

Effect of process parameters on sheath forming of continuous extrusion sheathing of aluminum

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Abstract: The effect of flow passage length in the die cavity and extrusion wheel velocity on the shape of aluminum sheath during the continuous extrusion sheathing process was analyzed by using finite element methods based on software DEFORM 3D and experimentally validated. The results show that by increasing the flow passage length, the velocity of metal at the cross-section of sheath tends toward uniformity, the values of the bending angles of sheath gradually approach the ideal value of zero and the cross-section exhibits a better shape. The extrusion wheel velocity has negligible effects on the bending shape and cross-section of the sheath product when a long flow passage is used.

Key words: continuous extrusion sheathing; aluminum sheath; sheath forming; die design; extrusion wheel velocity; finite element

1 Introduction

The continuous extrusion aluminum sheathing process based on the continuous extrusion technology presents the advantages of high efficiency and substantial energy conservation. This technology uses the frictional forces generated between the wheel and feedstock as the driving force to continuously produce products of unlimited length. The continuous extrusion sheathing process can produce aluminum sheath as a loose fit around a core cable, and this process is called the indirect cladding process [1,2]. Continuous extrusion sheathing technology is an ideal production process for fabricating external protection for cable sheaths, which is one of the key factors to ensure the cable service life [3]. With the increase of electricity consumption, more and more high voltage cables with large section are needed [4]. Hence, it is necessary to research that how to produce larger section and better quality of the cable aluminum sheath. As shown in Fig. 1, a rotational extrusion wheel has two grooves in its periphery, which accommodates two aluminum rods and transfers the metal to the fixed chamber. In the chamber, the plasticized aluminum from

two grooves converges and is welded around the mandrel before exiting from the die in the form of a near-seamless tube. Meanwhile, the core wire is fed through the hollow mandrel in the tangential direction, and the aluminum tube is wrapped loosely around the cable core for fabricating into a sheathing product.

The geometry of the die chamber is complicated. Thus, metal flow during the entire continuous sheathing process is complex. The current understanding of metal flow in the continuous sheathing process is mostly based on the earlier research conducted with basic experiments, photo plastic simulation, and analytical studies. By establishing photo plasticity experimental procedures, the three-dimensional strain distributions in the die chamber were obtained [5,6]. Using experimental studies as bases, SONG et al [7] and LIU et al [8] established the theoretical velocity field in the deformation zone and put forward the theoretical expressions related to the geometric parameters of the convergence chamber and homogeneity of metal flow. These methods are constrained when incorporating thermal effects into the process, and therefore have limited practical use in optimizing die design and sheathing extrusion. Few studies that explore the continuous extrusion sheathing

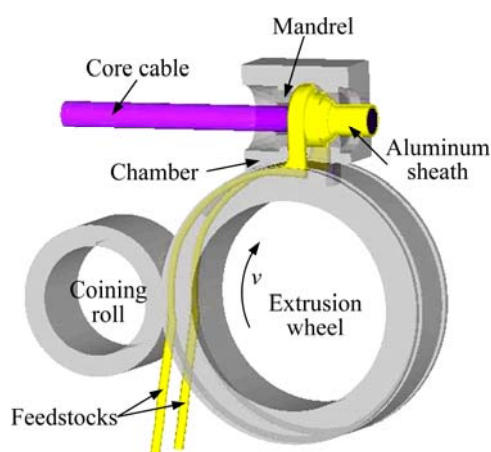


Fig. 1 Principle of continuous extrusion sheathing

process, especially under the 3D finite element mode, have been conducted.

In the continuous extrusion aluminum sheathing process, metal flows through the die bearing tend to bend up or down with an elliptical cross-section, especially for a sheath of large diameter. Difficulty is encountered as the cable core enters the aluminum sheath with a large bending angle. Non-uniform metal flows cause bends and twists at the die outgoing port in continuous extrusion process [9]. ZHAO et al [10] proposed that non-uniform metal flow is caused primarily by the up-down non-symmetrical structure of the die cavity, which can cause different flow resistances and varied temperatures in the die cavity. The current work aims to minimize the bending phenomenon and elliptical cross-section using FEM simulation to select the appropriate combination of die cavity design and process parameters.

