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ARTICLE

Simulation Research on Effect of Extrusion Parameters on Welding Pressure During Porthole Extrusion Process of AZ91 Pipe Through Angle Welding Chamber Die

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Abstract: A novel porthole extrusion process combined with corner extrusion principle for AZ91 pipe was presented. This new extrusion process can not only extend the length of the welding chamber, but also increase the rigidity of the latch needle, thereby ensuring the dimensional accuracy of pipe. Meanwhile, this new extrusion method can increase the deform degree and improve the dynamic recrystallization of the pre-welded metal, which can improve the welding quality and pipe quality. Then, the metal flowing characteristic, distribution feature of effective strain and mean stress in the corner porthole chamber were revealed; the results show that the effective strain of the separated metal becomes larger after flowing through the corner of the welding chamber, which can promote the quality of the welding seam. And the mean stress in the welding chamber is larger than 240 MPa, which satisfies the welding pressure condition. The influence rules of extrusion speed, die angle and billet preheating temperature on the mean stress in the welding chamber were also discussed; the result shows that the higher extrusion speed and the higher preheating temperature of the billet can enhance the mean stress in the welding chamber, which can improve the welding quality. The larger die angle can lead to higher mean pressure.

Key words: AZ91 magnesium alloy; porthole extrusion; angle welding chamber; mean stress

Due to the lower density, higher specific strength and completed recyclability of magnesium alloy, the pipe made of it has been widely used in many significant industries such as transportation and aerospace. The magnesium alloy pipe can be manufactured by needle extrusion process and porthole extrusion process, while the porthole extrusion process is the primary method to extrude magnesium alloy pipe due to its higher size precision and higher production efficiency[1,2]. Nonetheless, the quality of the welding seam in the porthole extrusion pipe can noticeably affect the pipe's forming property and usability. And cracking will occur across the welding line in the subsequent forming process[3]. Fig.1 shows the weld line cracking in the bulging process and flaring process of the pipe formed through porthole extrusion method.

The traditional porthole extrusion method to produce the pipe is shown in Fig.2a. In order to improve the strength of welding seam of the pipe in the porthole extrusion process, many researches have been carried out on the die structure and metal deformation feature. He[5] studied the effects of welding chamber height on the welding quality of AA6061 pipe, and the result showed that larger welding height can result in a better welding quality. Yu[6] studied the effect of welding chamber height on the welding quality of AA6063 profile, and the microstructure of the weld seam was observed; it is concluded that the larger height of welding chamber can lead to a better welding quality. Liu[7] studied the effect of die structure on the welding quality of AA6061 pipe, and the results showed that with the increase of welding height, the welding pressure on the welding plane increases, and the effective stress decreases. This can lead to a higher pressure-to-effective stress ratio, which will be more conducive to the welding quality improvement. Kim[2] studied the influence of

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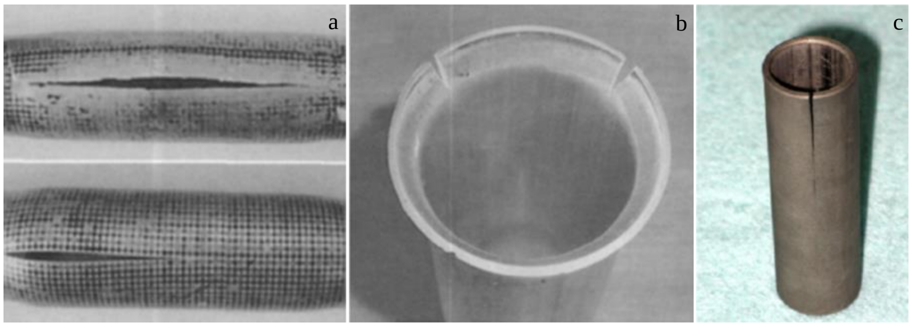

Fig.1 Cracking of the welding line of the pipe formed by the porthole extrusion method in bulging process[3] (a), extension process[3] (b), and push bending process[4] (c)

