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Computer-Aided Optimization of the Extrusion Process of Automobile Rubber Seal

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In this work, the extrusion process of a kind of π-shape automobile rubber seal was considered using computer-aided simulation technology. The extrusion flow was assumed to be isothermal and steady, and the finite element method was used to analyze the extrusion process. It was found that the velocity profile was quite uneven near the die exit when a straight die, developed strictly according to the desirable product dimension, was used and the local distortion of the extrudate was fairly prominent when compared with the die geometry. We adjusted the structure of the die and predicted the extrudate's swell by the computer simulation in advance. Simulation results confirmed that the distortion of the seal was greatly suppressed if a short enlarged inflow part was added to the upstream of the original straight die. Then, the extrusion experiment, using the newly designed die, was performed under practical conditions and the swell of the rubber seal was reduced to be within the range of acceptable tolerance. The profiles of the acceptable rubber seals were also well predicted by the computer simulation. Finally, the influences of the take-up imposed on the end of extrudate and flow rate on the final seal shape were also investigated numerically.

Keywords: EPDM; rubber; simulations; extrusion; rheology

1 Introduction

Extrusion is used to manufacture products in continuous lengths with a uniform cross-section. A number of plastic and rubber products in our daily life have been produced by the extrusion process (1). For the various applications, the cross-section of the product can be either quite simple, i.e., circular, annular, rectangular profiles, or very complex, such as window profiles and rubber car seals. It is usually observed in practice that the shape of the final product is quite different from that of the extrusion die and this phenomenon is well known as die swell (2–5). The die swell defect is believed to be caused by the combined effects of the velocity redistribution and the relaxation of the stress for viscoelastic material as it leaves the die. How to suppress the die swell or design an appropriate extrusion die with the lowest cost is still a great challenge in the extrusion process of polymeric materials.

Many parts of the automobile are also manufactured through the extrusion process, such as various seals. Usually, automobile seals have complex shapes and are made from rubber composites. Given a fixed die, it is rather difficult to imagine the final shape of the seal products because of the complex rheological features of the rubber composites. Traditionally, in industry, trial-and-error testing is used to find a suitable extrusion die. Many trials are often needed to modify the dimensions of the die, which is expensive and time-consuming, however.

Recently, advanced computer simulation technology has been widely used in the analysis and optimization of the processing processes in polymeric industries, including extrusion, mixing, blow molding, film casting and fiber spinning (6–11). This method helps the engineers and designers to predict the flow behavior of the melt, heat transfer and even final properties of the products under the complex processing conditions. The computer acts like a virtual laboratory, providing insight, foresight, return on investment, and cost savings. Therefore, the establishment of a technical platform for simulating the extrusion process of rubber seals is a major job in our research group.

Aided by an advanced computer or even a high-performance computer cluster, simulation work on the extrusion of polymers with simple profiles has been conducted by many predecessors. Arpin et al. (12) developed a personal computer simulation program to simulate the two-dimensional flow of a polymer melt in a coat-hanger die. The predicted flow

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fields were compared with the measurements and some satisfactory results were obtained. Gifford (13) simulated flow in a plate die and analyzed the distortion of the product under a high pressure by using the finite element method (FEM). Limper and Schramm (14) characterized the rheological behaviors of a rubber compound and presented a new approach to model the flow in a twin screw extruder. They suggested that rubber processing was a complex theme and the application of a simulation tool made the systematic analysis and optimization of the extrusion process possible in reasonable time. Kajiwara and Yoshida (15) investigated the influences of material and processing conditions on the die swelling phenomenon and found that the first normal stress difference and shear thinning effect greatly affect the swell. However, the laws of die swell summarized from simple die geometries are not applicable to complex products (1).

As to the extrusion process of rubber composites, the die design is a rather troublesome and difficult task especially when the cross-section of the product is complex. In this paper, computer-aided simulation technology will be used to study the extrusion process of a π-shape automobile rubber seal and help to design the extrusion die on the computer instead of in real operation. In the experimental section, the rheological characterization of the rubber composite and details of extrusion experiment will be discussed. Finite element method will be utilized to solve the extrusion problem and further discussion will be made on the simulation and experimental results. Finally, some conclusions are reached.

