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Quick Profile Die Balancing of Automotive Rubber Seal Extrusion by CAE Technology

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The extrusion process of a type of automotive rubber seal was considered by using Computer Aided Engineering (CAE) technology. Based on the die balancing requirement, CAE technology was utilized to speed up the die development and balancing process. The rubber material was EPDM and unacceptable extrusion deformation was found by using a parallel die. More balancing dies were then designed following the procedures proposed by the die balancing method and the effect of them was evaluated with respect to CAE analytical results. It was found that the addition of an opening section in the die would provide a more uniform velocity distribution at the die exit than the parallel die. The length of opening section was also found to affect the die balancing and so an optimum length of the opening section was determined by CAE analysis. Further optimization of the die was carried out by adjusting the local length of the opening section. Finally, a real die was cut based on the optimization results and used for production. Ideal profile products were obtained and very small and acceptable deviation from the die was observed, which validated the advantage and accuracy of CAE technology combined with die balancing requirement.

Keywords: Automobile rubber seal, extrusion, CAE, die balance, rheology, optimization

1. Introduction

Extrusion processing is widely used to produce rubber profile products, such as automotive seals, tire tread bands, rubber tubes, and hoses. In this industry, cutting a balancing profile die is a key issue to obtain product with good quality. Complete die balancing is defined as the uniform fluid velocity distribution at the die exit and no lateral flow within the die. Modification of the die in industry is, in essence, looking for a more and more balancing die and less lateral movement of polymeric particles within the die. If the die is unbalanced, the shape of the extrudate is always observed to be quite different from the die, and the production process and product quality are quite unsteady. Traditionally, manufacturers need to modify the extrusion die several times according to the observation of the extrusion process and the shape of the extrudate, which always requires a high cost and much time. Research studies of polymer flow in the extrusion process aim at the quick design of a more balancing die for a complex profile product in the industry.

Many previous studies have focused on the mechanism of extrusion deformation of polymer materials. The results showed that two main reasons cause the extrusion deformation: one is the elastic recoil of polymer chains (1–2), and the other is due to the reorganization of the velocity profile from Poiseuille-type flow to free jet flow at the exit. Tanner et al. (3) pointed out that the deformation of polymer melt during the extrusion process is the sum of these two contributions. However, the elastic swelling of polymer melt also greatly depends on the velocity gradient at the die exit during the flow (4); therefore, balancing of the die, i.e., obtaining a uniform velocity distribution, is helpful to reduce the extrusion deformation and stabilize the process.

From practice, some valuable experiences have been summarized to speed up the die design process in the profile extrusion industry. Ruan et al. (5) deemed that for a complicated profile, increasing the molding length in the thick zone of the profile or decreasing the molding length in the thin region can make the flow velocity at the die exit more uniform. Stevenson et al. (6) found that a back-relieved die was more balancing, but it was difficult to manufacture the continuous back-relieved die in real operation. Rubin et al.

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(7) put forward the guideline to modify the entry of the die, i.e., opening the die land corresponding to the narrow zone in the profile cross-section would improve the velocity distribution at the die exit. Taddmor and Gogos (8) and Michael and Rauwendaal (9) concluded that die design for profile products should follow the guidelines extracted from the practical experiences and scientific calculations.

Recently, an advanced Computer Aided Engineering (CAE) technology has been developed and is gradually being increasingly used in the analysis and optimization of polymer processing in industry (10–15). CAE technology works as a virtual experimental platform, on which the design and optimization of polymer flow is carried out instead of the practical operation. Results from CAE are expected to be close to the optimum solution to the process and the proposed guidelines are helpful to reduce the number of or even avoid time-consuming trials. Therefore, CAE technology has been considered as a faster and more efficient design method and becomes more and more important in the plastic and rubber industries.

From the above introduction, it was natural to conclude that combining the die balancing requirement and CAE technology is potentially a more advantageous method for die design. Die balancing is the target and CAE works as a tool to move straightly forward to the target. However, until now, there has not been a study illustrating the application of die balancing method in the profile die design with the help of CAE technology. In this paper, we will use this method to design a more balancing extrusion die for an automotive rubber seal with complex profile, illustrating the basic quantification, procedures and advantages of this design method. Experimental verification will also be conducted to verify the validity and veracity of the method.