In the continuous extrusion process, no pre-heating of feedstock is conducted and the adjustable process parameters are less than conventional extrusion. The extrusion wheel velocity is one of the most important process parameters because it affects the maximum temperature and uniformity of metal flow in the continuous extrusion process. Some researchers studied the influence of the extrusion wheel velocity on the continuous extrusion process by FEM simulation. KIM et al [11] revealed that the wheel driving velocity did not cause remarkable changes on the material flow, unless it reached an extremely high value. CHO et al [12] investigated the influence of wheel velocity on surface defect occurrence, while WU et al [13] analyzed the distributions of effective stress, effective strain, and temperature of copper concave bus bar under different extrusion wheel velocities. This work focuses on investigating the influence of the extrusion wheel velocity on the shape of product.

The die cavities with different horizontal passage

lengths were designed and the extrusion wheel velocity was varied. The extrusion velocity, temperature, extrusion wheel torque, bending phenomenon, and cross-section shape of aluminum sheath were predicted and experimentally validated. A production sheath with an external diameter of 45 mm and a thickness of 2 mm was simulated using DEFORM 3D.

2 Design of die cavity with different flow passage lengths

Figure 2 shows the longitudinal section of the flow passage in the die cavity, which is composed of the chamber, mandrel, and dies. The flow passage in the chamber is the space where the metals from different grooves converge, weld, and form the final round shape. Passage length H consists of two parts: H_1 and H_2 , where H_1 denotes the horizontal flow passage and H_2 represents the preformed passage. The die cavities with horizontal passage lengths (H_1) of 37, 44, 51 and 58 mm were adopted in the extrusion simulation. When H_1 is changed, the value of H_2 is fixed.

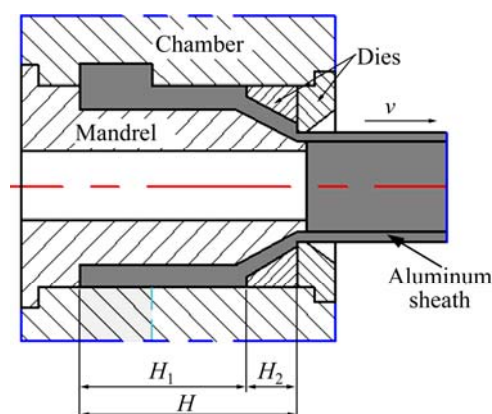


Fig. 2 Schematic diagram of flow passage in die cavity

3 Finite element model

A sophisticated finite element model was employed to investigate the continuous extrusion sheathing process and optimize the tool design by an commercial software DEFORM 3D. The software adopts implicit FEM to calculate the rigid-visco-plastic deformation behaviour of the workpiece incorporated with thermal effects [14]. The material properties of Al 1100 in the DEFORM database were used in the simulations. AISI H13 was chosen for the extrusion wheel, coining roll, mandrel, dies, and chamber. Being the symmetric part, only 1/2 of the geometry was considered in the simulation. The 3D assembly models and meshes used in the simulation are shown in Fig. 3. The core cable was simplified in the simulation, because the process was indirect cladding. An extrusion wheel velocity of 8 r/min was adopted initially.

The friction at the feedstock–tooling interfaces is regarded as shear type. Friction factor m is expressed as

$$f_s = mk \quad (1)$$

where f_s is the frictional stress, k is the shear yield stress, and m is the friction factor. These indicate that the friction is a function of the yield stress of the deforming body. To approximate the actual operating conditions of aluminum continuous extrusion, a friction factor of 0.95 was chosen at the extrusion wheel–billet. The large friction factor represents a nearly sticking condition where the billet is pressed into the extrusion wheel groove with aluminum lining by the coining roll [15,16]. For the friction between the other tools and the billet, a friction factor of 0.4 was assumed, which is proposed by DEFORM software system for aluminum extrusion process. The initial temperature of feedstock, extrusion wheel and coining roll was set as 20 °C. For mandrel, chamber and dies which were preheated, the temperature was set as 450 °C. All the simulation material parameters and geometric data are listed in Table 1.