2 Experimental

2.1 Rheological Characterization

The material used in this work is designated as EPDM60, which is a rubber composite of uncrosslinked Ethylene-Propylene-Diene-Monomer (EPDM) and carbon black and some inorganic additives. The vulcanization of the rubber products is performed just after the extrusion process. The rubber sheet, with a thickness of about 2 mm, was provided by Shanghai Saic-Metzeler Sealing Systems Corporation, China. The rheological tests of the compound were carried out in a rotational rheometer (Gemini 2000 HR, Bohlin Instrument, UK) with parallel plates geometry (plate diameter = 25 mm, gap ranges from 1 to 2 mm). The measured temperature was the same as the processing temperature, 160°C. To avoid the divergence of experimental data under large shear rates caused by a slip between the plates and sample, both the upper and lower plates were coarsened mechanically, in advance, to increase the friction between their interfaces.

The first normal stress difference (N1) and the shear stress (τ_{12}) versus shear rate are shown together in Figure 1. The EPDM60 shows elasticity since the first normal stress difference under the shear is non-zero. Usually, a dimensionless number, called the Weissenberg number (We), is used to characterize the elasticity of polymer material. The parameter is defined as the ratio of the first normal stress difference to the shear force. The We number can be estimated from the experimental results in Figure 1, showing that We ≈ 0.1, which is smaller than one; So we can confirm that the viscous effect is dominant for this EPDM rubber composite (16, 17).

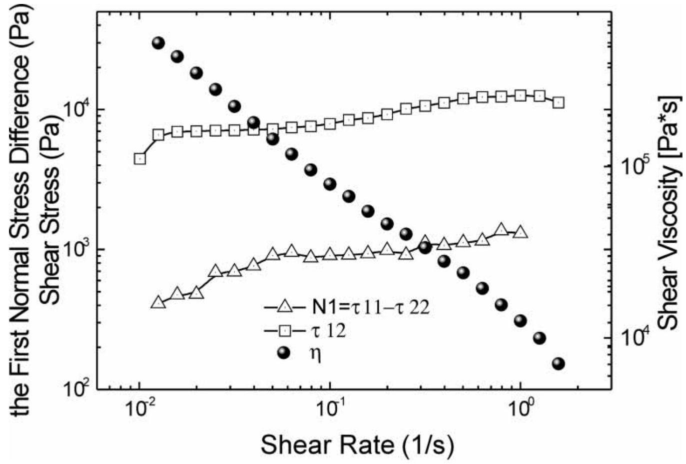

Fig. 1. The first normal stress difference, shear stress and shear viscosity of EPDM60 as a function of shear rate.

Creep and recovery experiments were also carried out to determine the elastic effect of the rubber composites, as shown in Figure 2. A constant shear force of 10^5 Pa was imposed on the EPDM60 disk-like sample to make it creep for 5 min, and then the force was relaxed suddenly to record the recovery process. Obviously, very little strain recovery was observed; that is, the equilibrium recoverable compliance (J_0^e) of EPDM60 nearly vanished. The vanishing of recoverable strain can be attributed to the recoiling of

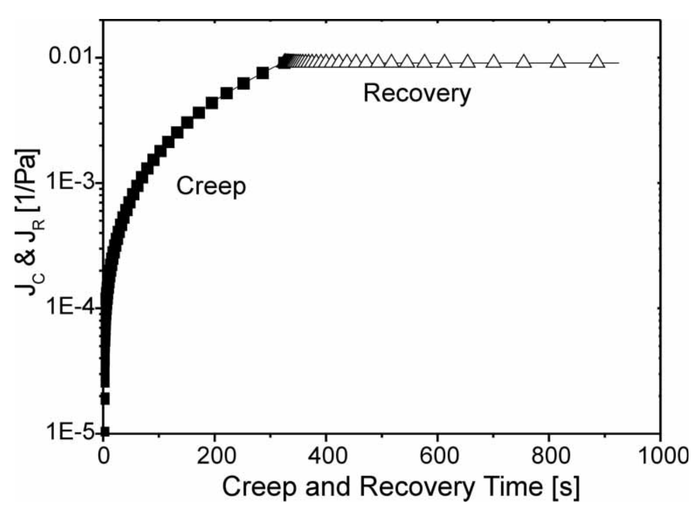

Fig. 2. The creep and recovery curves of EPDM60 at 160°C. J_c and J_R represent the creep and recovery compliance, respectively.

macromolecules being hindered by the large number of carbon black particles and the stored elastic energy was also rapidly transferred to these solid particles (18, 19). Therefore, the memory effect of the EPDM60 composites was greatly suppressed and was supposed to play a tiny role on the distortion in the shear-dominated extrusion process.