2. Experiment

2.1. *Profile extrusion experiments*

In this study, an extrusion die lip of an automotive rubber seal product schematically shown in Figure 1, was the product of interest. The profile is relatively complex, including a base on the bottom and two side arms. In addition, there are six isolating branches denoted as A∼F attaching to the base and side arms. The rubber material used for this product is an EPDM rubber with Shore hardness 60°C, it is an industrial rubber composite of uncrosslinked ethylene-propylene-diene-monomer (EPDM), carbon black and some inorganic additives. The extrusion experiments with EPDM 60 were performed on a production line at the Shanghai Saic-Metzeler Sealing Systems Corporation, China. A single-screw extruder was used to transport the EPDM rubber and the die temperature was fixed at 160°C. A straight parallel die and CAE optimized die, based on the following, were used in the extrusion experiments. When the rubber flow was steady, a part of the rubber extrudate, close to the die exit, was immerged into liquid nitrogen and frozen quickly. Thus, the shapes of extrudate by using different extrusion dies were easily recorded for comparison.

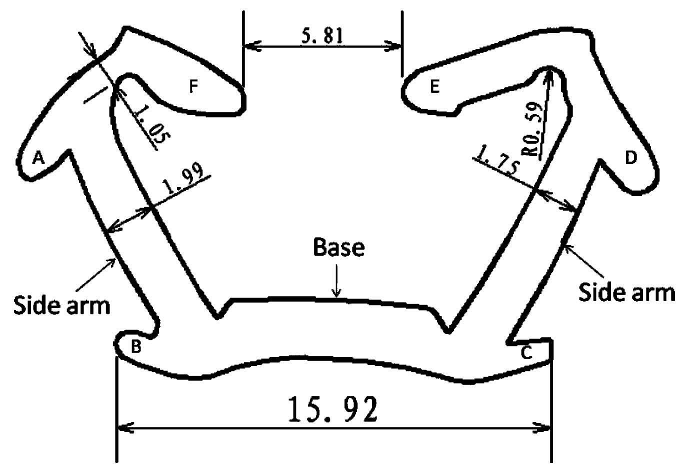

Fig. 1. Dimension of the extrusion die lip of an automotive rubber seal and the dimensional unit are millimeters.

2.2. *Scientific calculation experiments*

2.2.1. *Governing equations*

The flow of rubber fluid is subject to the conservation laws of mass, momentum and energy. Due to the high viscosity of EPDM melt, inertial force and self-weight effects are neglected. Moreover, EPDM flow in the die head is assumed to be isothermal and shear-dominant (10). Therefore, the conservation equations of mass and momentum can be described as follows (16):

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

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

Where **v** is the velocity, p is the isotropic pressure, η denotes the viscosity of the melt and ∇ is the gradient operator.

The dependence of the flow viscosity of EPDM 60 on the shear rate was measured by using a capillary rheometer (Rosand RH7-2, UK) and a rotational rheometer (Bohlin Gemini 200HR, UK) with parallel plates geometry (plate diameter 25 mm, plate gap 2 mm). The two different measuring methods showed a fairly good consistency between the low shear rates and high ones. Combining these data together, as shown in Figure 2, a strong shear thinning was found for EPDM under the shear. A well-known viscosity law, named Bird-Carreau, was adopted to describe the shear-thinning feature of this rubber composite:

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

Where η_0 is the zero-shear-rate viscosity, λ is the natural time, and m is the flow index. Through fitting the

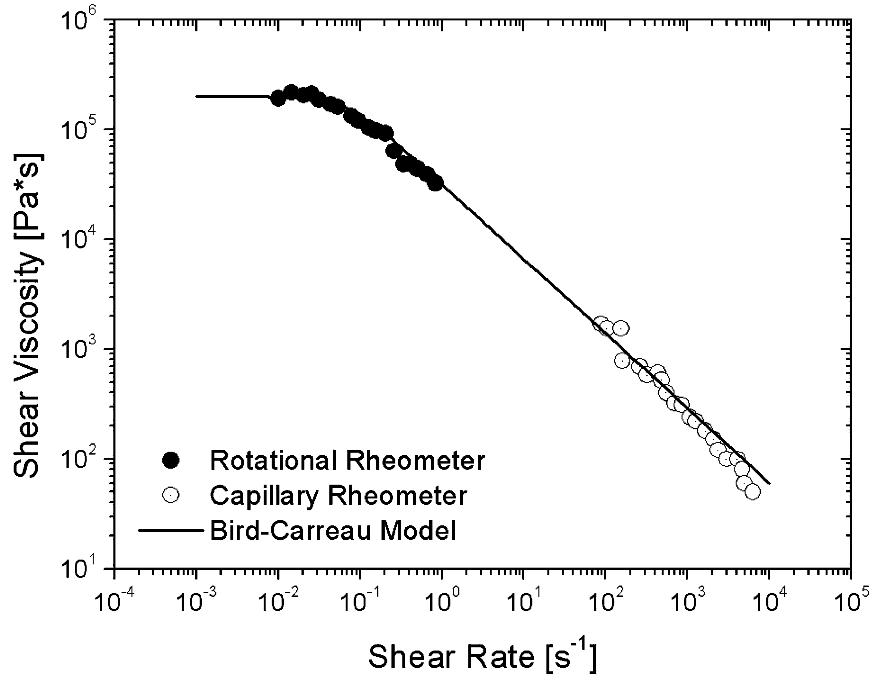

Fig. 2. Flow curve of EPDM 60 at 160°C and rheological model fitting.

experimental data was based on the least square method, we obtained the appropriate values for model parameters: $\eta_0 = 2.0 \times 10^5\ Pa \cdot s$, $\lambda = 15$s, m = 0.32.