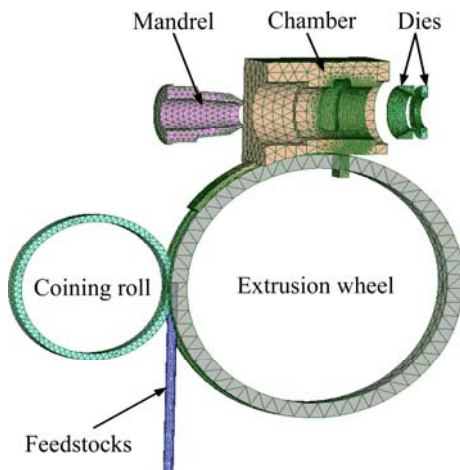


Fig. 3 FEM meshes of feedstock, extrusion wheel, mandrel, and other extrusion tools

Table 1 Simulation material parameters and geometric data

Material	Conductivity/ (N·s ⁻¹ ·°C ⁻¹)	Heat capacity/ (N·mm ⁻² ·°C ⁻¹)	Friction coefficient, m
Al 1100	238	2.3	0.95 (wheel), 0.4 (other tools)
Extrusion wheel diameter, D /mm	Feedstock diameter, d /mm	Product diameter, d_1 /mm	Product thickness/ mm
400	15	45	2

4 Results and discussion

4.1 Effect of horizontal flow passage lengths

4.1.1 Velocity distribution

As shown in Fig. 4, eight tracking points distributed

in the semicircle of the product were chosen from the upper to the bottom parts to determine the velocity distribution at the bearing exit.

The velocity distributions of each point under different lengths of the horizontal flow passage are shown in Fig. 5.

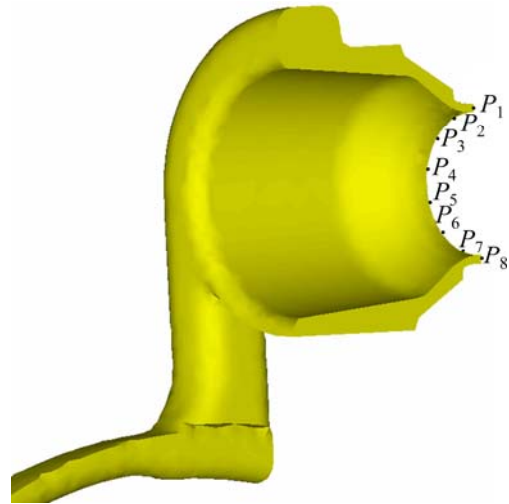


Fig. 4 Position of tracking points at die bearing

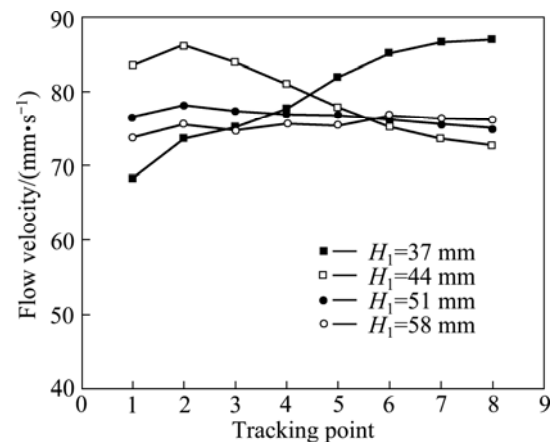


Fig. 5 Distribution of velocity at die bearing under different horizontal flow passage lengths

The velocity distribution along the cross-section is clearly non-uniform at short flow passage lengths of $H_1=37$ mm and $H_1=44$ mm, and the metal flow velocity difference is more than 28%. The velocity distribution is almost uniform at long flow passage lengths of $H_1=51$ mm and $H_1=58$ mm, and the metal flow velocity difference is within 5%. The velocity at the cross-section tends toward uniformity as the length of the horizontal flow passage increases. The non-uniform metal flow can generate a poor product shape.

4.1.2 Bending angles of product

A bending angle (α) was used as the target function to estimate the curvature of the extruded sheathing [17]. It is defined as

$$\alpha = \tan^{-1} \left(\frac{x_2 - x_1}{y_2 - y_1} \right) \quad (2)$$

As shown in Fig. 6, the coordinates of end points P_1 and P_2 are denoted by (x_1, y_1, z_1) and (x_2, y_2, z_2) . When P_1 and P_2 lie on the symmetric plane $x-y$, a positive bending angle indicates upward bending and a negative bending angle points to downward bending.