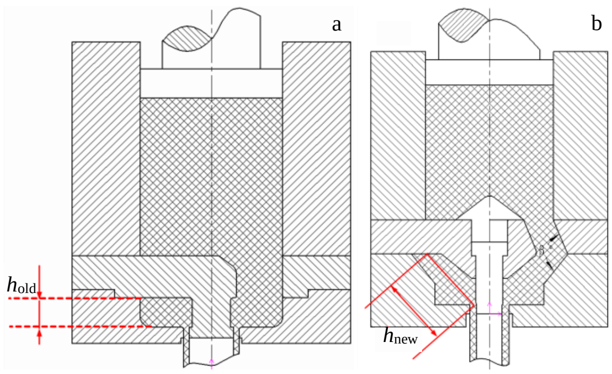

Fig.2 Present pothole extrusion method: (a) traditional extrusion and (b) welding chamber with angle

die structure on the welding quality of Al3003 pipe, and found that the higher welding chamber can lead to higher strength welding quality of the pipe.

It can be found from above researches that the welding quality of the pipe in the porthole extrusion process can be enhanced by higher welding chamber. However, the higher welding chamber needs longer mandrel, which will decrease the stiffness of the mandrel, and decrease the precision of the pipe thickness[8,9].

Therefore, it is incompatible to improve the precision of the pipe thickness and strength of welding seam in the traditional extrusion process (Fig. 2a). Therefore, in this study, a novel extrusion method was proposed to solve the contradiction of improving strength and precision of the pipe mentioned above. The principle of the new extrusion method is shown in Fig. 2b. It can be seen from Fig. 2b that the welding chamber length becomes larger than that produced by traditional pothole extrusion method (Fig. 2a), and this will be beneficial to improve the welding quality. It can also be seen from Fig. 2b that the split metal will undergo shear deformation when it flows through the corner constituted by bottom die and porthole die. Also, some research reported that the welding quality can be improved with the increase of deformation degree of the pre-weld metal[7]. So the shear deformation of the pre-welded metal flowing through the corner of the weld chamber can enhance the welding quality.

However, the flow behavior of the metal in the new porthole extrusion method will become very complex due to the intense thermo-mechanical coupling effect caused by shear deformation mechanism. And this will affect the welding pressure, welding temperature and the strain. Therefore, it is necessary to reveal the influence rules of the key extrusion parameters on the deformation behavior of the metal in the new extrusion process. But it is difficult to obtain the filed information including welding pressure, deformation status, etc by experiment, while the finite element method is convenient and fast.

Therefore, in this study, the finite element method was firstly developed and verified based on the DEFORM-3D platform and experimental extrusion of AZ91 plate. And then, the metal flow behavior, deformation status and distribution of mean pressure in the corner porthole extrusion process were revealed. Finally, the influence rules of key extrusion parameters on the deformation temperature, welding pressure and deformation status of the pipe were revealed. The obtained result can provide very useful guidance for improving the welding quality of pipe in the porthole extrusion process.

1 Development of Finite Element Model

The accurate and reliable finite element model is firstly needed for researching the magnesium profile extrusion process by finite element method. However, for obtaining the accurate and reliable finite element model, the accurate model information including precise boundary conditions (friction coefficient, heat transform coefficient, etc), accurate material model and reasonable mesh distribution is the primary condition. Therefore, in this section, the needed information mentioned above for the development of finite element model is verified and ensured.

1.1 Geometry model

Due to the similar forming principle of the plate extrusion and pipe extrusion, the needed information for the finite element model of these two extrusion processes can be used commonly. Therefore, AZ91 plate extrusion process is simulated to verify the accuracy of the information for the finite element model. In Ref.[10], the AZ91 plate with the size of $w \times t$=30 mm×3 mm (w is the width, t is the thickness) was experimentally extruded, and the extrusion load in the extrusion process was recorded by computer. The information about geometry model was also reported, as shown in Table 1. According to the information in Table 1, the geometry model for the AZ91 plate extrusion was redeveloped, as shown in Fig.3.

1.2 Material model and boundary conditions

1.2.1 Material model

The needed information for the material model in the FE model includes constitutive model of material and physical parameters of material.