2.2.2. *Computational domains and boundary conditions*

The flow channel in the die head is shown in Figure 3, including a reservoir and an extrusion die. The length of the extrusion die was fixed and set as 15 mm. A long extrudate part with the length of 100 mm was used in the model to get a uniform velocity profile at the end and account for all the deformation during the extrusion. A fully developed flow was assumed at the inlet of the 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 was calculated from the imposed volumetric flow rate Q_0. At the wall surface of the reservoir and the extrusion die, a no-slip condition was assumed. For the free surfaces of the extrudate, the normal force must be equal to zero. Moreover, the normal velocity must be also equal to zero, i.e. $\mathbf{v} \cdot \mathbf{n} = 0$, where **n** is the normal unit vector of the free surface. The whole computational domains are sub-divided by more than 50,000 unstructured finite element meshes, as also shown in Figure 3.

2.2.3. *Finite element algorithm*

The extrusion process of EPDM60 melt was solved by the Galerkin finite element method. The basic solution procedures are described in Figure 4. Due to the highly

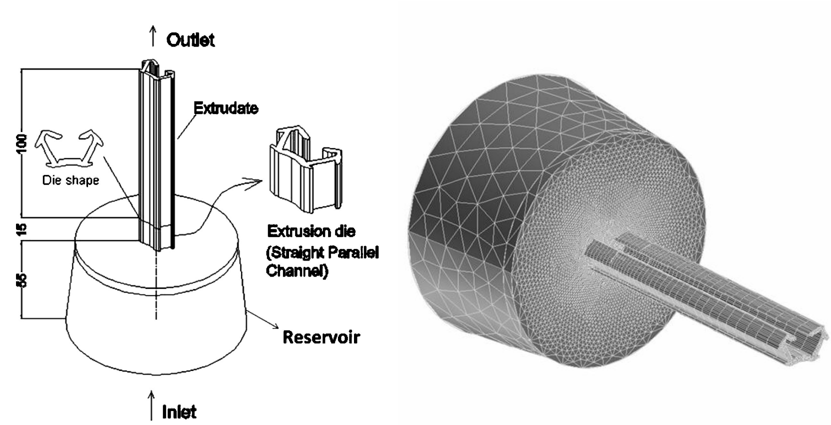

Fig. 3. Schematic of flow channel and finite element meshes.

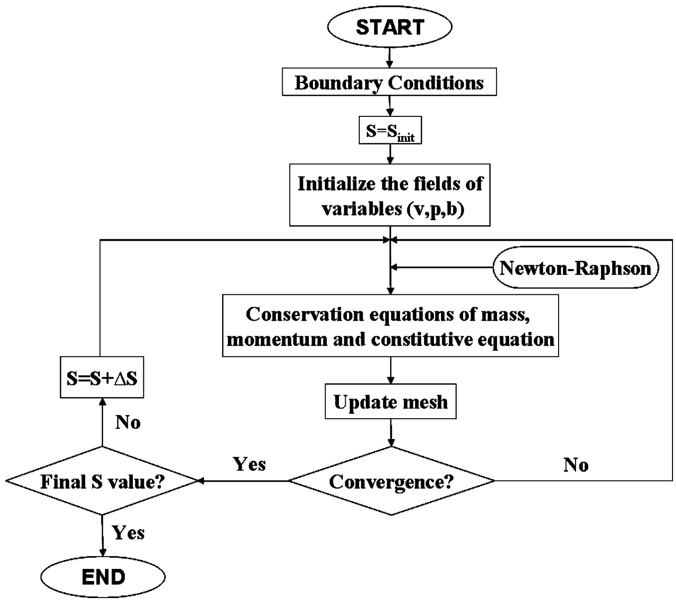

Fig. 4. Simulation algorithm.

non-linear nature of the problem, a parameter evolution was introduced in the algorithm (16~17). 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:

On the free surface:

$$(v \cdot n) = \{v \cdot n\} \cdot S \tag{4}$$

For the Bird-Carreau model:

$$m = \{m\} \cdot 1/S \tag{5}$$

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 then solved 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 the 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. $v \cdot n = 0$ for a free surface or imposed to zero for all other cases. In the tangential direction, nodes were relocated to satisfy the equilibrium of forces (17). 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.