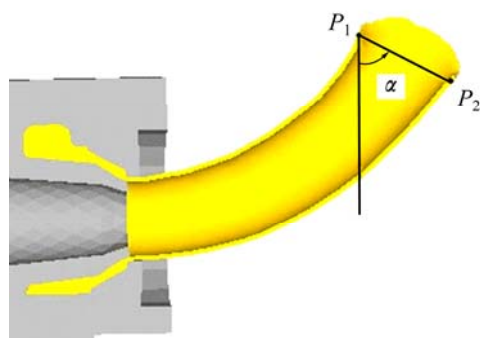


Fig. 6 Bending angle of extruded sheathing sheath

Figure 7 shows the extruded sheath under different horizontal flow passage lengths. Figures 7(a) and (b) illustrate that the sheath bends upward then downward when H_1 changes from 37 mm to 44 mm. As shown in Figs. 7(c) and (d), the sheathing sheath is nearly straight at die cavities of $H_1=51$ mm and $H_1=58$. The bending defect is due to the non-uniform metal flow. For the interaction between the fast-flowing and slow-flowing parts, the slow-flowing metal drags the fast-flowing metal. Hence, the fast-flowing metal shifts in direction of the slow-flowing metal. Thus, the product bends in an

upward or downward fashion. The entire model is of lateral symmetry, so no lateral asymmetry velocity exists. As shown in Fig. 8, the bending angles of the extruded sheath were calculated at selected strokes. When short flow passages (H_1) of 37 and 44 mm are used in the simulation, increasing the length can significantly alter the bending angles. At long flow passages ($H_1=51$ mm and $H_1=58$ mm), all sheaths are extruded with slight negative bending. The absolute value of the bending angle decreases as the length of flow passage increases.

The above-mentioned phenomena can be attributed to the fact that adopting long horizontal flow passages in the extrusion process generates enough space and time for the unbalanced metal flow to even out the velocity along the circumferential of the product. Among the four simulations, the product extruded by the die cavity with the maximum flow passage length of 58 mm has the lowest bending angle of -1.6° . This indicates that a long flow passage can improve the unbalanced metal flow at the die exit.

4.1.3 Cross-section shape of aluminum sheath

The cross-section of the extruded sheath tends to be elliptical because of the uneven metal flow (Fig. 9). The cross-section distortion degree (β) was defined to assess the variations in the cross-section distortion. The distortion degree (β) is defined as

$$\beta = d_y/d_x \quad (3)$$

As shown in Fig. 9(a), d_x is the length of the X -axis of the product section cut by the horizontal plane at the center, and d_y is the length of the Y -axis cut by the vertical plane at the center. Hence, the ideal value of

