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ORIGINAL ARTICLE

Effects of ram velocity on pyramid die extrusion of hollow aluminum profile

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Abstract During the extrusion process of aluminum alloy, the ram velocity should be well controlled, since it is an important parameter affecting the profile quality and extrusion productivity. The effects of ram velocity on conventional porthole die extrusion have been investigated by some researchers, while its influence on pyramid die extrusion has not been fully clarified. Thus, in this study, the pyramid die extrusion process for producing a hollow rectangular aluminum tube was comprehensively investigated by performing analysis of steady state, transient state, and billet skin tracking. Importantly, the effects of ram velocity on some evaluation parameters of pyramid die extrusion, such as the material flow behavior, extrudate temperature, extrusion force, transverse weld, quality of longitudinal weld, and back end defect, were overall investigated. The results show that the flowing velocity, extrudate temperature, extrusion force, and welding pressure tend to increase as the increase of ram velocity, while the length of transverse weld is reduced at higher ram velocity. However, the effect of ram velocity on the back end defect is quite slight. Moreover, the advantages and shortcomings of pyramid die were also discussed by comparing with the conventional porthole die.

Keywords Pyramid die · Ram velocity · Extrusion force · Material flow · Back end defect

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1 Introduction

In recent decade, the consumption of aluminum profile experiences sustained and rapid growth worldwide. The extruded aluminum profile has been widely used in the fields of traffic transportation, civil architecture, aerospace, and automobile due to its advantages in light-weight, less exhaust emissions, high surface quality, and easy recycling [1–6]. It can be forecasted that the aluminum profile will act as one of the dominant materials in a long period of the future.

The porthole die extrusion has been proved to be the most suitable method to produce hollow aluminum profile due to its high capacity and low cost [7, 8]. In order to improve the extrusion process and profile quality, the extrusion industry has put large efforts on pursuing the optimum geometry of the porthole die. Under such circumstances, an innovative porthole die called pyramid die was developed in recent years. The front end of port-bridge was designed to have a draft angle for pyramid die rather than a flat shape for conventional porthole die. Therefore, it was expected that the pyramid die could be effective in reducing the extrusion load. However, the other advantages and shortcomings of such modification on port-bridge have not been well studied. On the other hand, the process control, especially the determination of ram velocity, is also quite important, since it has been reported that the ram velocity could significantly affect the evaluation parameters of extrusion, such as the material flow behavior, extrudate temperature, extrusion force, and welding quality. If the ram velocity is inappropriate, it might cause some defects on the dimensional accuracy and mechanical properties of the profile [9]. Hence, it is of great importance to clarify the effects of ram velocity on the pyramid die extrusion, which could be helpful to have a deep understanding on such innovative die.

The extrusion process generally involves in large degree of plastic deformation, complex friction conditions, high temperature, and high pressure. Moreover, it is difficult to perform accurate measurements inside the enclosed die during extrusion in practice. With the rapid development of computer technology, the numerical simulation has become a powerful tool on studying extrusion process. Bastani et al. [10] performed the finite element simulation to study the influence of process parameters, such as the ram velocity, initial billet temperature, and cooling rate of container, on the temperature evolution and the material flow behavior during flat die extrusion. Jo et al. [11] analyzed the porthole die extrusion of an aluminum tube by performing non-steady state finite element simulation, and the effects of initial billet temperature and extrusion ratio on extrusion force, surface quality, and welding pressure were well concluded. Abdul Jawwad et al. [12] predicted the maximum extrusion force at varying billet temperature, extrusion ratio, and ram velocity by artificial neural network (ANN)-based partial modeling technique. Fang et al. [13] investigated the effects of ram velocity on extrudate temperature and extrusion force during flat die extrusion of a complex solid profile by means of 3D simulation. Ketabchi et al. [14] investigated the influence of ram velocity and billet temperatures on the backward extrusion process of AA7075 using the software of Defom-3D, by which the forming load and stress/strain distribution were obtained. Li et al. [15] studied the formation and evolution of transverse weld through 2D finite element simulation and discussed the factors affecting the length of transverse weld. Zhang et al. [16] analyzed the effects of ram velocity on the material flow, extrudate temperature, extrusion force, and welding pressure during the porthole die extrusion of a hollow aluminum profile through steady state simulation. Reggiani et al. [17] found that the sticking friction model could well reflect the evolution of transverse weld. Liu et al. [18] carried out finite element analysis for porthole die extrusion of magnesium square tube and found that the quality of longitudinal welding could be enhanced at higher ram velocity. Hatzenbichler et al. [19] studied the effects of billet temperature, ram velocity, and friction condition on the appearance of back end defect during rod extrusion by a numerical sensitivity study with finite elements.