2.2 Extrusion Experiments

To study the die swell defect, extrusion experiments of EPDM60 were performed on a production line at the Shanghai Saic-Metzeler Sealing Systems Corporation, China. A single-screw extruder was used to transport the EPMD material. The die temperature was fixed at 160°C, and the melt extruded from the complex die could be stretched by a take-up device. When the flow was steady, a part of rubber extrudate near the die exit was immerged into liquid nitrogen and finalized. Then the shape of extrudate was easily recorded by drawing its profile.

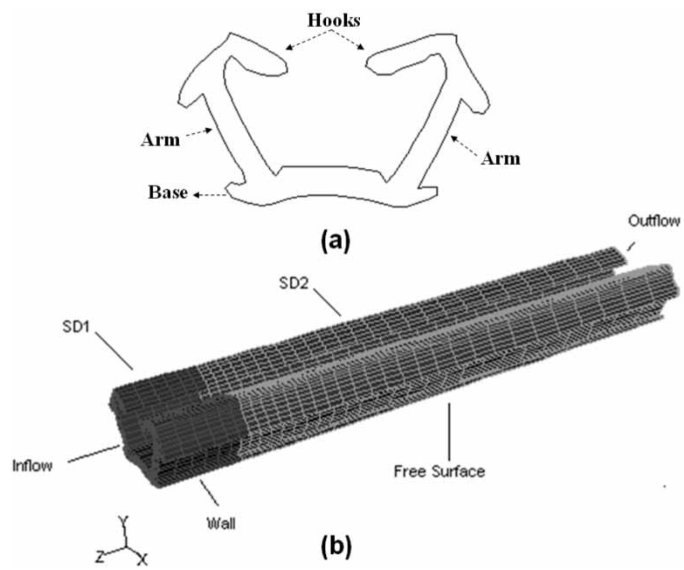

Fig. 3. Physical model of extrusion process of EPDM60: (a) cross-section shape of the required automobile rubber seal; (b) flow domains, boundaries and finite element meshes.

3 Results and Discussion

3.1 Computer Simulation

Some reasonable assumptions were made in the present simulation experiment to simplify the calculation. Since the extrusion rates are very slow during the processing of the EPDM60, usually several meters per minute, inertial force and self-weight of rubber material were neglected. From the above analysis of the rheological flow behavior of EPDM60, we concluded that the present extrusion of EPDM60 was dominated by the viscous effect of the material, so the elasticity was excluded in the calculation to simplify the model. Also, the extrusion flow is assumed to be incompressible, steady-state and isothermal.

Therefore, the conservation equations of mass and momentum can be described as follows (20):

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

$$-\nabla p + \eta \cdot \nabla \cdot \nabla \mathbf{v} = 0 \tag{2}$$

where $\boldsymbol{v}$ is the velocity, p is the isotropic pressure, η denotes the viscosity of the melt and ∇ is the gradient operator.

As shown in Figure 1, a strong shear thinning was found for EPDM60 under the shear. A well-known viscosity law, named Bird-Carreau, was adopted to describe the shear-thinning feature of the rubber composite:

$$\eta = \eta_0 (1 + \lambda^2 \dot{\gamma}^2)^{m-1/2} \tag{3}$$

where η_0 is the zero-shear-rate viscosity, λ is the natural time, and m is the flow index. Through fitting the experimental data based on the least square method, we can obtain the appropriate values for these model parameters: $\eta_0 = 2.4 \times 10^6\ Pa \cdot s$, $\lambda = 110$ s, m = 0.324.

The required π-shape profile of the automobile seal product is shown in Figure 3. It is made up of a flat base and two side arms and two upper hooks. The flow domains consist of an extrusion die and the following extrudate, denoted as sub-domain 1 (SD 1) and sub-domain 2 (SD 2). The extrudate is long enough to account for all the deformation of the extrudate. The whole computational domains are sub-divided into about 9000 unstructured finite element meshes, as shown in Figure 3.

The boundary conditions necessary for the simulation are analyzed as follows:

1. A fully developed flow is assumed at the inlet of the SD 1 flow domain, i.e., all derivatives normal to the inlet are zero, except the pressure gradient, which is assumed to be constant. The velocity profile is calculated from the imposed volumetric flow rate Q_0.
2. A no-slip condition is assumed for the fluid at the wall.
3. For the free surfaces of the extrudate in SD 2, the normal force must be equal to zero. Moreover, the normal velocity must also be equal to zero, i.e., $\mathbf{v} \cdot \mathbf{n} = 0$, where $\mathbf{n}$ is the normal unit vector of the free surface.
4. At the end of extrudate, either free extrusion or a take-up velocity is a possible case for the extrusion process. The extrusion, without stretch and with a stretch, are both considered in our work. For the pulling extrusion, usually, the following criterion is satisfied in practice: $v_z = 1.2 \sim 1.6 v_0$, where v_z denotes the take-up velocity imposed on the extrudate and v_0 is the average velocity at the die exit.

