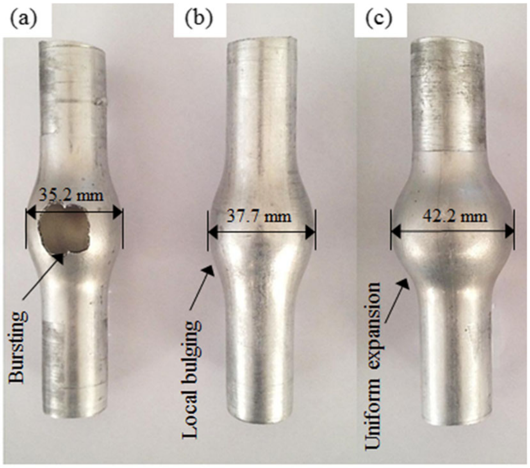


Fig. 6 Temperature distribution graph along the tube



Peak pressure & fixed heating system

Pulsating pressure & fixed heating system

Pulsating pressure & oscillating heating system

Fig. 7 Deformed tubes by different heating methods obtained by experiments (S = 10 mm)

In order to show the mechanism of this phenomenon, the thinning behavior of bulging area for one cycle of pulsating pressure path is magnified and illustrated in Fig. 13. According to this figure, the reason for the mentioned phenomenon is that the axial feeding supplies the material in lower inner pressure and then forming occurs by higher pressures and thus bulge height can be increased during a cyclic loading whereas for the peak pressure, the thickness is reduced more quickly and linearly. Due to the thinning of the tube's wall thickness, the peak pressure causes the tube bursting in a lower process time.

3.3 Influence of axial feeding on pulsating hot gas bulging

The formed tube by pulsating pressure with a mean pressure of 0.55 MPa, amplitude of 0.15 MPa, and frequency of 0.25 Hz is illustrated in Fig. 14. Tests were performed without axial feeding (a) and also with axial feeding of 10 mm (b). Maximum bulge heights in these two conditions, with and without axial feeding, are about 8.6 and 4.75 mm, respectively. The results show that the bulge height is increased by the axial feeding of the tube. Applying axial feeding developed the improvement of formability caused by pulsating pressure, and thus, bursting was prevented.

Table 3 Comparison of maximum bulge heights of different formed tubes obtained by experiment

Bulge height (mm)	Fixed heating flame	Oscillating heating flame
Peak pressure	5.1 (Bursting)	7 (Bursting)
Pulsating pressure	6.35	8.6

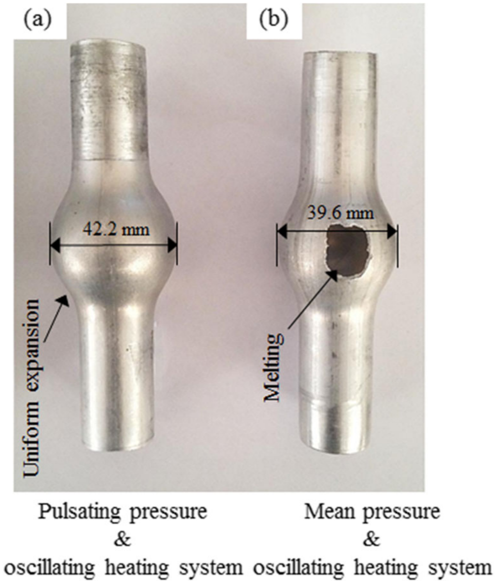


Fig. 8 Deformed tubes by different pressure paths obtained by experiments (S = 10 mm)

The bulge heights of the deformed tubes by pulsating pressure for different strokes obtained by FE simulations are demonstrated in Fig. 15. It can be seen that the higher axial feeding (stroke) leads to a larger bulge height. The axial feeding caused better material flow during the oscillation of the internal pressure on the deformation area, and thus, rapid bursting was prevented.