From the above open literature, it is known that the process parameters are of great importance on controlling profile quality, and the numerical simulation technology has been proved to be an accurate tool in studying the extrusion process. However, to the best knowledge of the authors, the report about the pyramid die extrusion is still quite rare.

The main purpose of the present study is to clarify the effects of ram velocity on the pyramid die extrusion process. Thus, a pyramid die for producing hollow aluminum profile was designed, and the finite element simulations including the steady state, transient state, and billet skin tracking analysis were carried out, respectively. Moreover, a conventional porthole die was designed and analyzed to reflect the advantages and shortcomings of pyramid die. Finally, it should be pointed out that the present study considered the aspects of material flow behavior, extrudate temperature, extrusion force, length of transverse weld, quality of longitudinal weld, and back end defect. Hence, the finite element simulation was selected as the main tool due to its convenience and time saving.

2 Design of extrusion dies

Since the present study focuses on the influence of ram velocity, a rectangular aluminum profile was selected as the study object to reduce the complexity. Figure 1 shows the dimension and geometry of the profile, which has an outer side length of 60 mm and equal wall thickness of 2 mm.

A conventional porthole die was designed for the rectangular profile, the 2D and 3D drawings of which are shown in Fig. 2. It should be noticed that the location pins and coupling bolts that will not affect the extrusion process were neglected for simplification. The upper die has a height of 75 mm and a diameter of 180 mm. To obtain uniform material flow behavior, four symmetrical portholes were designed in the upper die. The chamfering of 30° is applied on both sides of the port-bridges. The height and diameter of the lower die were 55 and 180 mm, respectively. The design of welding chamber significantly affects the quality of longitudinal weld. In the present case, the welding chamber has cylindrical shape with a height of 13 mm. The bearing was set to have an equal length of 8 mm, and the run out with two steps was designed to support the bearing band and ensure that the profile could be successfully extruded out from the die orifice.

The pyramid die investigated in this paper was designed on basis of the conventional porthole die. The most remarkable

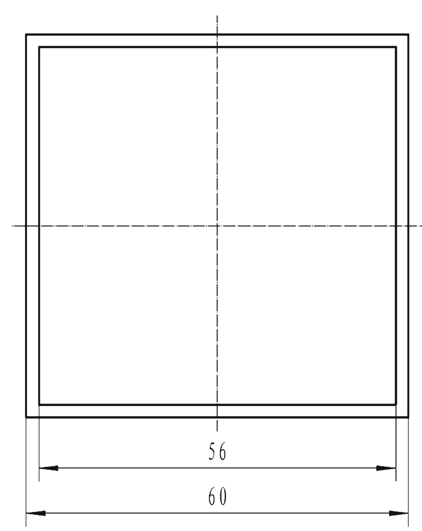


Fig. 1 Dimension and geometry of the hollow aluminum rectangular pipe. (Unit, mm)

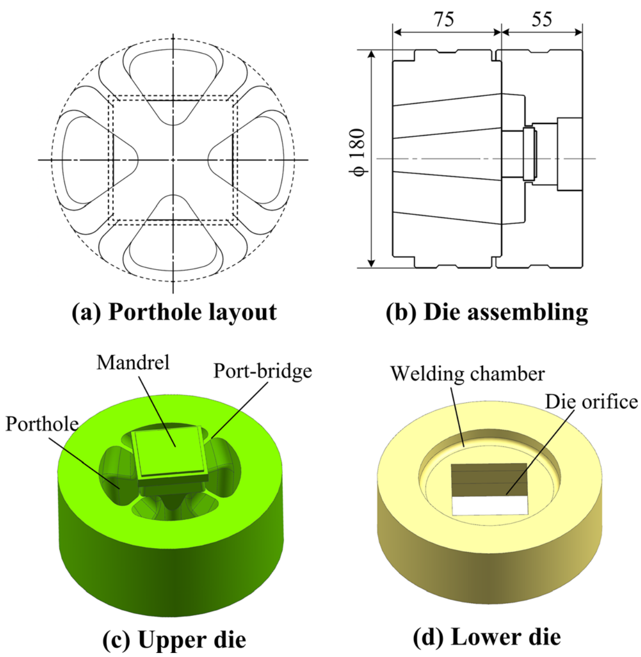


Fig. 2 Conventional porthole die designed in this study. **a** Porthole layout, **b** die assembling, **c** upper die, **d** lower die. (Unit, mm)

difference between these dies is the modification on port-bridge, as shown in Fig. 3. The front end of port-bridge, viz., the entrance side of billet, was designed to have a draft angle of 30° for pyramid die rather than a flat surface for conventional porthole die. Moreover, the chamfering of 30° was adopted at the front end of port-bridge to reduce its width to 6 mm. The dimension and geometry of the other components in pyramid die were kept same as the porthole die in order to make a comparative study.