The constitutive model of AZ91 can be obtained from Ref.[11], which can be expressed as Eq.(1). In this formula, R is gas constant, whose value is 8.314 J/(mol·K), T is the deformation temperature of the billet and the value of other parameters in Eq.(1) is shown in Table 2.

The needed physical parameters include elasticity modulus, Poisson's ratio, heat conductivity and specific heat. Their values for AZ91 are shown in Table 3.

$$\dot{\varepsilon} = A[\sinh(\alpha\bar{\sigma})]^n e^{-\Delta H/RT_{abs}} \quad (1)$$

1.2.2 Boundary condition

The necessary boundary conditions for the FE model includes friction coefficient, heat transform coefficient between billet and extrusion tools, heat radiation coefficient of

Table 1 Information of geometry model [10]

Object	Label	Value
Billet size/mm	$\varphi \times L$	47×200
Container size/mm	φ	50
Extruded plant size/mm	$w \times t$	30×3

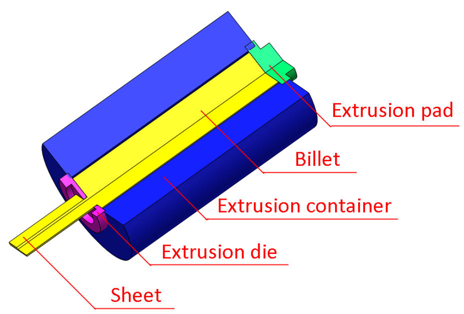

Fig.3 Geometry model for AZ91 plate extrusion process

Table 2 Parameter of Eq.(1) [11]

Parameter	Value
$A/\times10^{12}$	5.8405
α	0.021
n	5.578
$\Delta H/\times10^5$	1.77

Table 3 Needed material model information for FE model[11]

Parameters	Value
Elasticity modulus/GPa	45
Poisson's ratio	0.35
Heat conductivity	96
Specific heat/N·mm^{-2}·°C^{-1}	2.096

billet and extrusion tools, and heat convection coefficient between heated billet and environment. Due to the high sensitivity of deformation behavior of AZ91 magnesium alloy to the deformation temperature, the heat loss in the billet transfer process from heat furnace to extrusion container is necessary to be considered. So the heat convection between heated billet and environment is opened in FE model, and the heat convection coefficient is set as 0.02 N·mm^{-1}·°C^{-1}. According to Ref.[10], in the extrusion process of AZ91 magnesium alloy, the heated billet directly contacts with extrusion tools without lubricant, so the shear friction model is used in this FE model, and the friction factor μ=1 is used in current study. Heat transform coefficient between billet and extrusion tools is set as H_{trs}=11 N·mm^{-1}·°C^{-1}. The heat radiation coefficient of AZ91 magnesium alloy and H13 steel is set as 0.12 and 0.7, respectively. In a brief, the needed information for the boundary condition is shown in Table 4.

1.3 Finite element model

In the section above, the geometry model, material model and the boundary conditions for the FE model are described. In this section, the FE model for the extrusion process of AZ91 profiles is established based on the DEFORM-3D platform. Due to the geometry plane symmetry of the extrusion model, the quarter model is simulated. Firstly, the geometry model is saved as STL stile format, and then imported into DEFROM-3D software through pre-processor module. Secondly, the billet and extrusion tools are meshed, and the meshed module can be seen from Fig.4. In order to ensure simulation efficiency and accuracy, the locally refined mesh is used, and the refine ratio is set as 0.01. Thirdly, the material model and boundary conditions are also added to the

Table 4 Boundary condition information for FE model[10]

Parameter	Value
Friction coefficient between billet and extrusion tools	1
Heat transform coefficient between billet and extrusion tools/N·mm^{-1}·°C^{-1}	11
Heat radiation coefficient of AZ91 billet	0.12
Heat radiation coefficient of H13 extrusion tools	0.7
Heat convection coefficient between heated billet and environment	0.02

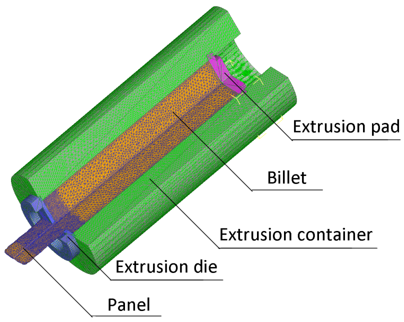

Fig.4 Meshed FE model of AZ91 plate

pre-processor module, and the simulation steps, increment of solution step and stop condition are defined as well in pre-processor module. And then, the DB files can be generated, and the extrusion process can be simulated.