3.4 Effect of preheating time on pulsating hot gas bulging

To investigate the effect of preheating time, two different curves of stroke-time were defined in the experiments. As it can be seen in Fig. 16 in the first experiment, the starting time was set at 60 s which means that the punch movement starts after 60 s of heating the tube. In the next experiment, preheating time was set at 90 s. Figure 17 shows the formed tubes with different preheating times of 60 and 90 s. In the first state (preheating time of 60 s) due to the lower temperature, the yield stress of the bulge area is higher than forming pressure, and thus, a disc-shape tube occurred. The results clarify the importance of preheating time to prevent defects such as disc-shaped tubes. As it was mentioned before, the axial feeding improves the formability; however, it should occur right after the start of bulging at a proper temperature range. Otherwise, if axial feeding applies prior to bulging, wrinkles or disc-shape tubes could be formed.

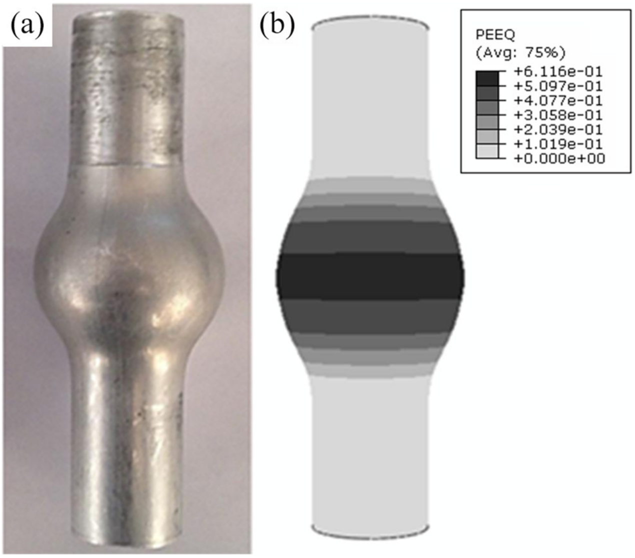


Fig. 9 Comparison between the deformed tubes shapes by experimental (a) and numerical (b) investigations

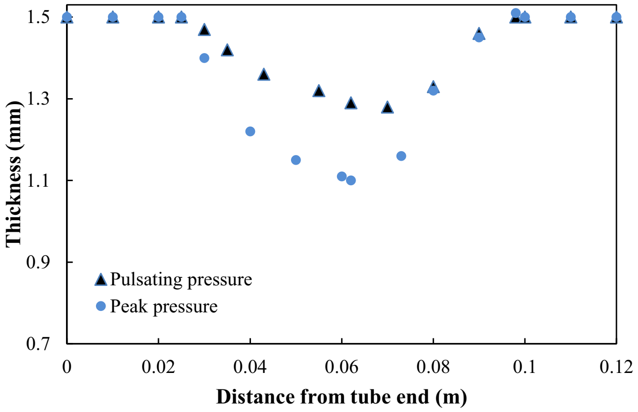


Fig. 10 Wall thickness distribution along the tube obtained by experiments

3.5 Influence of pulsating pressure amplitude and frequency on deformation behavior of the tube

Figure 18 shows the parts formed by three different amplitudes of the pulsating pressure path. It can be observed that the deformation behavior is greatly affected by the

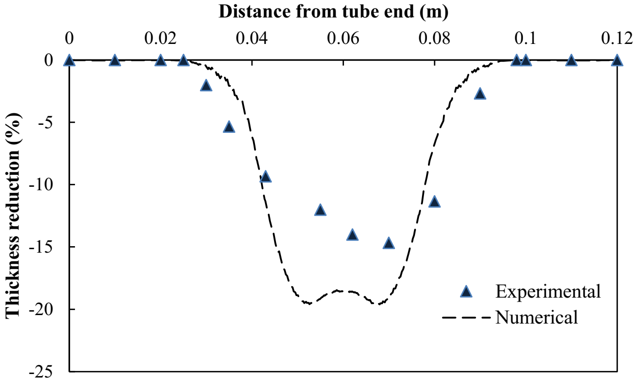


Fig. 11 Comparison between the numerical and experimental results of the wall thickness reduction through longitudinal direction of deformed tubes with 10 mm of axial feed