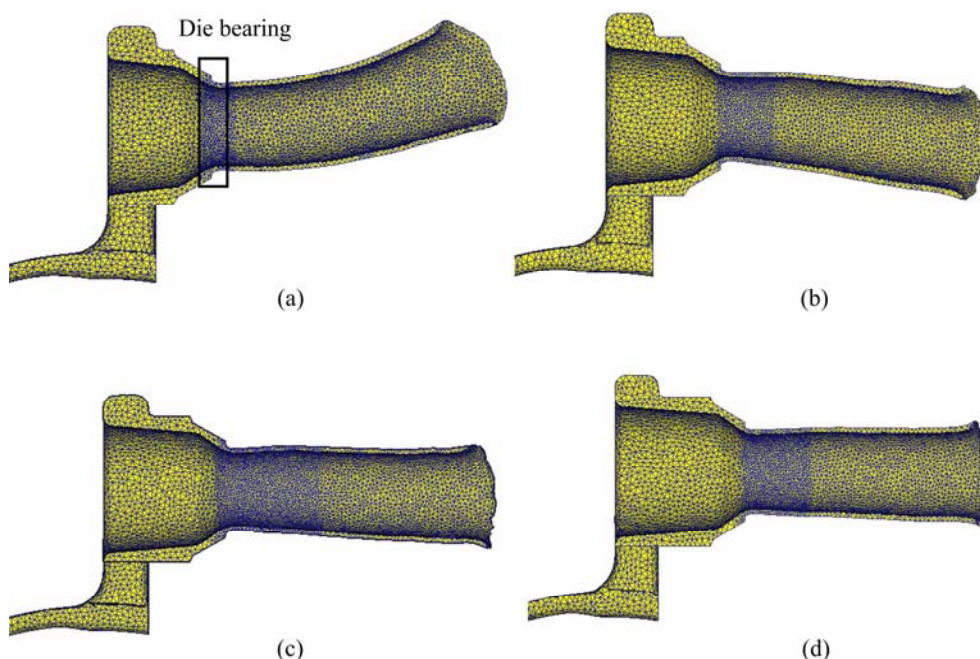


Fig. 7 Extruded sheath under different horizontal flow passage lengths: (a) $H_1=37$ mm; (b) $H_1=44$ mm; (c) $H_1=51$ mm; (d) $H_1=58$ mm

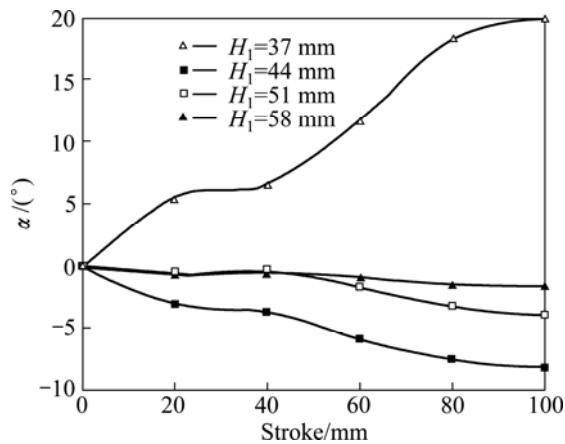


Fig. 8 Bending angles under different horizontal flow passage lengths

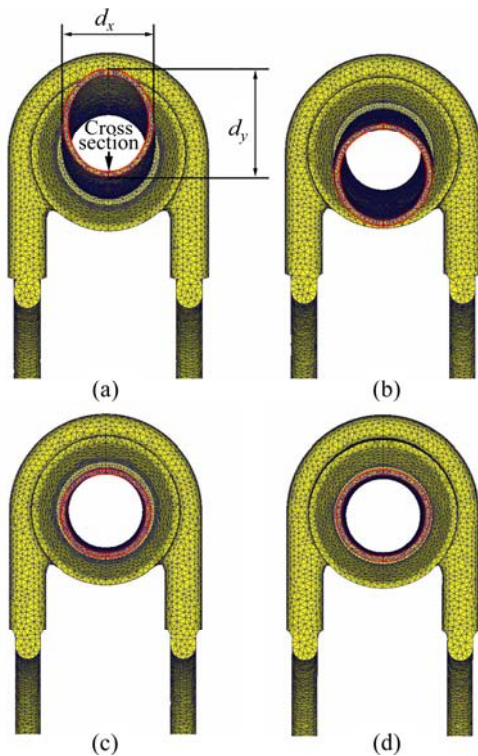


Fig. 9 Cross-section shapes of product at selected stroke of 100 mm: (a) $H_1=37$ mm; (b) $H_1=44$ mm; (c) $H_1=51$ mm; (d) $H_1=58$ mm

distortion degree β is 1. Table 2 lists the cross-section distortion degrees of the product. All the distortion degree values are more than 1, indicating that the vertical diameter is larger than the horizontal diameter. The product exhibits the worst shape at the cross-section when the die cavity with a horizontal flow passage length (H_1) of 37 mm is used. The cross-section shapes have negligible changes with almost the same distortion degree values when H_1 changes from 51 to 58 mm. The distortion degree (β) decreases with the increase in the flow passage length. These variation tendencies are

consistent with the above-mentioned analysis results of the bending angles under different horizontal flow passage lengths. This confirms that the uneven metal flow can cause not only large bending angles, but also marked variations in cross-section distortion in the continuous extrusion aluminum sheathing process.