1.4 Verification of finite element model

Extrusion load is the comprehensive expression of the friction and material deformation character under different deformation conditions, which is widely used to verify the accuracy of the FE model[12-14]. Therefore, the simulated and experimental extrusion loads are also used to verify the accuracy of current FE model. Fig.5 shows the simulated and experimental extrusion load under the extrusion condition shown in Table 1, Table 2 and Table 3. It can be seen that a good match between simulated and experimental results can be observed, and the maximum relative error calculated through Eq.(2) is 5.6% (F_{sim} is the simulated extrusion load, F_{exp} is the experimental extrusion load). These indicate that the developed FE model can precisely describe the deformation behavior of AZ91 magnesium alloy in the extrusion process, so the material model, boundary conditions and mesh method used in this FE model is fairly reasonable, which can be used to simulate the deformation behavior of the AZ91 pipe in the porthole extrusion process.

$$F_{error} = \frac{|F_{exp} - F_{sim}|}{F_{exp}} \times 100\% \quad (2)$$

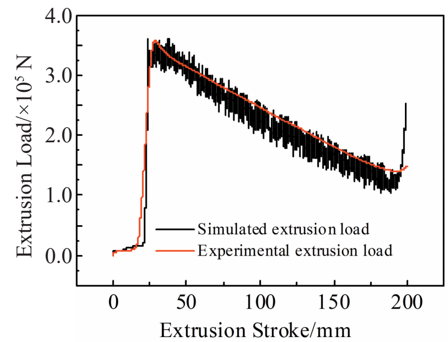

Fig.5 Comparison of extrusion load between the simulated and experimental results

2 Deformation Process of Pipe in the Extrusion Process of Corner Porthole Die

The needed information for the finite element model is verified in above section. Based on the accurate boundary condition and the material model, the finite element model for the corner porthole extrusion of AZ91 pipe is developed. The deformation behavior of the pipe in the extrusion is analyzed.

2.1 Extrusion conditions for corner porthole extrusion of AZ91 pipe

In current study, the simulated cylinder billet size is $\varphi\times L$=120 mm×220 mm, the extruded pipe size is $\varphi\times t$=70 mm×6 mm, the extrusion ratio is λ=9.375. The deformation temperature is 420 °C, and extrusion speed is 5 mm/s. The material model and boundary conditions used in this section are the same as those in the section above. In summary, the simulation information for the pipe extrusion process of corner porthole die is shown in Table 5.

2.2 Deformation procedure

2.2.1 Deformation behavior of billet in the extrusion process

(1) Metal flow behavior

The metal flowing behavior of metal has a significant effect on the control of pipe quality[15], so it is necessary to reveal the flowing behavior of metal. The metal flowing behavior in the

Table 5 Boundary condition information for FE model[10, 11]

Parameter	Value
Billet size, $\varphi\times L$/mm	120×220
Pipe size, $\varphi\times t$/mm	70×6
Extrusion ratio, λ	9.375
Initial billet temperature/°C	420
Extrusion speed/mm·s^{-1}	5
Corner angel of welding chamber/(°)	50
Friction coefficient between billet and extrusion tools	1
Heat transform coefficient between billet and extrusion tools N·mm^{-1}·°C^{-1}	11
Heat radiation coefficient of AZ91 billet	0.12
Heat radiation coefficient of H13 extrusion tools	0.7
Heat convection coefficient between heated billet and environment	0.02

extrusion process can be seen from Fig.6, and it can be found that the billet is separated when it flows through the porthole die. Also, the separated metal is expanded to a degree due to the larger diameter of the porthole die at the corner (Fig.6b).