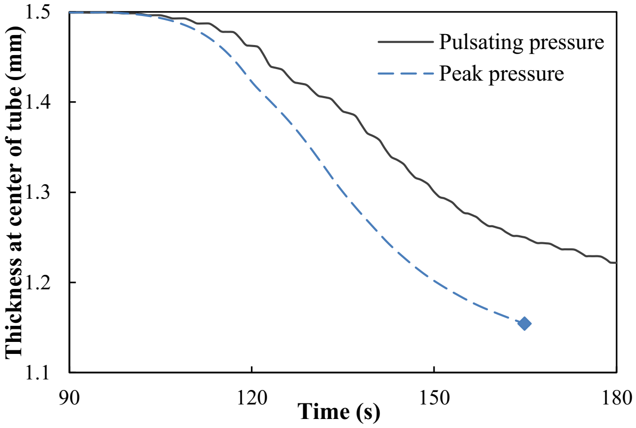


Fig. 12 Effect of the pulsating and peak pressure paths on the thinning behavior at the center of tube obtained by FE simulations

amplitude of the pressure. A uniform expansion is formed for the amplitude of 0.15 MPa, whereas the melting phenomenon and local bulging occur for the pressure amplitudes of 0.05 and 0.25 MPa, respectively. It should be noted that for the small amplitude, the deformation behavior of the tube becomes similar to that of the non-pulsating peak pressure. However, when the amplitude increases, the average of pulsating pressure becomes smaller. If the average of pulsating pressure is below the yielding pressure of the tube material, it leads to the reduction of the plastic deformation. Consequently, a pulsating pressure path with a very large amplitude is not able to influence the plastic deformation of the tube.

The effect of the pressure amplitude of pulsating pressure was investigated by the FE simulation and compared in Fig. 19. Four different amplitudes of 0.25, 0.15, 0.1, and 0.05 MPa, with the same frequency and axial feeding were studied by the finite element method. The results show that the increase of the amplitude leads to less reduction of wall thickness. According to Fig. 13, the thickness reduction in each cycle of pulsating pressure is related to the pressure amplitude and when the amplitude decreases, the thickness reduction increases and gets close to thickness of non-pulsating pressure.

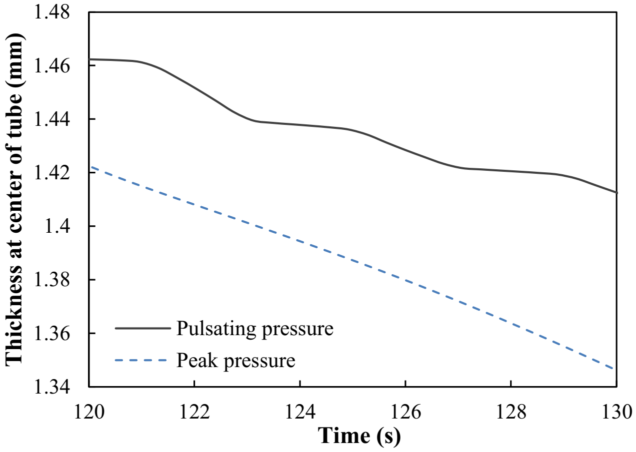


Fig. 13 Thinning behavior for peak and pulsating pressures in one cycle of pulsating pressure path

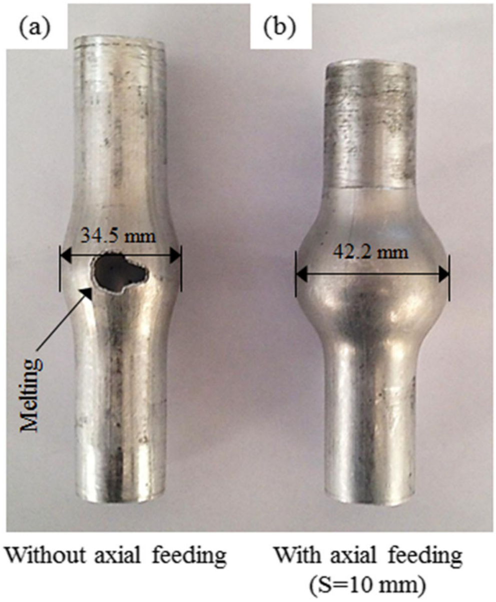


Fig. 14 The formed tubes by pulsating pressure (a) without axial feed and (b) with 10 mm of axial feed