The extrusion process of the EPDM60 melt was solved by the Galerkin finite element method. The basic solution procedures are described in Figure 4. Due to the highly non-linear nature of the problem, a parameter evolution is introduced in the algorithm (21). It was found that the moving surface and the very small flow index in the Bird-Carreau model are the main sources of non-linearity. Therefore, we introduced a parameter S to control the evolution process of these two factors:

$$\text{On the free surface:} \quad (v \cdot n) = \{v \cdot n\} \cdot S \tag{4}$$

$$\text{For the Bird-Carreau model:} \quad m = \{m\} \cdot \frac{1}{S} \tag{5}$$

where $\{\cdot\}$ means the desirable value of the variable. First, we began a simple calculation, i.e., $S = 0.01$, in which non-linearity is not as troublesome. From this solution, we can then solve a sequence of problems of increasing non-linearity, using the solution of one problem as the initial condition for the subsequent problem. Ultimately, the sequence should lead to the original problem and its solution, i.e. $S = 1$. The Newton-Raphson method was used to solve the system, including conservation equations of mass and momentum and constitutive equation. An additional degree of freedom is required for a free-surface problem, called the geometrical degree of freedom. The geometrical degree of freedom is denoted by b, which describes the amplitude of the displacement of boundary nodes in the normal direction. Due to the movement of the boundary nodes, interior nodes nearby the boundary surface should be relocated to minimize the mesh deformation. An Optimesh algorithm was used to relocate the mesh positions near the free surfaces, which relocates nodes of an element in such a way as to minimize the energy of deformation of the mesh. This energy of deformation is a function of the angular distortion of the elements, and of the elongation of 'springs' located along the segments and diagonals of the mesh. In the present simulation work, along the boundaries of the remeshing domain, the normal displacement was prescribed by the kinematic condition i.e., $\boldsymbol{v} \cdot \boldsymbol{n} = 0$ for a free surface or imposed to zero for all other cases. In the tangential direction, nodes are relocated to satisfy the equilibrium of forces (21). The convergence criterion used in the computation is based on the global highest relative variation for velocity fields and the following expression should be satisfied.

$$\sum_i (V_i^n - V_i^{n-1}) / \sum_i (V_i^n) < \varepsilon \tag{6}$$

where $\boldsymbol{V}_i^n$ means the velocity at node i and iteration n. The convergence tolerance ε in our simulation is set to the value 0.0001. Simulations in this work were carried out on a PC with one AMD 2500+ MHz processor and a RAM size of 1024M bytes. About two hours were needed to complete a computational project.

3.2 Die Swell Defect

It is frequently observed that the shape of an extrudate deviates from the extrusion die. The distortion of the