3 Numerical modeling

The present simulation work was based on Arbitrary Lagrangian Eulerian (ALE) algorithm provided by the commercial code of HyperXtrude. Since large deformation occurs during the extrusion process, the ALE method has advantages in avoiding the mesh distortion emerged in Lagrangian algorithm and the problems of free surface tracking emerged in Eulerian algorithm [20]. In this paper, different types of analysis were carried out to have comprehensive understanding on pyramid die extrusion. The steady state analysis was used to obtain the information of material flow, extrudate temperature, and welding pressure, while the transient state analysis with moving boundary condition was performed to study the formation and evolution of transverse weld. Moreover, the back end defect was investigated through the billet skin tracking analysis.

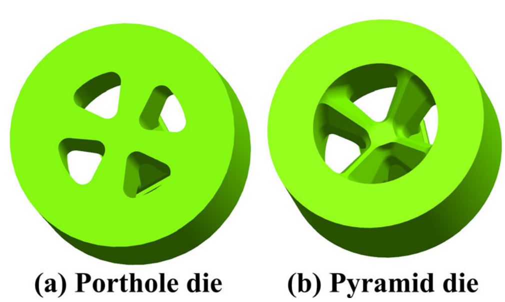


Fig. 3 Upper die of the **a** conventional porthole die and **b** pyramid die

3.1 Mesh generation scheme

The domains that material flows through were extracted from the 3D model of the porthole and pyramid dies. For the convenience of applying different boundary conditions, these domains were divided into different components, as shown in Fig. 4a. The components of bearing and profile would experience severe shear deformation, and thus fine tri-prism elements with size of 0.5 mm were meshed for them. The tetrahedral elements were used for the other components, and the element size varied from 0.5 to 8.0 mm in accordance with the degree of deformation. For example, the deformation in billet domain is slight and the element size is set to be 8.0 mm. By such kind of mesh generation scheme, both of the accurate simulation results and reduction of computation time could be achieved. The model shown in Fig. 4a is used for the steady state and transient state analysis.

For billet skin tracking analysis, the billet skin with a thickness of 2 mm was added as an additional component, as shown in Fig. 4b. There are two layers of elements in the cross section of billet skin. And it should be noticed that the element size in Fig. 4b for both of the billet and skin is set to be much smaller than that shown in Fig. 4a, in order to obtain accurate evolution behavior of the billet skin.

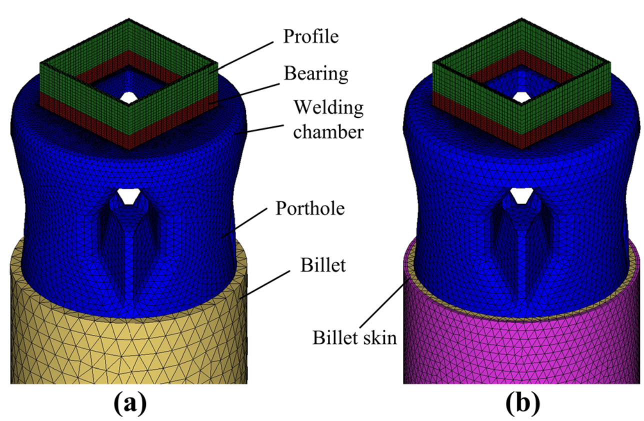


Fig. 4 Mesh generation scheme for analysis of **a** steady state and transient state and **b** billet skin tracking

3.2 Material properties and constitutive equation

The billet material is aluminum alloy 6005 with viscoplastic behavior. Aluminum alloy 6005 has medium strength and excellent corrosion resistance and has been widely applied in extrusion process to produce profiles used in railway and bus bodies. H13 tool steel as the most common material of for extrusion die was used for both of the porthole and pyramid dies. Some of the important physical and thermal parameters of the AA6005 and H13 tool steel used in the present simulation were listed in Table 1.

An appropriate constitutive equation that could well describe the flow stress of AA6005 under different deformation condition is essential to obtain accurate simulated results. It has been proved that the Sellars-Tegart model is suitable for aluminum alloy [21, 22], which is expressed as:

$$\sigma = \frac{1}{\beta}\sinh^{-1}\left(\frac{\dot{\bar{\varepsilon}}e^{Q/RT}}{A}\right)^{1/n} \tag{1}$$

where σ is the flow stress; $\dot{\bar{\varepsilon}}$ is the mean equivalent strain rate; R is the universal gas constant; Q is the activation energy for deformation; T is the absolute temperature; β, n, and A are the material constants. The exact values of above parameters for AA6005 used in the present simulation were R=8.314 J/(mol K), Q=1.648E5 J/mol, n=3.649, A=7.55E10 s^{-1}, β=3.96E−8 m^2/N.