The wall thickness distribution of the tubes obtained by the simulation for amplitudes of 0.15 and 0.05 MPa is compared in Fig. 20. It can be seen that the wall thickness distribution of the deformed tube by amplitudes of 0.15 MPa is more uniform and that the thickness distribution has been improved significantly.

Figure 21 shows the experimental results of the tubes formed by different frequencies for $\Delta P = 0.15$ MPa. It can be observed that when the frequency increases, the bulge height is increased. The experimental results show that when

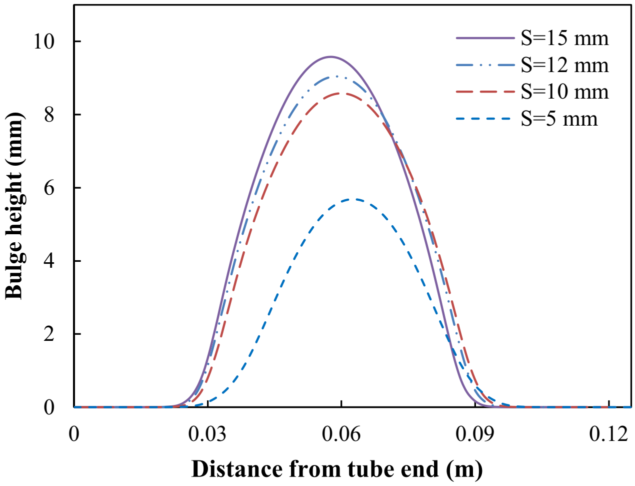


Fig. 15 Effect of strokes (axial feeding) on the bulge heights of the tubes obtained by FE simulations

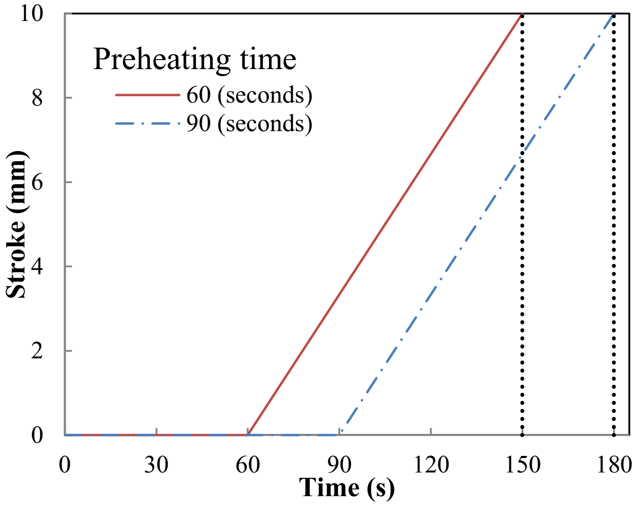
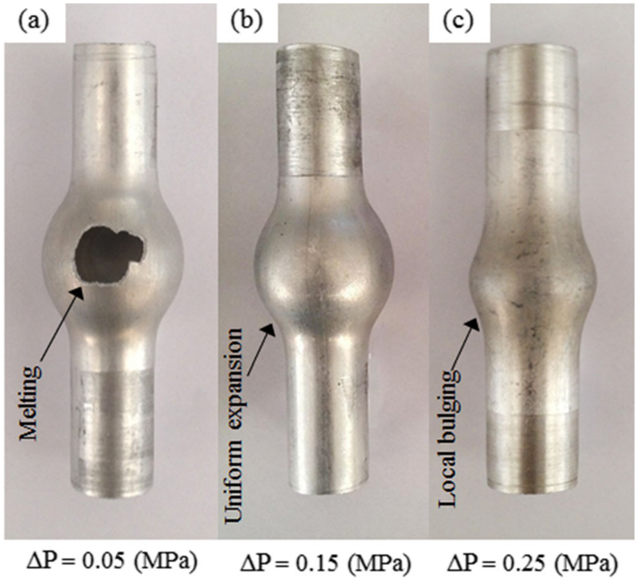


Fig. 16 Stroke-time curves for different preheating conditions

the frequency increases, the total number of the hammering impacts of internal pressure caused by the oscillating pressure is increased in an equal forming time, and thus, the amount of expansion or bulge height is increased.