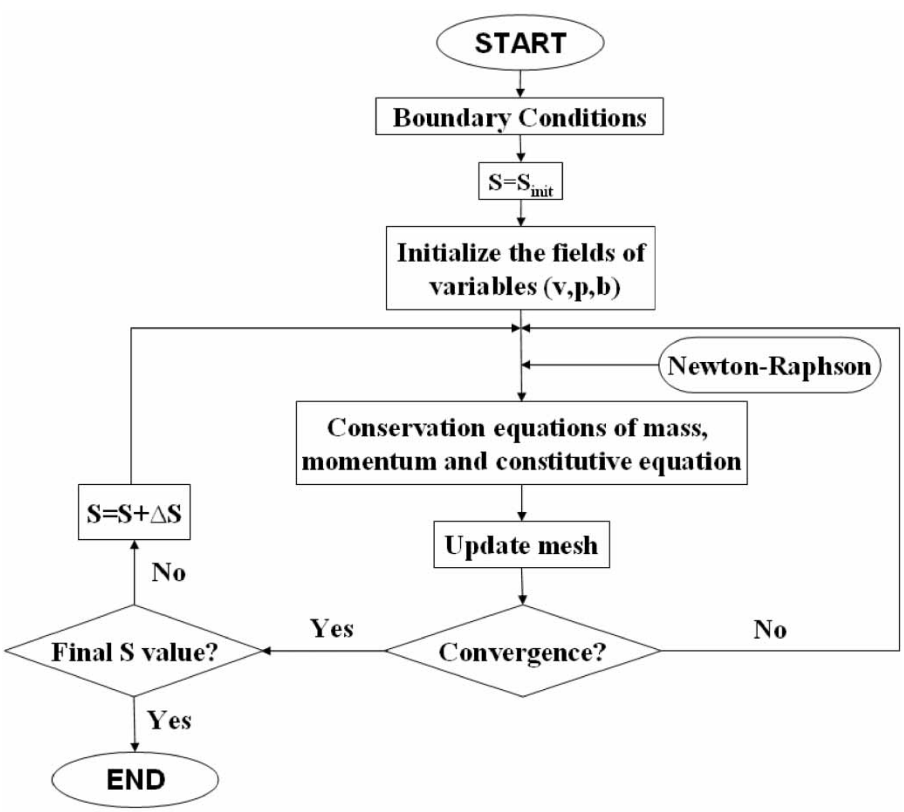

Fig. 4. Simulation algorithm.

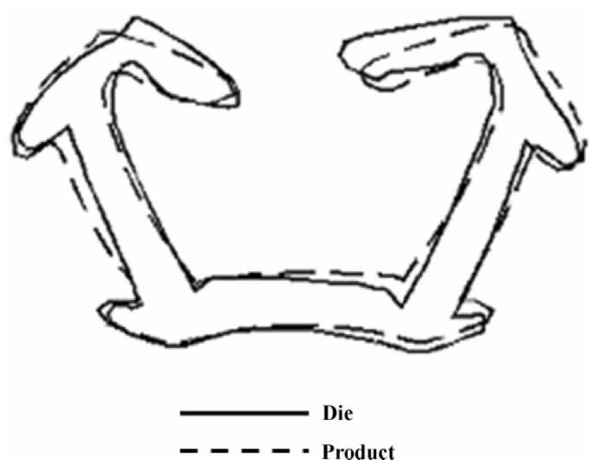

Fig. 5. Die swell of EPDM60 as it is extruded from the designed die.

extrudate as it flows away from the die must be restricted within an allowable error; otherwise many defective seals will be produced. The profile of an automobile rubber seal is complex and it is difficult for us to imagine the die swell phenomenon in advance. Therefore, as the first step, we designed an extrusion die strictly according to the dimension of the desirable product, and then an extrusion experiment was performed using this die on a production line at the Shanghai Saic-Metzeler Sealing Systems Corporation. The flow rate was 18,000 $mm^3\ s^{-1}$ and no stretch was imposed at the flow exit. The final shape of the extrudate was recorded and compared with the die, as shown in Figure 5. It was found that the two arms of the extrudate tend to spread outward but the upper two hooks are slightly concave. Obvious swell can be seen in the right half part of the base, but on the left, the extrudate geometry is nearly the same with the die. The shape deviation between the extrudate and die is considered to be related with the velocity redistribution at the die exit and elastic effect of the material. The elasticity is excluded at present, so the velocity redistribution near the die exit is the main cause for the distortion of the extrudate, which will be discussed further later. Therefore, for the complex π-shape seal product, the die swell is very complicated and even unimaginable.

As the EPDM60 melt flows away from the die, the constraint of the wall is released suddenly and the melt will undergo a new flow condition. The velocity of EPDM60 must change from a non-uniform profile to a constant throughout the cross-section of the extrudate as it moves to the flow exit. Just after the die exit, there is a transitional zone where the velocity profile is reorganized. This velocity rearrangement is the source of the deformation of the extrudate. The contour of the x-component and y-component of the velocity are shown together in Figure 6. It is clear that the velocity profile of the melt is quite non-uniform just after the die exit. The largest x-velocity mostly occurs on the two hooks, but for y-velocity, a high level is observed on both hooks and arms. As the melt flows forward, particles coming from high-speed regions in the die must slow down, while particles coming from low-speed regions must accelerate. A way to change the speed is to enlarge the flowing section. A tube of fluid at high speed in the die will enlarge its cross-section in the extrudate in order to decrease its average velocity; a tube of fluid at low speed in the die will reduce its cross-section in the extrudate in order to increase its average speed. The deformation of the extrudate in Figure 5 is the comprehensive consequence of the velocity adjustment near the die exit. Since the combined effects of cross-sectional enlargements and reductions are very difficult to be imagined, a computer simulation is very necessary for moderate- and high-complexity extrusion dies.