Table 2 Cross-section distortion degree of product under different horizontal passage lengths

H_1/mm	d_x/mm	d_y/mm	Distortion degree, β
37	41.8	50.8	1.22
44	44.9	49	1.09
51	45	45.8	1.02
58	44.4	45.5	1.02

4.1.4 Maximum temperature and extrusion wheel torque

The simulation was also performed to determine the effect of the passage length setting on the maximum temperature and extrusion wheel torque. High-forming temperature causes surface quality problems, and high torque leads to energy wastage. The metal at the die bearing exhibits peak temperature. Figure 10 shows the production peak temperature at the die bearing and extrusion wheel torque under different lengths of the horizontal flow passage. It also illustrates that increasing the flow passage length only slightly increases the production temperature by 3.6%. The extrusion wheel torque first increases by 1.2% because of rising frictional resistance caused by the long flow passage, and then slightly decreases because of the low flow stress of the material at high temperatures. Increasing the flow passage length does not markedly raise the production temperature and extrusion wheel torque.

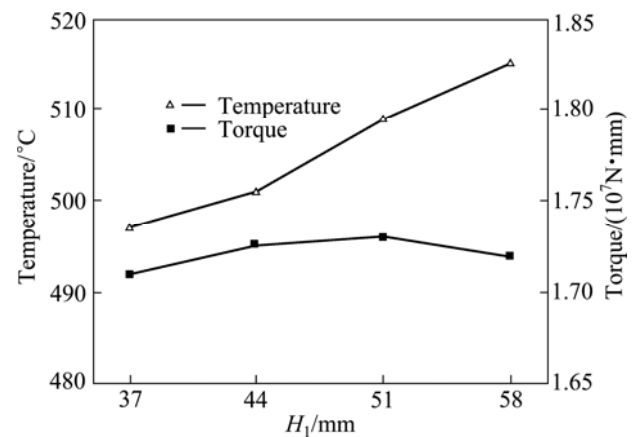


Fig. 10 Peak temperature and torque under different horizontal flow passage lengths

4.2 Effect of extrusion wheel velocity

The effects of the extrusion wheel velocities on the bending angles and variations in the cross-section were

also investigated. The other wheel velocities of 6 and 10 r/min were used for the die cavity of lengths $H_1=37$ mm and $H_1=58$ mm in the simulations. Figure 11 shows the bending angles that correspond to the wheel velocities of 6, 8, and 10 r/min. Under different rotational velocities, when the die cavity with $H_1=37$ mm is used, the products bend upward with bending angles above 10° at a selected stroke of 100 mm (Fig. 11(a)). When the die cavity with $H_1=37$ mm is adopted, the changes in the bending angles are relatively small, ranging from -0.45° to -3.33° at a selected stroke of 100 mm (Fig. 11(b)).

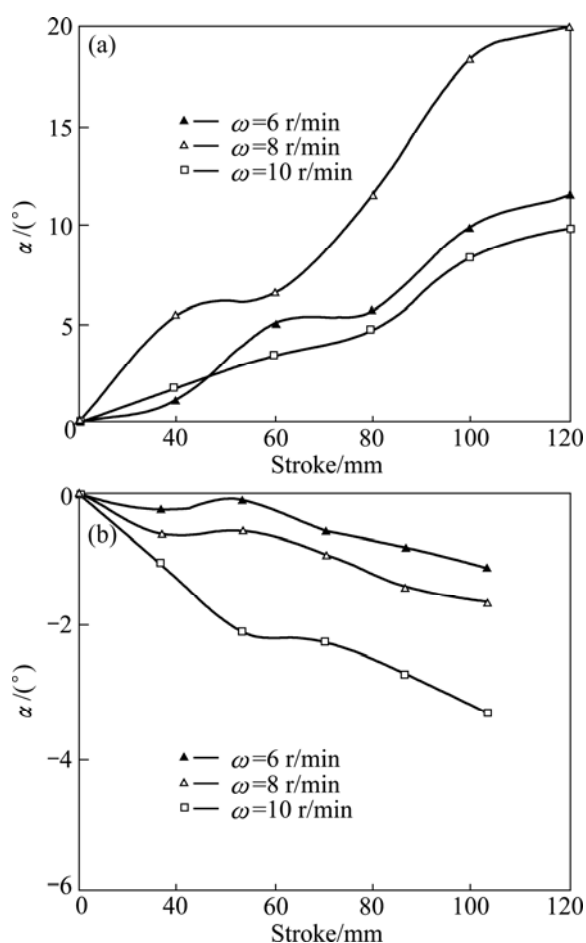


Fig. 11 Bending angles under different extrusion wheel velocities: (a) $H_1=37$ mm; (b) $H_1=58$ mm