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

Where V_i^n means the velocity at node i and iteration n. The convergence tolerance ε in our simulation was set to the value 0.0001. The solving procedures were executed on a PC with two AMD 2500+ MHz processors and a RAM size of 2048 M bytes. About one hour was needed to complete a computational project.

3. Results and discussion

The measure of the die balance is based on the deviation degree of normal velocity with respect to the average velocity along the die exit. The die balancing factor f is defined as follows:

$$f = \frac{1}{n} \cdot \sum_{i=1}^{n} (v_i - \overline{v})^2 = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(v_i - \frac{Q}{A}\right)^2 \tag{7}$$

With $\overline{v}$, Q and A being the average velocity, volume flow rate across the inflow boundary set and area of the die exit.

In addition, another parameter was also used to evaluate the die balancing, i.e.,

$$\sigma = (v_{\max,i} - v_{\min,i}) \tag{8}$$

Which represents the difference between the maximum and minimum velocity among the selected probe points along the die exit, referring to Figure 5.

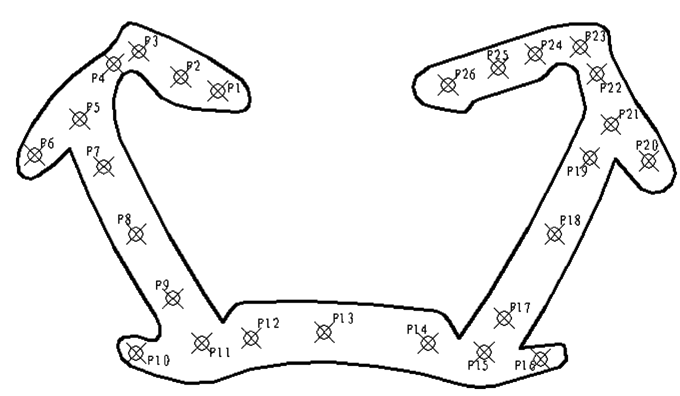

Fig. 5. Probe points at the die exit.

Totally, 26 probe points at the die exit were used to calculate the die balancing factor f and σ, as shown in Figure 5. The smaller the values of these two parameters, the more balancing of the die is expected; or vice versa.

3.1. *Parallel die*

At the first step, a parallel die, i.e., directly having a cross-section everywhere along the flow direction, the same as that of the desired product, was used as an initial one the same as the model shown in Figure 3. Extrusion experiment and CAE simulation of this parallel die were both conducted to measure the effect of die unbalancing. The flow rate was gauged as 15,000 $mm^3 \cdot s^{-1}$. The results are shown in Figure 6, which indicates a clear non-uniform fluid velocity at the die exit and the resulting great deformation of the EPDM extrudate. The calculated die balancing factor f was as great as 5566.2 and $\sigma = 272.3$ $mm^3 \cdot s^{-1}$. It was found that the velocity of EPDM melt in the bottom base and the intersection zone between the side arms and isolating branches were large, while the velocity was small in the six isolating branches. When the EPDM melt flows from the die, the flow develops from the confined flow to a free jet. The region with larger velocity will swell to slow down the flow, which also causes the redistribution of material along the cross-section. The deformation of the extrudate is very complex for the profile product and closely related with the velocity distribution at the die exit. In the case of the current parallel die, the final shape of the extrudate was recorded and compared with the die, is shown in Figure 6. Unacceptable deviation from the desirable product is observed and the extrusion die must be balanced or improved to suppress the great deformation.

3.2. *Balancing the die*

The basic principle to balance a die is to open the zones where the velocity is slow, while closing the zones where the velocity is too high. The procedures to form a new balancing die are illustrated in Figure 7 with a resulting die shown in Figure 8. As indicated in the results with the parallel die (Figure 6), very low velocity was observed in the six isolating branches, denoted as S1∼S6 in Figure 7. To balance the die, i.e., get the more uniform velocity along the die exit, these six zones at the entrance should be opened so that the area of each are nearly the same as that of the bottom base or side arms. The opening procedure can be easily accomplished in any CAD software such as AutoCAD or UG. The intersection parts of these enlarged branches are then eliminated and next the geometry is smoothed. The definition of the length of the opening zone finalizes the new die construction.

The amplifying ratios during the opening procedure are summarized in Table 1 with respect to the area of the bottom base. The area of the six isolating branches after opening was expected to be nearly the same as that of the bottom base or side arms. When EPDM flows across the newly opened cross-section, the material is redistributed and expected to be more uniform than the previous parallel one due to the equal area of these zones.