3.3 Process parameters

The process parameters used in the simulation work were determined according to the practical production. The initial temperature for AA6005 billet was set to be 460 °C, while the temperature of container and extrusion die was 430 °C. The diameter and height of the cylindrical billet were 114 and 230 mm, respectively, and the calculated extrusion ratio is around 21.2. The ram velocity (v) was varied from 0.5 to 5.0 mm/s to study their effects. The friction condition during extrusion is complex, and thus different friction models were applied. The sticking condition was adopted on the surfaces between billet and tool (container and die) except the bearing band, since it can be considered that there is no relative motion on these surfaces due to strong adhesion [17, 23, 24]. The coulomb friction model was adopted on the surfaces in contact with bearing, and the friction coefficient was 0.3 [25, 26].

For transient state and billet skin tracking analysis, the variable time steps were used to reduce the total computational time. At the initial 5 s, each step was set to be quite small to reach the steady state, and the following time steps were enlarged to reduce the computational time. The meshes of profile, bearing, and porthole were fixed during the proceeding of simulation, but the dummy block and billet would keep moving down.

Table 1 Physical and thermal parameters of AA6005 and H13 used in the present simulation

	AA6005	H13 Steel
Density (kg m^3)	2700	7870
Thermal conductivity (W/(m K))	180	24.3
Specific heat (J/(kg K))	896	460
Coefficient of thermal expansion (1/K)	1.0E-5	–
Young's modulus (Pa)	4.0E10	2.1E10
Poisson's ratio	3.5E-1	0.35

4 Results and discussion

4.1 Effects of ram velocity on flowing velocity

The material flow behavior during extrusion process is often complex, and many researchers have performed work on the optimization of process parameters and die design to make it favorable. The ideal material flow pattern should ensure that the material flows out from the die orifice with the same velocity. Otherwise, the defects of twist, wave, and curve easily emerge in the profile, which is detrimental for its dimensional accuracy. In this study, the distribution of flowing velocity in the cross section of the profile is similar at varying ram velocity, and thus only one group of the simulated results at v=2.0 mm/s was shown in Fig. 5 as an example. Since the mesh generation cannot be kept strictly symmetric, the slight non-symmetric of flowing velocity was observed. Due to the strong resistance on material flow at the corners of the profile, the flowing velocity at the corner is generally slower than the other parts in both of porthole and pyramid dies. The maximum and minimum flowing velocity of the profile in each case was summarized and plotted in Fig. 6. It can be seen that the flowing velocity increases almost linearly with the increase of ram velocity, which is consistent with the actual condition. Moreover, the velocity difference for pyramid die is always higher than that of the porthole die, and the maximum difference of 23.96 mm/s appears in pyramid die when v=5.0 mm/s.

In order to quantitatively evaluate the uniformity of flowing velocity, the index of velocity relative difference (VRD) was introduced here, which can be described as:

$$VRD = \frac{\sum_{i=1}^{n}\frac{|v_i - \bar{v}|}{\bar{v}}}{n} \tag{2}$$

where v_i is the velocity for node i, $\bar{v}$ is the average velocity for all nodes, and n is the total number of selected nodes for

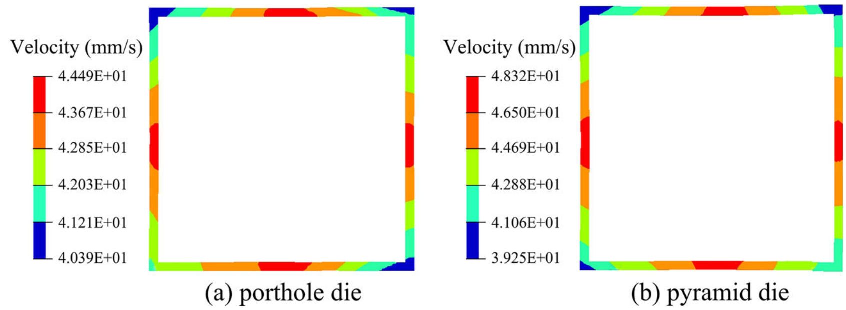


Fig. 5 Distribution of flowing velocity at the ram velocity of 2.0 mm/s. **a** Porthole die and **b** pyramid die

calculation. In this study, all of the nodes in the profile cross section were selected for calculation, where n=2352. The *VRD* values for all cases were plotted in Fig. 7. It can be seen that the *VRD* has higher values with the increase of ram velocity, and it is always higher for pyramid die than that of the porthole die. This evidence indicates that the modification on port-bridge has some negative effects on the distribution of flowing velocity in this study. To further improve the material flow behavior during pyramid die extrusion, some optimization work on die structure should be carried out.