3.3 *Modification of the Die*

As mentioned above, the velocity rearrangement near the die exit is the main reason for the extrudate's distortion. The velocity profile along the cross-section of the extrudate in Figure 6, as was induced by the previous straight die, is unsatisfactory. So the extrusion die needs modification to provide a uniform velocity profile, which is helpful to suppress some

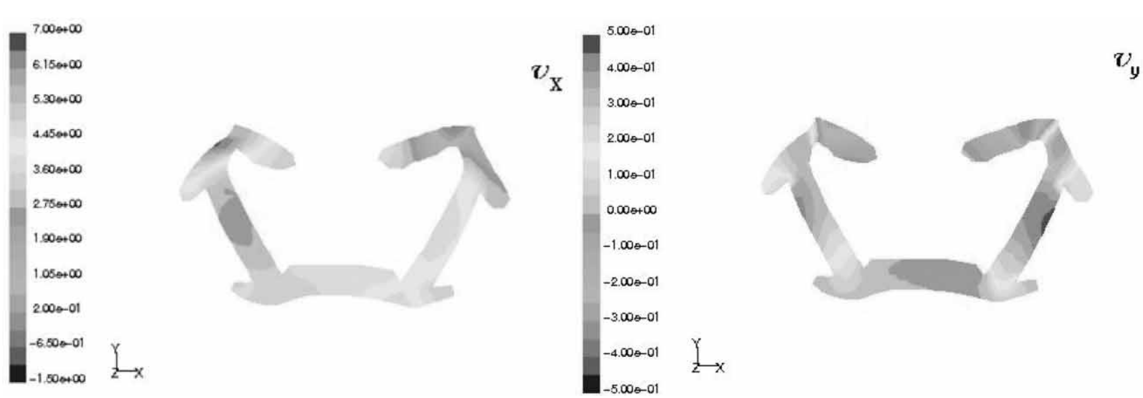

Fig. 6. Distributions of x-velocity and y-velocity near the die exit.

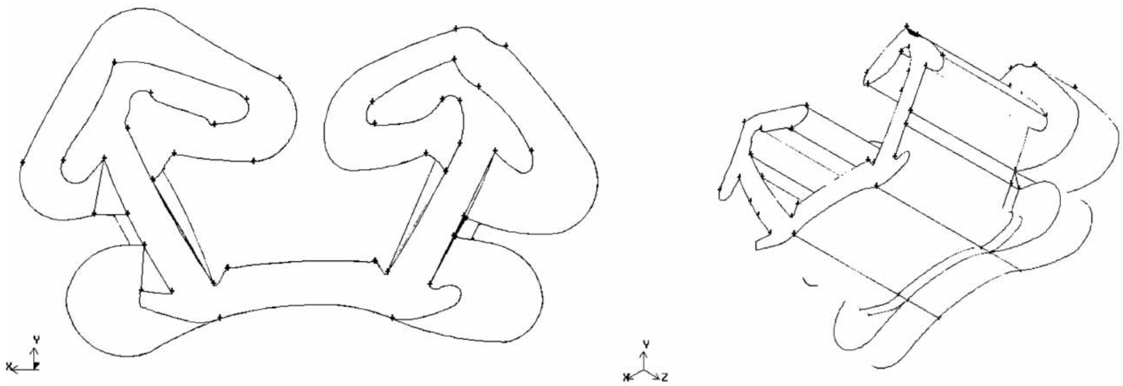

Fig. 7. Schematic of modified die from different views.

distortion of the extrudate. In this paper, we will propose a simulation method to modify the extrusion die with the help of the computer.

One of the measures is to change the structure of the extrusion die. Suppose that an enlarged inflow part with a length of 5 mm is added to the original straight die in the upstream; the schematic of the modified extrusion die is shown in Figure 7. We wonder whether the modification is effective to improve the flow conditions. The extrusion processes of the EPDM60 material in both the original and the new dies were simulated under a more realistic processing condition, for which the flow rate was 18,000 $mm^3 s^{-1}$ and the take-up velocity was 265 mms^{-1}.

The predicted velocity distribution near the exit of the newly-designed die is shown in Figure 8. It should be noted here that the scale of velocity legends in Figure 6 and Figure 8 has been set the same. It is predicted theoretically that the new velocity distribution is more uniform than the previous one. The largest values of x- and y-velocity in the case of the new die are also greatly reduced. Therefore, it was expected that the newly designed die would produce a seal with less deviation from the die, which will be demonstrated in the following.