Comparing with the parallel die, the new balancing die consists of two parts, i.e., opening section connected with the reservoir and the subsequent finalizing section. The total length of the extrusion die was fixed, i.e., 15 mm in this study. The length of the opening section is supposed to affect the velocity distribution along the die exit; therefore the length of the opening zone is also an optimization factor for the die design. One of the new dies with equal length for both opening and finalizing sections, denoted as model I, was investigated as follows. The three-dimensional geometrical model of the die is shown in Figure 8. The velocity distribution at the die exit was concentrated on to investigate the improvement of die balancing after the adjustment according to the die balancing requirement.

The predicted velocity profile by using the model I is shown and compared with that of the straight parallel die

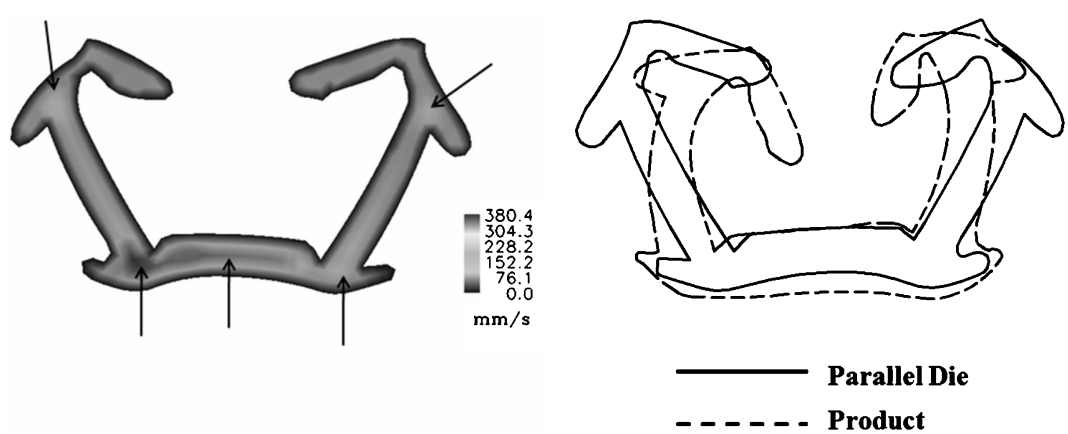

Fig. 6. CAE simulation and experimental results for a parallel die; left: predicted velocity distribution at the die exit; right: comparison of product shape and die.

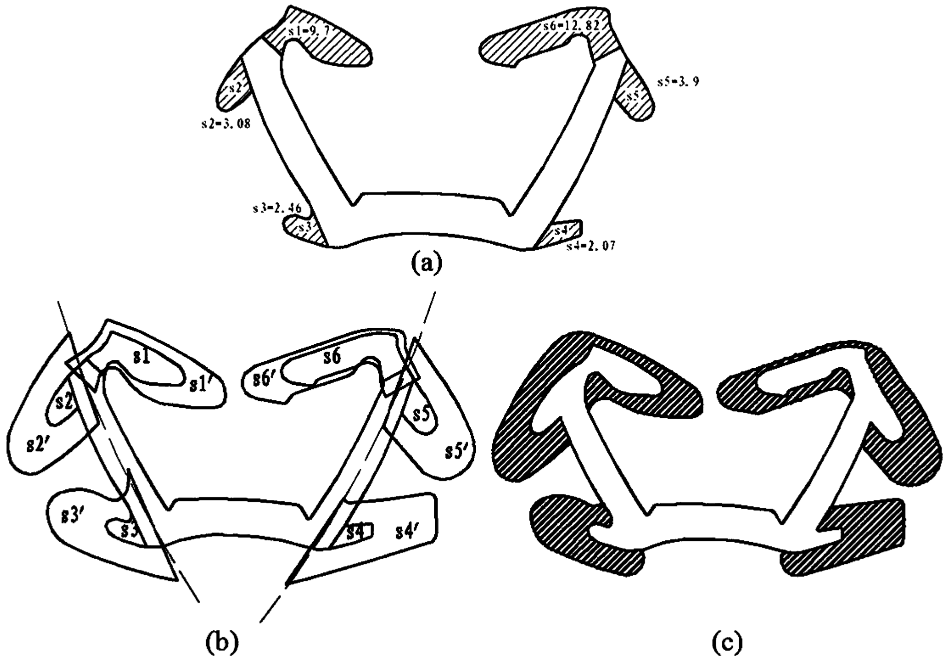

Fig. 7. Die balancing procedures: (a) identifying six isolating branches with low velocity; (b) opening the zones with low velocity; (c) smoothing and finalizing the die.