4.2 Effects of ram velocity on extrudate temperature

The extrudate temperature is another important evaluation indicator for extrusion process, which should be paid high attention to. If it is too high, some defects such as oxidation and over burning might occur resulting in the profile scrapping. Moreover, the distribution of extrudate temperature should also be uniform. Otherwise, it might cause harmful effects on the final microstructure and mechanical properties of the profile. Figure 8 shows the distribution of extrudate temperature at v=2.0 mm/s. It can be observed that the region with high temperature corresponds to the region with high flowing velocity, as shown in Fig. 5. Moreover, the maximum and minimum extrudate temperature for each case is plotted in Fig. 9. It is obvious that the increase of ram velocity leads to higher temperature for both dies. The heat generation during extrusion process is mainly due to the plastic deformation and friction, among which the plastic deformation is the dominant one. With the increase of ram velocity, the plastic deformation becomes severe and there is not enough time for heat dissipation. Both of these reasons are responsible for the rise up of extrudate temperature. Moreover, it should be noticed that the pyramid die has higher temperature at the same ram velocity, which is in line with the tendency shown in Fig. 6. The peak plot of 553 °C appears in pyramid die at v=5.0 mm/s, which is close to the melting temperature of AA6005 (605 °C). Thus, it could be concluded that the extrudate temperature depends on the material flow behavior. Higher flowing velocity indicates severe plastic deformation and more heat generation, which causes the rise up of extrudate temperature. It is expected that the extrudate temperature for both porthole and pyramid dies could be reduced if the material flow behavior is well controlled.

4.3 Effects of ram velocity on extrusion force

The prediction of extrusion force is an important reference for choosing appropriate extruder. For a given profile, higher required extrusion force needs an extruder with higher capacity, which would increase the investment of equipment. On the other hand, higher extrusion force aggravates the wear of die

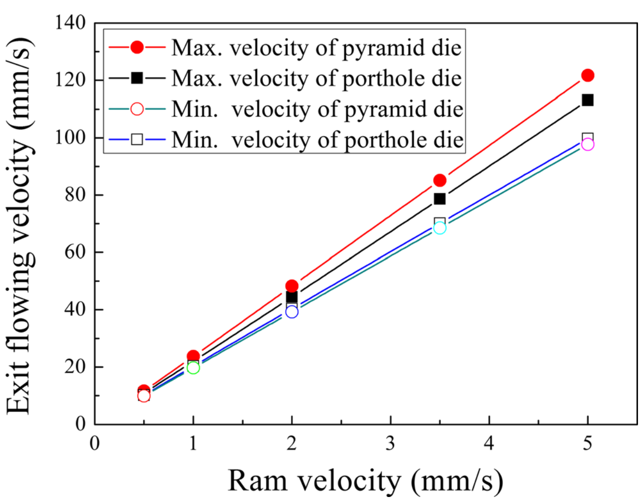


Fig. 6 Maximum and minimum flowing velocity at varying ram velocity

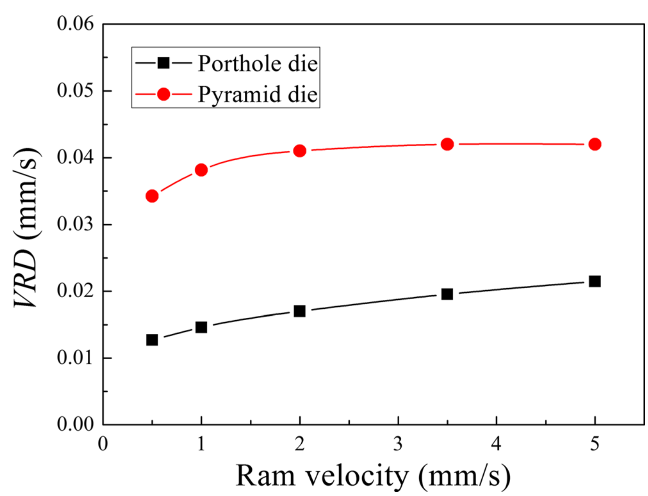


Fig. 7 Effects of ram velocity on *VRD* in profile cross section at die exit

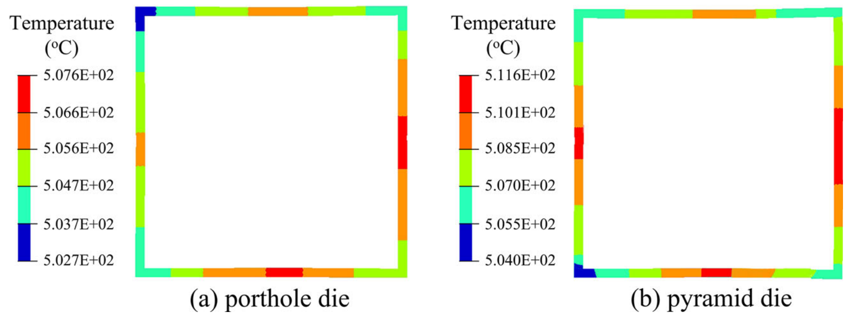


Fig. 8 Distribution of extrudate temperature at the ram velocity of 2.0 mm/s. **a** Porthole die and **b** pyramid die