Figure 22 shows the FE results of the variation of the wall thickness at the center of the protrusion in different frequencies. It can be seen that the thickness of the tube decreases when the frequency increases.



ΔP = 0.05 (MPa) ΔP = 0.15 (MPa) ΔP = 0.25 (MPa)

Fig. 18 Tubes deformed by different amplitudes obtained by experiments ($f = 0.25$ Hz)

4 Conclusion

In this paper, the effect of pulsating pressure on hot gas bulging is investigated with an innovative technique and an oscillating heating mechanism. An oscillating flame mechanism was successfully used to make a uniform temperature distribution on the bulging area. The experimental and numerical results showed that pulsating pressure has a significant effect on both deformation behavior and wall thickness of the tube in the hot metal gas bulging process. It was shown that the expansion ratio for the deformed bulge height has been increased to 69%. It was concluded that the formability could be improved by utilizing pulsating oscillations. Thus, the bursting was postponed by the pulsating gas pressure and the tubes which are formed using this procedure lead to more complex components with higher expansion and more uniform thickness distribution. To enhance the effect of pulsating pressure, choosing proper axial feeding and preheating time is essential to improve the formability. It was found that the axial feeding intensifies the effect of pulsating pressure on formability and it should

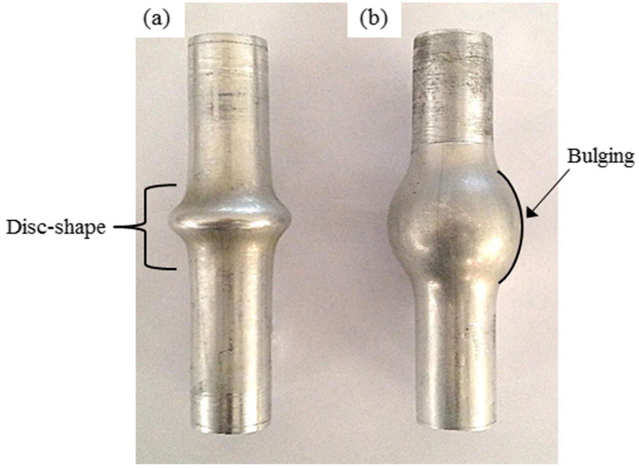


Fig. 17 Comparing the formed tubes (a) preheating time = 60 s, (b) preheating time = 90 s

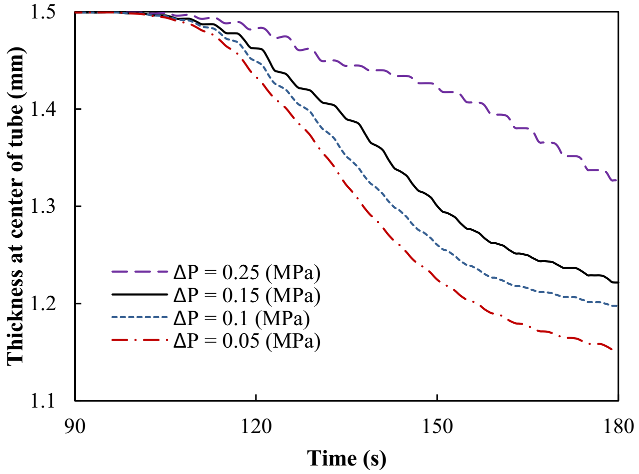


Fig. 19 Effect of pressure amplitude on the thickness variation during pulsating gas bulging, obtained by FE simulation ($f = 0.25$ Hz)