Next, the separated metal flows through the corner (Fig.6c), which will result in shear deformation. And then, with the extrusion process proceeding, the welding chamber is filled gradually (Fig. 6b~6e). Finally, the welded metal is extruded through the die exit to form the pipe (Fig.6f and Fig.6g).

(2) Effective strain evolution

The evolution of the effective strain in the extrusion process of corner weld chamber is observed, as shown in Fig.7. It can be seen from Fig.7a that the effective strain increases greatly when the separated metal flows through the corner due to the corner shear deformation mechanism. Fig.7b shows the values of effective strain of the observed points shown in Fig.7a. We can find that the effective strain can reach 1.4. This can induce a completed dynamic recrystallization of the deformed AZ91 magnesium alloy, which is beneficial to reinforce the quality of the welding seam.

2.2.2 Evolution behavior of mean stress in the extrusion process

Mean stress in welding chamber is a very important index to measure the welding quality[16,17], and the higher mean pressure signifies the better welding quality. Moreover, the value of the mean pressure must be higher than the yield strength under the immediate deformation condition.

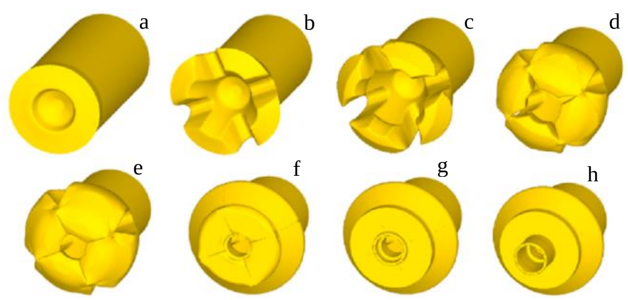

Fig.6 Metal flowing behavior in the extrusion process: (a) step 30, (b) step 70, (c) step 100, (d) step 150, (e) step 190, (f) step 220, (g) step 260, and (h) step 290

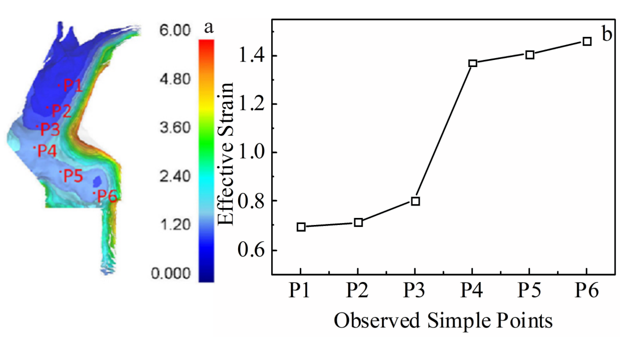

Fig.7 Effective strain distribution (a) and values (b) of the separated metal in the extrusion process of corner porthole die

Fig.8a shows the mean stress under the extrusion condition in Table 4. We can find that the distribution of mean pressure is relatively uniform. The strength of mean pressure can be higher than 270 MPa, which is much higher than the yield strength of AZ91 magnesium alloy under the deformation condition (less than 50 MPa). This indicates that the excellent pressure condition for getting a higher welding quality can be obtained in the corner welding chamber extrusion process.

Fig. 8b exhibits the distribution of the mean stress in the welding chamber along the radial direction, and it can be found that the mean stress increases from inner to outer in the radial direction. Apart from this, it can also be found that the pressure decreases gradually with the point approaching the die exit.

3 Effect of Key Extrusion Parameters on the Mean Stress

3.1 Extrusion conditions

In the extrusion process of AZ91 pipe, the extrusion speed and billet preheat temperature are two key extrusion parameters to control the pipe's quality, so it is necessary to understand the effects of these two extrusion parameters on the welding pressure. Except this, the effect of die angle on the mean pressure is also discussed. In order to reveal the influence law of these three extrusion parameters on the mean pressure, the following simulation conditions are used.

(1) For revealing the influence rule of the billet preheating temperature T_0 on the mean pressure, take T_0 as 380, 400, 420, and 440 °C, and keep other extrusion parameters unchanged, including extrusion speed v=5 mm/s, die preheating temperature T_m=400 °C. Meanwhile, maintain other needed simulation information the same as that shown in Table 2 and Table 4.