and reduces the die service life. Figure 10 gives the relationship between ram velocity and extrusion force for both of porthole and pyramid dies. It can be seen that the extrusion force significantly increases, especially at relative low ram velocity. The amount of extrusion force mainly depends on two opposite factors, viz., the work hardening and material softening due to the rise up of temperature. The work hardening is the dominated one and becomes severe with higher ram velocity, and thus causes the increase of extrusion force. However, the extrudate temperature could reach high level at high ram velocity as discussed in effects of ram velocity on extrudate temperature section, which brings obvious material softening and counteracts the work hardening. This reason explains that the increase of extrusion force becomes slowly at high ram velocity.

It should also be noticed from Fig. 10 that the pyramid die is effective in reducing the extrusion force, and the reduction at ram velocity varying from 0.5 to 5.0 mm/s is calculated as 8.9, 8.5, 8.4, 7.7, and 7.3 %, respectively. For pyramid die, its port-bridge has conical shape and smaller width, which makes the occurrence of material dividing gradually and reduces the contacting friction between billet and port-bridge. Moreover, the billet near the center of upper die will become to dead zones because it is difficult to flow into the portholes, and this region is much smaller for pyramid die, which is also beneficial for reducing extrusion force.

4.4 Effects of ram velocity on transverse weld

The transverse weld is a common characteristic in case of continuous extrusion. In practice, after finishing one billet, the new billet will be loaded into the container and then the extrusion continues. Under this circumstance, the interface between old and new billet could be welded by high pressure and temperature. This welded interface maintains flat shape at the initial stage. However, with the proceeding of extrusion, it could be bended to a tongued or parabolic shape due to the complex material flow pattern. Finally, the old/new billet interface appears in one certain length of the profile. The formation and evolution of transverse weld in pyramid die extrusion with v=1.0 mm/s are shown in Fig. 11. The timing of loading new billet was defined to 0 in the present study. The blue and red colors represent the old and new billets, respectively. It can be seen that the profile contains full old billet at the initial stage (Fig. 11a), since the old billet remained inside the porthole and welding chamber should be firstly extruded out. Then the new billet starts to emerge (Fig. 11b), and the profile gradually changes to complete new material (Fig. 11c, d).