3.4 Experimental Validation

We developed a second extrusion die according to the dimensions of the newly-designed one shown in Figure 7, adding an enlarged inflow part in the upstream. The extrusion experiment of EPDM60 was carried out again using the modified die and the shape of the seal product was recorded. The flow rate was 18,000 $mm^3 s^{-1}$ and the take-up velocity was 265 $mm s^{-1}$. Due to the stretch, the cross-section of the seal product was reduced comparing with the extrusion die; thus it is not clear if we simply put the two profiles of the extrusion die and the product together for the comparison. Since the main difference between the extrudate and extrusion die lies in the expansion of two arms and the concavity of the two hooks, four characteristic angles, depicted in Figure 9, were measured to show the deviation among them. The modification of the die causes a great change in θ_1, the corner between the left arm and left hook. Comparing with the die, the change in angle of the extrudate is greatly reduced if the modified die is used; however, the left hook of the extrudate is observed to slightly bulge when the modified die is applied. The distortion of the extrudate using the modified die is much smaller than that of the original die, which can be attributed to the improvement of the velocity distribution

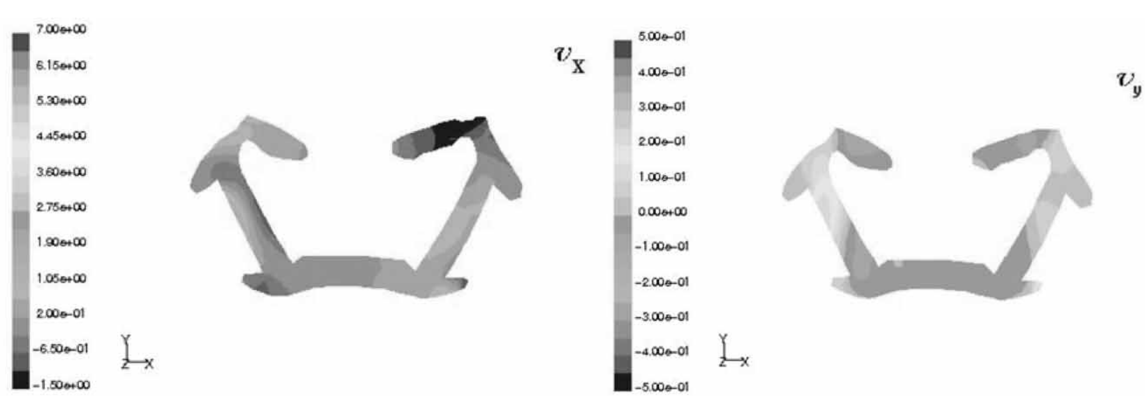

Fig. 8. Distribution of x-velocity and y-velocity near the exit of the newly designed die.

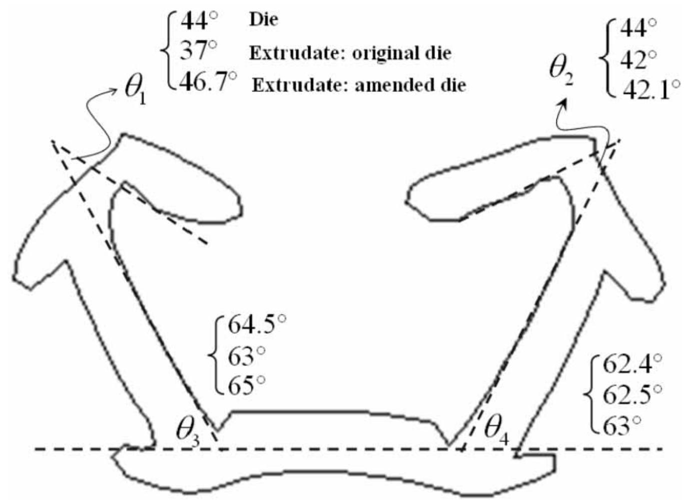

Fig. 9. Distortion of the extrudates comparing with the profile of die. The angles, from top to bottom, mean the characteristic angle of the die, the extrudate of original straight die and the extrudate of modified die, respectively.

along the cross-section for the modified die. For the other three characteristic positions, a relatively small distortion is observed no matter which die is used. According to the standard tolerance of this kind of seal, the seal products produced by the new die are acceptable.