(2) In order to reveal the effect law of extrusion speed v on the mean pressure, take v as 2, 4, 6, 8, and 10 mm/s, and keep other extrusion parameters at a constant, including billet preheating temperature T_0=410 °C, die preheating temperature T_m=400 °C. At the same time, keep other needed simulation

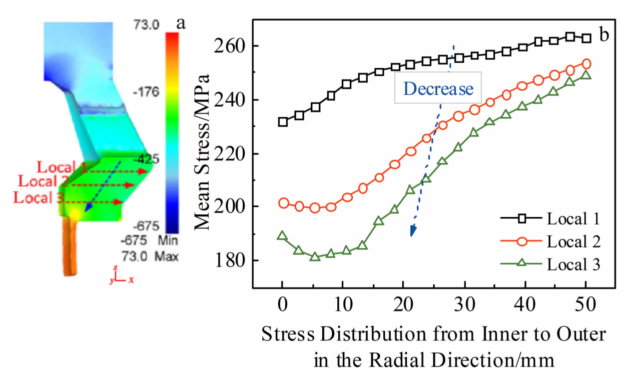

Fig.8 Mean stress distribution in welding chamber (a) and change of mean stress in the diameter direction at different locations (b)

information the same as that shown in Table 2 and Table 4.

(3) For revealing the influence rule of the angle β on the mean pressure, take β as 105°, 110° 115°, and 120°, and keep other extrusion parameters unchanged, including extrusion speed v=5 mm/s, die preheating temperature T_m=400 °C, billet preheating temperature T_0=410 °C. Meanwhile, maintain other needed simulation information the same as that shown in Table 2 and Table 4.

In current study, the iso-surface of mean stress in the welding chamber is presented and analyzed. Besides, the average value of the 60 sample points shown in Fig.8 is used to represent the measurement index of mean stress in the welding chamber.

3.2 Extrusion speed

The iso-surface of mean stress under different extrusion speeds in the welding chamber can be seen from Fig. 9. We can find that the mean stress value becomes smaller when the stress surface is close to the die exit. And with the increase of extrusion speed, the stress surface face with smaller value shrinks. This indicates that the mean stress in the welding chamber increases with extrusion speed.

It also can be found from Fig. 10 that the average mean stress in the welding chamber increases with extrusion speed. The reason for this phenomenon can be explained by the fact that increasing the extrusion speed can result in more metal flowing into the welding chamber, and the larger extrusion speed can lead to higher flowing speed of the metal, which can lead to the increase of the welding pressure in the welding chamber.

3.3 Billet preheating temperature

The iso-surface of mean stress at different billet preheating

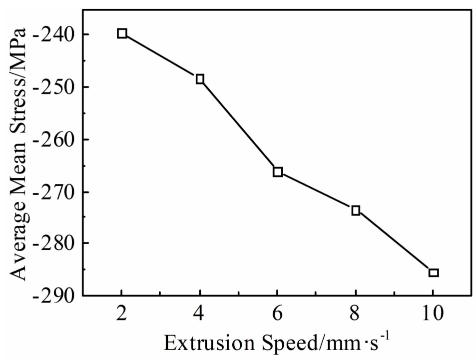

Fig.10 Effect of extrusion speed on the average mean stress in the welding chamber

temperatures is shown in Fig. 11. It can be seen that the value of the stress surface increases with billet preheating temperature. Meanwhile, the stress surface with smaller value at the die exit becomes smaller with the billet preheating temperature.

At the same time, the influence rule of the billet preheating temperature on the welding pressure can be seem from Fig.12. We can find that the welding pressure increases firstly and then decreases. The reason for this is that the flow stress of the AZ91 alloy is larger when the pipe is extruded at lower temperatures, so the friction force between billet and extrusion die becomes larger, which can hinder the flowing of the metal.