Figure 12 shows the degree of cross-section distortion of the product under three different extrusion wheel velocities. When the die cavity with $H_1=58$ mm is used, all the distortion degree values (β) under different extrusion wheel velocities are below 1.05, indicating a better shape at the cross-section. When the die cavity with $H_1=37$ mm is used, the distortion degree values (β) fluctuate with changes in the extrusion wheel speed. All the distortion degree values are above 1.1, which represent a worse shape at the cross-section.

This trend of the effect of extrusion wheel velocity is consistent with that of the effect on the bending angles.

When a short flow passage is used, the space is insufficient for the metal to establish mobile equilibrium along the circumferential of the product; the product is likely to cause non-uniformity in the metal velocity with larger bending angles and elliptical cross-section. Therefore, no rule exists between the extrusion wheel velocity and the shape of the product when the die cavity with a short flow passage is used. When a long flow passage is used, the space is sufficient for the metal to establish mobile equilibrium, and the extrusion wheel velocity has little effect on the bending angles and cross-section.

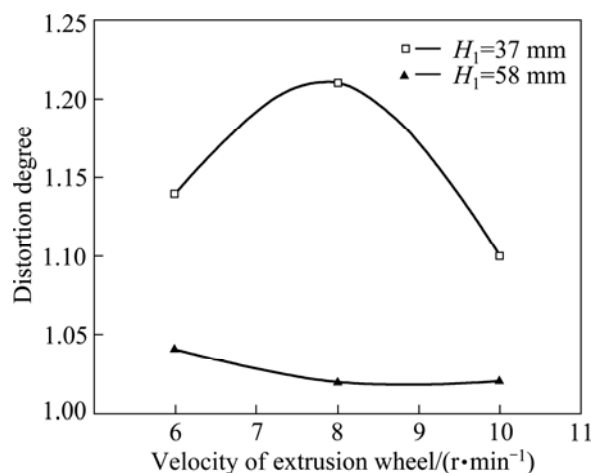


Fig. 12 Cross-section distortion degree of product under different extrusion wheel velocities

5 Experimental validation

The experiment was conducted on a continuous extrusion machine (SLB400) at an extrusion wheel velocity of 8 r/min. The process parameters used in the extrusion experiment are the same as those adopted in the simulation. The die cavities with horizontal flow passage lengths (H_1) of 37 and 58 mm were used in the experiments. The sheaths extruded in the experiment are shown in Fig. 13. As seen in Fig. 13(a), pronounced upward bending occurs when the die cavity with $H_1=37$ mm is used. The extruded product with slight downward bending is obtained when a long flow passage of 58 mm is adopted (Fig. 13(b)). These results are in accordance with those of a previous simulation study on product bending angles (Fig. 8). We can conclude that a long flow passage can improve the unbalanced metal flow at the die exit.

The experimental results for the cross-section and temperature of the product were also compared. Figure 14 and Table 3 show the cross-section comparison of the cladding sheath extruded in the experiment under different passage lengths. The product shows an evident elliptical cross-section with a cross-section distortion

degree of 1.11 when a short passage length ($H_1=37$ mm) is used in the experiment. The product has a fine cross-section with a cross-section distortion degree of 1.01 when a long passage length ($H_1=58$ mm) is used. The experimental results share the same trend as that in the simulation.