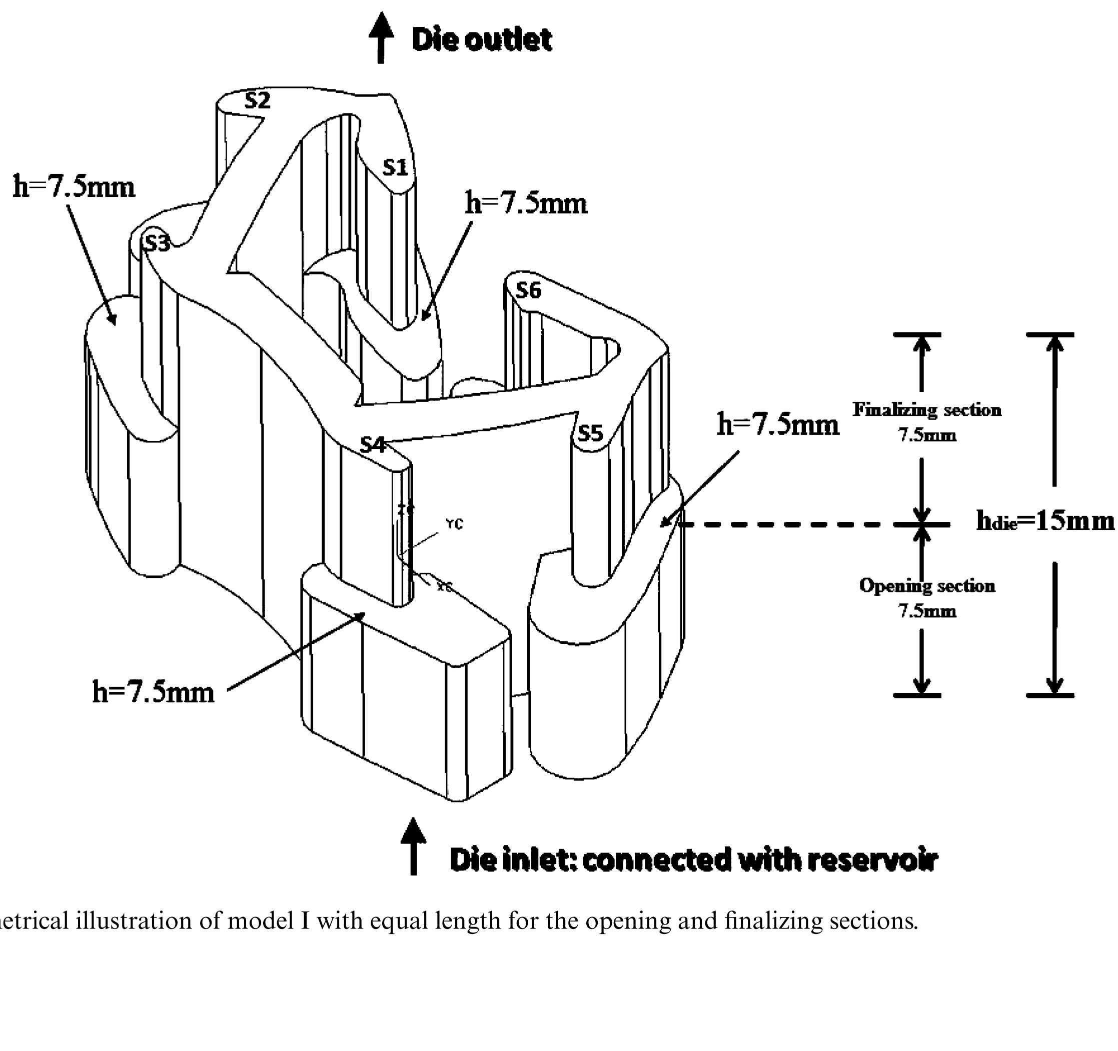

Fig. 8. Geometrical illustration of model I with equal length for the opening and finalizing sections.

Table 1. Amplifying ratio during the opening procedure

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*Bottom Base*
Area before opening (mm^2)	9.7	3.08	2.46	2.07	3.9	12.87	25.74
Area after opening (mm^2)	25.74	25.74	25.74	25.74	25.74	25.74	25.74
Amplifying ratio	2.65	8.36	10.46	12.43	6.6	2	1

in Figure 9. The two pictures in Figure 9 share the same scale legend of velocity. Comparison shows a more uniform velocity distribution at the die exit for the new die with the equal length of the opening and finalizing sections. In this case the measure of the die balance decreased from 5562.2 to 3635.7, which is about a 35% reduction. Another parameter, i.e., the difference between the maximum and minimum velocity, also reduced from 272.3 mm/s to 222.5 mm/s corresponding to an 18% decrease. Obviously we can conclude that a more balancing die was obtained following adjustment of the extrusion die based on the die balancing requirement.