3.5 Comparison between the Simulation and Experiment

The extrusion process of EPDM60 using the new die was also simulated to predict the profile of the products. Comparison between the simulation result and experiment in Figure 10 shows that similar extrudate shapes are obtained. Even though some deviation occurs in the left hook region, we deem that the simulation result is reasonable and acceptable, since we have excluded the elasticity of material and influence of temperature variation. Incorporating these factors, the numerical results are expected to agree with the experiment better, but the computational cost and difficulty will also increase sharply.

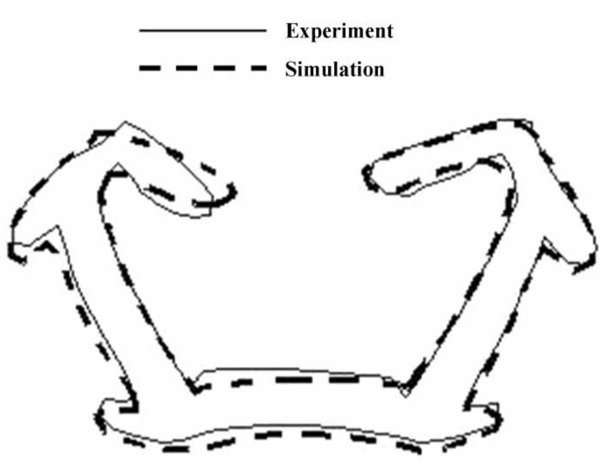

Fig. 10. Comparison of the seal profile between the simulation and experiment. The flow rate was 18,000 $mm^3\ s^{-1}$ and the take-up velocity was 265 mms^{-1}.

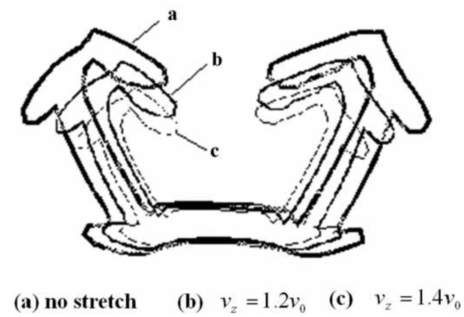

Fig. 11. Predicted profiles of the final extrudates under different take-up speeds.

3.6 Influence of Processing Conditions

Usually, a drag force or a constant take-up velocity is imposed at the end of the extrudate to make the extrusion more stable. Not only is the area of the cross-section of final extrudate decreased, but also the velocity fields of the melt are changed when a take-up is applied. Therefore, the influence of the take-up velocity on the final cross-section of product was studied with the simulation method. As shown in Figure 11, the left hook concaves downward more significantly and the two arms are observed to fold inward a little with increasing the take-up velocity. However, it seems that the take-up velocity has little effect on the geometry of the base and right part of the seal.

The influence of volumetric flow rate on the shape change of the product was also predicted by the simulation method. The investigated flow rates ranged from 5,000 to 18,000 $mm^3\ s^{-1}$, according to the practice in the factory. It was found that the flow rates have no obvious effects on the shape change of the extrudate no matter whether the stretch was applied or not. Therefore, we suggest that the seal production should be performed at a high flow rate for the purpose of high output.

4 Conclusions

In the paper, a computer-aided simulation technology was used to investigate the extrusion process of a kind of π-shape automobile rubber seal. The rheological characterization of the unvulcanized EPDM rubber composite indicated that the recoverable stain of the material was very small and therefore it was believed that the elasticity was rather small and could be ignored in the simulation work.

First, we developed a die according to the required product geometry. Extrusion experiments showed that the die swell of the EPDM60 in such a complex π-shape die was notable and complex when a straight extrusion die was used, which was attributed to the velocity rearrangement near the die exit.

Next, we modified the extrusion die by adding an enlarged inflow part in the upstream of the original straight die. The effect of the modification was predicted by the computer simulation instead of actual operation. It was indicated by the simulation results that the new die provided more uniform and better velocity profiles and most importantly, the distortion of the extrudate was greatly reduced. The deviation of the products from the desirable shape was predicted to be within the standard tolerance range.

Finally, we developed a new extrusion die according to the newly designed die geometry, i.e., adding an enlarged inflow part in the upstream of the straight die. Real extrusion experiments of EPDM material and computer simulation were performed under the practical processing conditions. Comparison of the extrudate shape between the experiment and numerical simulation demonstrated the accuracy and validity of the computer-aided simulation technology. The influences of some processing conditions such as take-up velocity and flow rate were also predicted by the simulation and showed that the stretch at the end of the extrudate caused local deformation of the extrudate but the flow rate showed little effect.

5 Acknowledgements

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