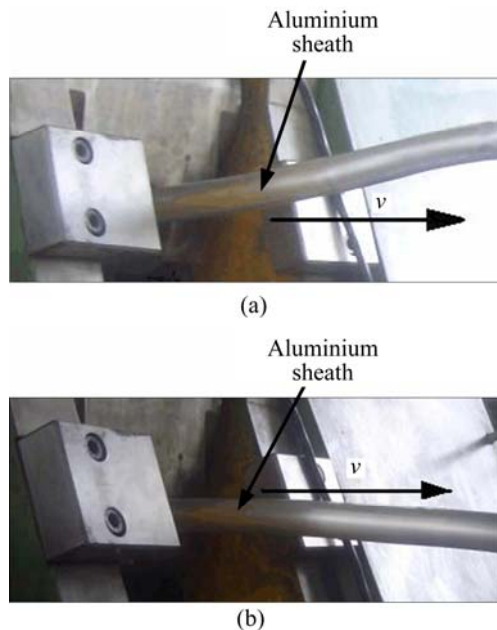


Fig. 13 Aluminium sheath extruded in experiment: (a) $H_1=37$ mm; (b) $H_1=58$ mm

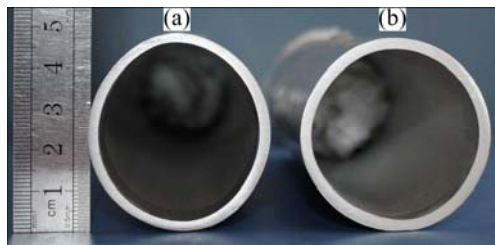


Fig. 14 Comparison of cross-section of aluminium sheath extruded in experiment under different passage lengths: (a) $H_1=37$ mm; (b) $H_1=58$ mm

Table 3 Comparison of cross-section distortion degree of product

H_1/mm	d_x/mm	d_y/mm	β
37	48.2	43.4	1.11
58	46.5	45.9	1.01

Using an infrared radiation thermometer (Marathon MM3M), the temperature of the product surface at the machine exit is measured. As shown in Fig. 15, the experimental temperature at the machine exit is lower than the simulation data obtained at the die bearing. Because a 200 mm of distance exists from the die bearing to the machine exit, and heat may be lost.

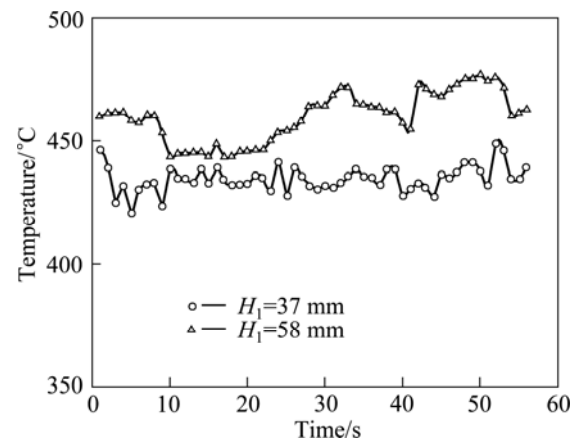


Fig. 15 Product temperature measured at machine exit

6 Conclusions

1) The FEM analysis reveals that the uneven metal flow at the die bearing causes not only large bending angles, but also marked cross-section distortion. A long flow passage can improve the unbalanced metal flow at the die exit.

2) The length of the flow passage in the die cavity plays an important role in improving the uniformity of extrusion velocity, the bending angles and elliptical shape at a cross-section in the continuous extrusion sheathing process. By increasing the flow passage length, the values of the bending angles gradually approach the ideal value of zero and the cross-section shape becomes better. Increasing the flow passage length does not markedly raise the extrusion wheel torque and production temperature.

3) The extrusion wheel velocity has negligible effects on the bending shape and elliptical cross-section of the product when a long flow passage is used.

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工艺参数对铝连续挤压包覆护套成型的影响

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摘要: 基于 DEFORM 3D 模拟软件, 针对连续挤压包覆过程中模腔流动通道长度和挤压轮转速对铝护套产品的影响进行有限元模拟分析, 并进行实验验证。结果表明, 模腔中流动通道长度对改善金属流动的均匀性、产品的弯曲角度和横截面的椭圆度发挥重要的作用, 增加流动通道长度, 可以使产品的流动速度变得均匀, 产品的弯曲角度接近理想的零值, 并可以获得良好的截面形状; 当使用较长的流动通道时, 挤压轮转速对产品的弯曲角影响不大。

关键词: 连续挤压包覆; 铝护套; 护套成形; 模具设计; 挤压轮速度; 有限元

(Edited by LI Xiang-qun)