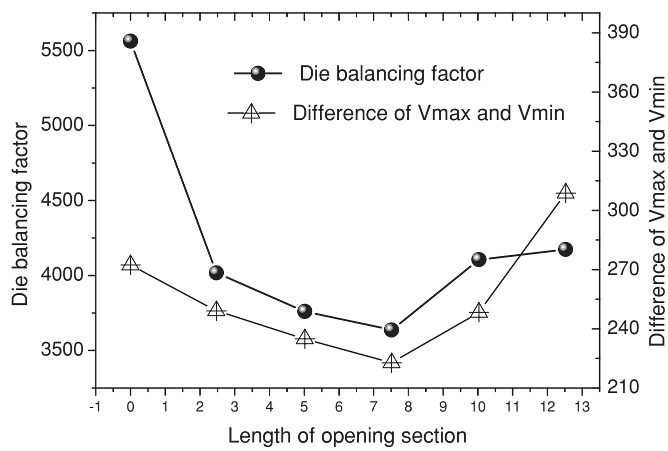

Fig. 10. Effect of length of opening section on the die balancing.

3.3. *Effect of length of opening section*

There was a sharp transition between the opening section just behind the reservoir and the subsequent finalizing zone. The variation of the opening section's length is supposed to affect the velocity distribution at the die exit. With CAE technology, a series of die designs involving changes in the length of opening section were quickly carried out on the computer system instead of actual operations. The measure of die balance was calculated with respect to the simulation result for each die design and summarized in Figure 10. Die balance was greatly improved when even a short opening section was cut at the beginning part of the extrusion die because the die balancing factor decreased greatly compared with the straight parallel die. In addition, the velocity at the die exit became more uniform as the length of opening section first increases and then become uneven again with the further lengthening of the opening section. The optimum value seems to lie in the half length of the whole extrusion die, i.e., 7.5 mm. The CAE analysis not only verifies the effect of die adjustment but also permitted determination of the optimum length of opening zone quickly, which greatly saves time and cost, and would be especially useful for new product development otherwise needing considerable practical processing experience by the operator.

3.4. *Further optimization of the extrusion die*

Reconsidering the best extrusion die indicated in Figure 10, the die consists of two sections with the same length: opening section and finalizing section. In this case, the length of opening zones corresponding to the six regions, i.e., S1~S6, is the same. Further balancing of the die was based on the principle proposed by Ruan et al. (5), For the opening section, the cross-section was unchanged but they suggest it is better to shorten the subsection leading to a narrow slit. The length of opening section corresponding to S5 and S6 zones was shortened from 7.5 mm to 5 mm, while the other parts remained the same with the previous one shown in Figure 8. The model is denoted as model II and shown in Figure 11. Through the CAE analysis, it was found that the measure of die balance for this design was reduced to

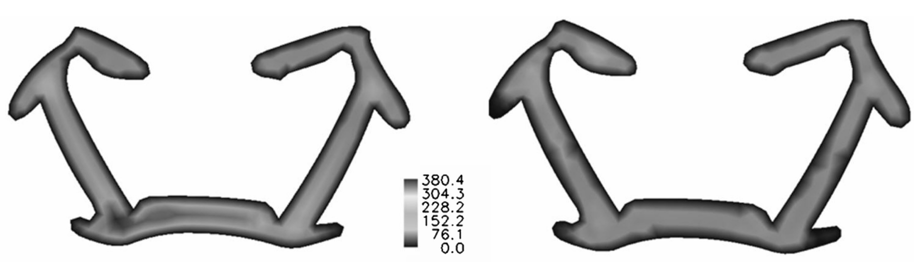

Fig. 9. Comparison of velocity distribution at the die exit between the parallel die and the new die with opening zone length 7.5 mm.

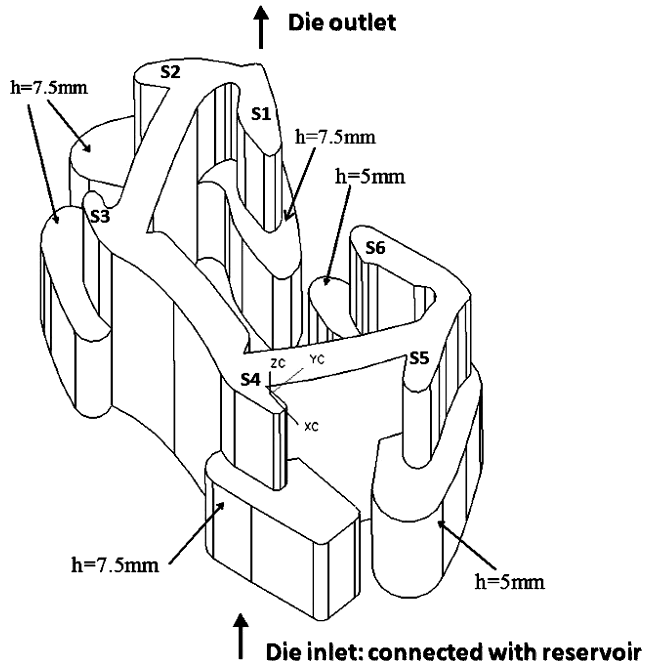

Fig. 11. Model II: further improvement by shortening the opening section's length corresponding to the narrowest slit.

as small as 3573.1 and the maximum velocity along the die exit was 205 $mm \cdot s^{-1}$. These data show a further improvement was obtained when we shortened the local opening zone corresponding to the narrow region at the die exit.