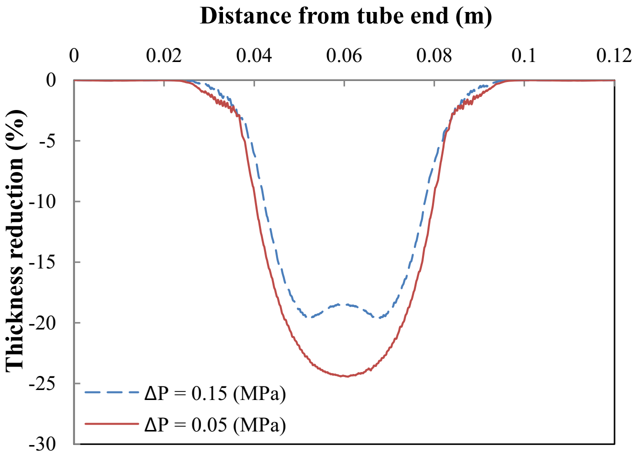


Fig. 20 Comparison of tube wall thickness distribution for different pressure amplitudes, obtained by FE simulation ($f = 0.25$ Hz)

be applied right after the start of bulging at a proper temperature to prevent wrinkles or disc-shaped tubes.

The effects of pressure amplitude and frequency on the deformation behavior of the tube were investigated by experiments and finite element simulations. It was concluded that reducing the amplitude of the pulsating pressure decreases the wall thickness. In addition, large amplitudes are not able to deform the tube sufficiently. The pressures which are lower than the yielding pressure are less effective in a plastic deformation and lead to lower bulge heights. It was also shown that the thickness of the tube decreased by increasing the frequency of the pulsating pressure path.

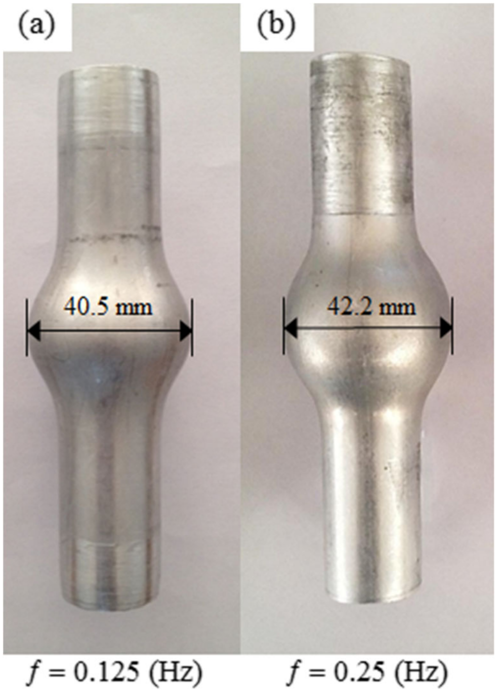


Fig. 21 Tubes deformed by different frequencies obtained by experiments ($\Delta P = 0.15$ MPa)

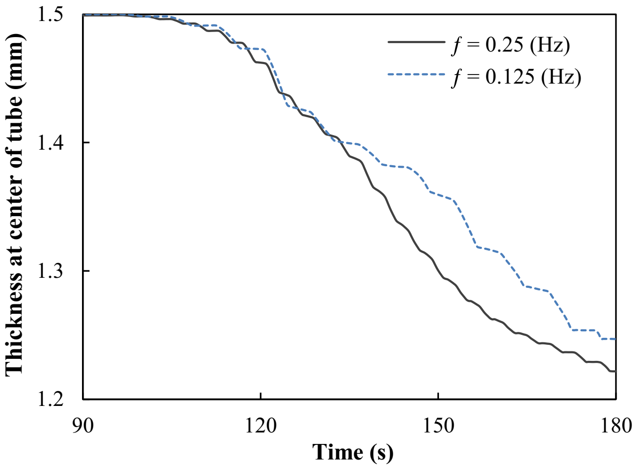


Fig. 22 Effect of the frequency on the thinning behavior at the center of the protrusion obtained by FE simulations ($\Delta P = 0.15$ MPa)

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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