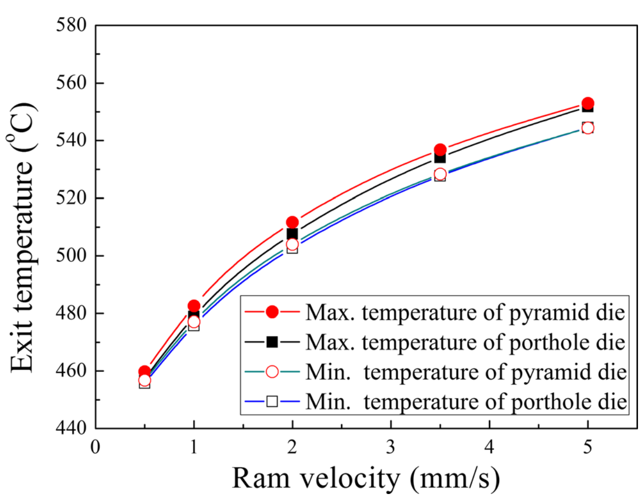


Fig. 9 Maximum and minimum extrudate temperature at varying ram velocity

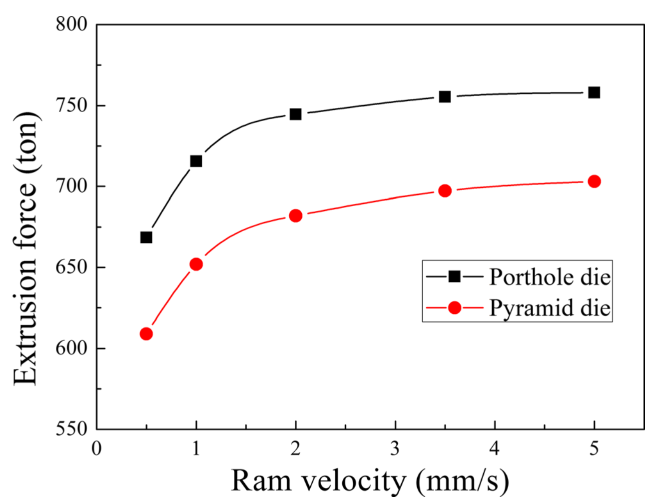


Fig. 10 Relationship between ram velocity and extrusion force

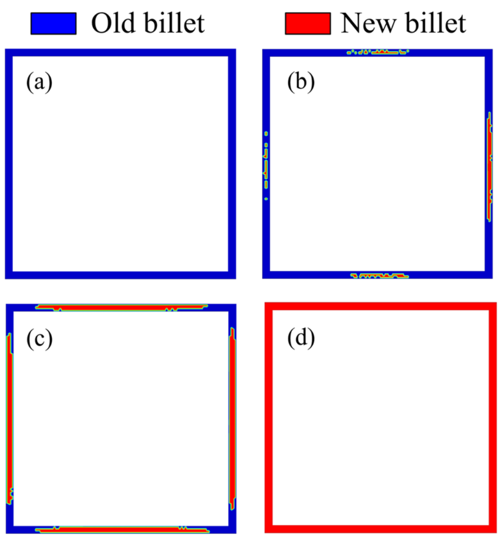


Fig. 11 Evolution of transverse weld in pyramid die extrusion at ram velocity of 1.0 mm/s

The transverse weld represents a discontinuity of the profile, which can significantly reduce the profile strength. Hence, the manufacturers usually expect to minimize the length of transverse weld through process control and die optimization. It can be seen from Fig. 12 that the percentage of new billet increases rapidly at the initial stage for each case, while in order to reach 100 % it takes long time. This is because the old billet exists in dead metal zone is difficult to be 'washed away' by the flowing of new billet. The transverse weld length (l_{TW}) could be approximately calculated by finding the position of 100 and 0 % of new billet. And it was found that the increase of ram velocity reduces l_{TW} for both dies. Moreover, by comparing Fig. 12a and b, one can see that the appearance of transverse weld is always laggard in pyramid die than that of the porthole die at the same ram velocity. This phenomenon is because that more amount of old billet was stored in the hollow space surrounded by the conical port-bridges, which needs longer time to be extruded out before the appearance of new billet. Based on the observation of Fig. 12, it is known that the pyramid die might be beneficial for the reduction of l_{TW}.

4.5 Effects of ram velocity on welding pressure

During the porthole die extrusion, the billet was firstly split by the port-bridge into several metal streams under high pressure. After that, these metal streams flow out from the portholes and enter the welding chamber, where they would rejoin together and form the so called longitudinal weld. Since this phenomenon occurs without any metal melting, the longitudinal weld easily becomes to the weakest point during the application of profile. Thus, its quality control is of great importance for designing one extrusion process.

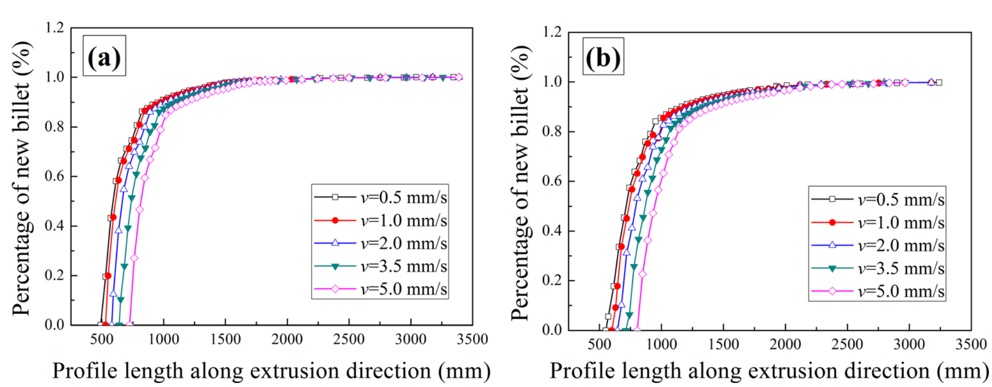
It has been widely accepted that the welding pressure, viz., the hydrostatic pressure in welding plane, is an indicator for welding quality. Figure 13 presents the results of average welding pressure with different ram velocity. One can see that the welding pressure gradually increases with higher ram velocity for both dies. Moreover, the welding pressure of pyramid die is always higher, such as 204.2 MPa in comparison with 182.5 MPa for porthole die at v=5.0 mm/s. This evidence indicates that the port-bridge with conical shape is preferable for transferring force to welding plane. Thus, the pyramid die might obtain better longitudinal welding quality due to the higher welding pressure, although its extrusion force is relative smaller.