With the increase of the preheating temperature, the friction between billet and extrusion die becomes smaller due to the lower deformation resistance, and this can increase the

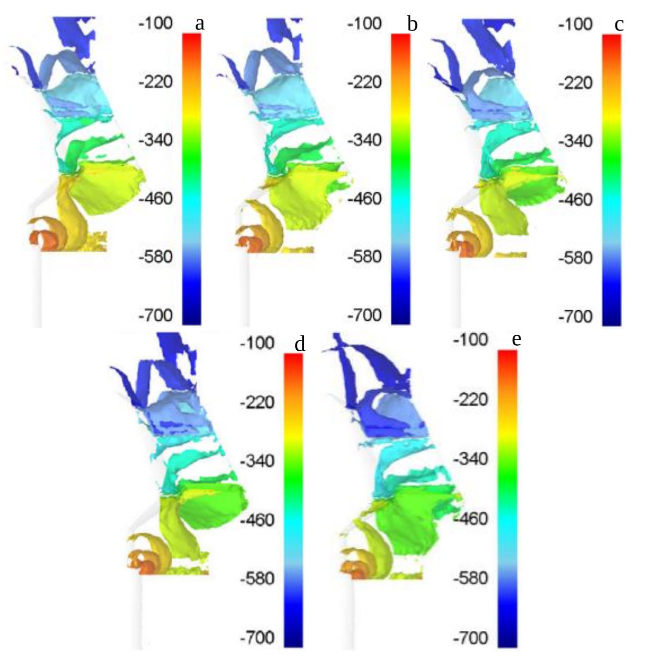

Fig.9 Iso-surface of mean stress in the welding chamber at different extrusion speeds: (a) v=2 mm/s, (b) v=4 mm/s, (c) v=6 mm/s, (d) v=8 mm/s, and (e) v=10 mm/s

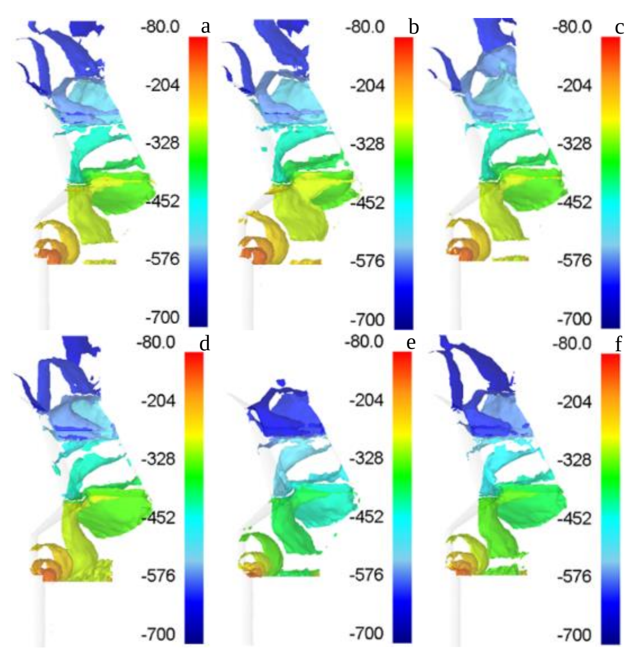

Fig.11 Iso-surface of mean stress at different billet preheating temperatures: (a) T_0=380 °C, (b) T_0=390 °C, (c) T_0=400 °C, (d) T_0=410 °C, (e) T_0=420 °C, and (f) T_0=430 °C

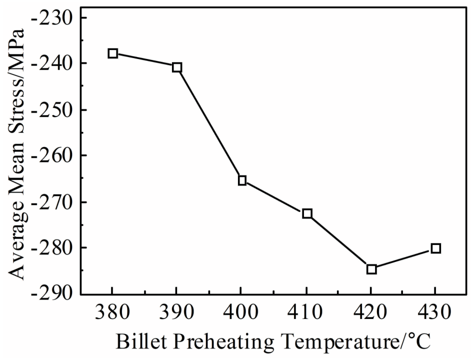

Fig.12 Effect of billet preheating temperature on the average mean stress in welding chamber