3.5. *Experimental verification*

A more balancing die, model II, was found through the CAE technology, as shown in Figure 11. A real extrusion die was then cut according to the geometry and dimension of the model in Figure 11. Figure 12 is a photo of the opening face of the real die that contains the desirable flow channel. The EPDM extrusion experiment was performed on the extrusion line fixed with this die. When the extrusion process was steady, EPDM extrudate was obtained and the shape of the EPDM extrudate was recorded as frozen to investigate the deviation from the die.

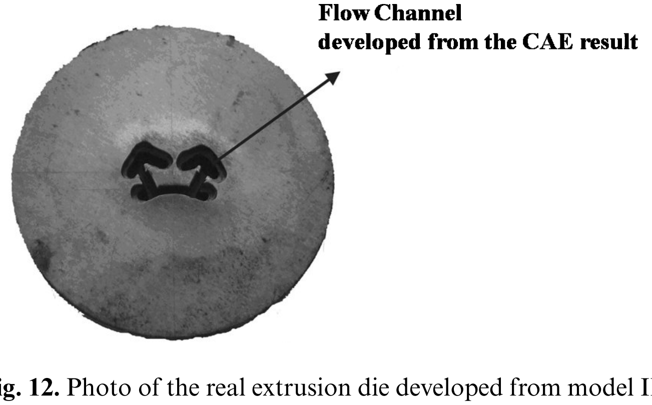

Fig. 12. Photo of the real extrusion die developed from model II.

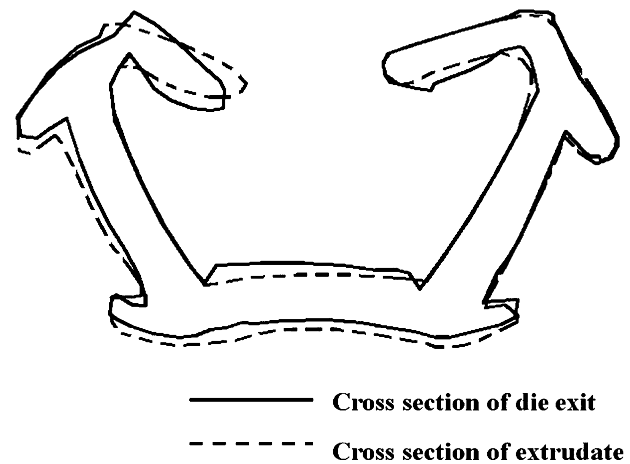

Fig. 13. Extrudate shape and comparison with extrusion die lip.

The improvement obtained using model II can be verified through the comparison in Figure 13. The dashed line describes the profile of the extrudate and is found to be very similar with the die lip. The die balancing greatly suppresses the swelling effect during the EPDM extrusion. The EPDM product produced by using model II was considered to be acceptable because the deviation between the product and the request was within the tolerance. Through this case and comparing with the traditional 'trial and error' method, it is advantageous to use the CAE technology to speed up die design process, which was shown to be time- and cost-saving and was also able to give us an overview of the flow in the complex profile die.

4. Conclusions

The combination of die balancing requirement and CAE technology was used to speed up the die balancing process of a kind of automotive rubber seal. By introducing two parameters, i.e., die balancing factors f and σ, the degree of die balancing was easily measured quantitatively for extrusion dies with different structures. The quantification and procedures of die balancing were first explained in detail and then the extrusion die was adjusted following the procedures. Simulation was carried out to assess the effect of the adjustment instead of actual operation. It was found that the addition of an opening section in the die provided a more uniform velocity distribution at the die exit than the parallel die. The length of opening section also affected the die balancing and an optimum length, i.e., about half of the die, was determined by CAE analysis quickly. Further optimization of the die was carried out by adjusting the local length of the opening section. Finally, a real die was cut based on the optimization results and used for production. Ideal profile products were obtained, which validated the advantage of CAE technology. To conclude, optimization conducted by CAE technology based on the die balancing requirement speeds up the die development process for profile extrusion. As all the optimization work is conducted on a computer platform, it is believed that the application of CAE technology in profile extrusion industry will greatly reduce the cost and development time of a product.

By experience, tapering the cross-section might be also helpful to balance the die, but in general it is difficult to be manufactured in real production. The die with opening section was not only easier to be made but also used more extensively in practice, which is more suitable and significant to be designed by simulation.

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