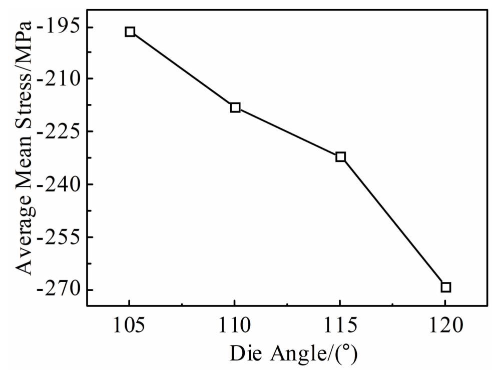

Fig.14 Effect of die angle on the average mean stress in the welding chamber

flowing ability of the metal in the welding chamber. Therefore, the welding pressure increases with increasing the preheating temperature from 380 °C to 420 °C. And then, as the preheating temperature of the billet increases from 420 °C to 440 °C, the flowing resistance can further decrease, which can further improve the flowing ability of the metal in the welding chamber to exit to form the pipe, and decrease the mean stress in the welding chamber.

3.4 Die angle

The iso-surface of mean stress at different angles is shown in Fig. 13. It can be found that the mean pressure value and volume in the chamber increase with the die angle. The reason for this is that the larger angle can improve the flowing ability of the metal in the extrusion direction, which can lead to the increase of the mean stress.

Fig. 14 shows the effect of the die angle on the mean stress in the welding chamber with angle. It can be found that the average value of the mean stress increases with increasing the die angle. Therefore, this indicates that the chamber with a bigger angle can improve the welding quality of the AZ91 pipe.

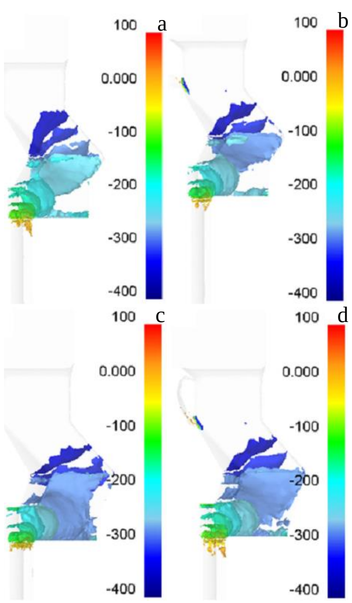

Fig.13 Iso-surface of mean stress at different die angles: (a) β=105°, (b) β=110°, (c) β=105°, and (d) β=120°

4 Conclusions

1) The deformation degree of the pre-welding metal can be improved, and the length of the welding chamber can be extended through combining channel angular extrusion technology with the porthole extrusion process, which can effectively enhance the welding quality of AZ91 pipe.

2) With the increase of extrusion speed, the welding pressure increases. With the increase of billet preheating temperature, the welding pressure firstly increases and then decreases, so the temperature range T_0=400~420 °C is recommended for the practical extrusion process.

3) The mean stress in the welding chamber increases with die angle increasing in the range of β=105°~120°.

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基于数值模拟的挤压参数对AZ91镁合金管转角焊合室分流挤压焊合压力的影响规律研究

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摘　要：提出了一种镁合金管材转角焊合室分流挤压新工艺，该工艺可在有效延长焊合室长度和焊合时间前提下保证舌针刚度，从而保证管材尺寸精度，并且可通过转角剪切变形机制增加预焊合金属变形量和动态再结晶程度，从而有利于提高管材性能和焊缝焊合性能。利用有限元法揭示了转角焊合室分流挤压成形过程中金属的流动特征，应变分布特征和焊合室内的静水压力分布特征。结果表明，整个挤压过程无金属折叠，从而保证管材的表面质量；流经转角后预焊合金属变形量明显增加，有利于提高管材质量和焊缝质量。最后，研究揭示了坯料初始温度，挤压速度和模具转角对焊合室内静水压力的影响规律。结果表明，随着挤压速度的增加和模具转角的增大，转角焊合室内静水压力增大；随着坯料预热温度的增加，转角焊合室内静水压力呈先增大后减小的趋势。

关键词：AZ91镁合金；分流挤压；转角焊合室；静水压力

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