4.6 Effects of ram velocity on back end defect

The so called back end defect means that the billet skin flows inside the die cavity and further emerges in the cross section of profile. The billet for extrusion is generally fabricated by cast and homogenization heat treatment, and thus the skin might contain some oxidation. Once the skin material appears in the profile, it will be detrimental on the profile's continuity and compactness.

To investigate the effects of ram velocity on back end defect, the billet skin analysis was carried out. The skin evolution during pyramid die extrusion at v=1.0 mm/s was presented in Fig. 14. Due to the friction between billet/container interface and flow stress difference resulting from the temperature gradient along the cross section of billet [27], the center part of the billet has faster flowing velocity, which causes the skin aggregates at the

Fig. 12 Relationship between profile length and percentage of new billet at varying ram velocity during **a** porthole die extrusion and **b** pyramid die extrusion



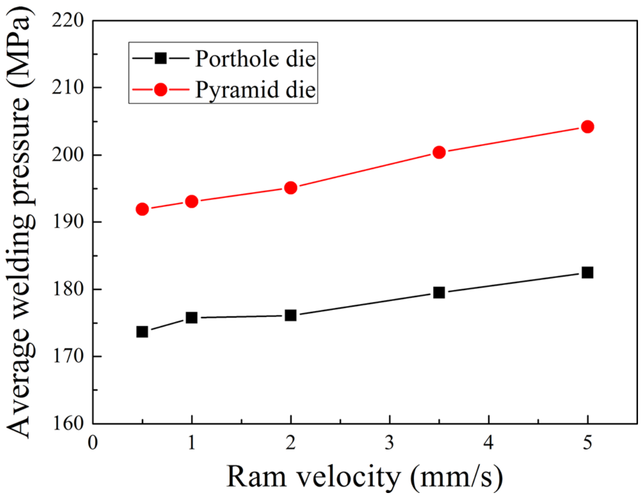


Fig. 13 Variation of average welding pressure at varying ram velocity

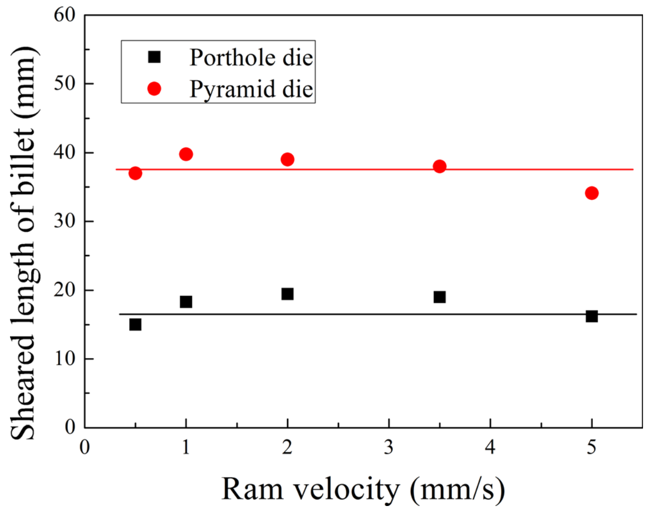


Fig. 15 Effects of ram velocity on the sheared off length of billet

billet center, as shown in Fig. 14a and b. At the simulation time of 190 s as shown in Fig. 14c, the skin starts to flow inside the portholes. At this timing, the remained billet should be sheared off in practice to avoid the occurrence of back end defect.

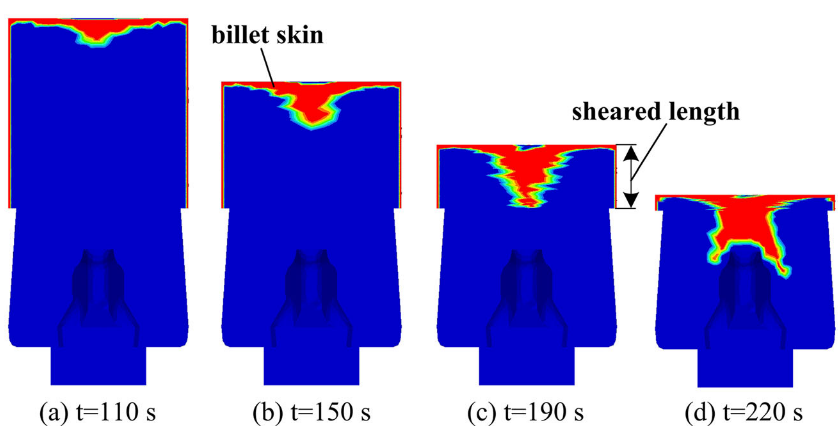
Figure 15 plots the sheared length of billet to avoid the occurrence of back end defect at different ram velocity. It can be seen that the effects of ram velocity are not obvious. For a given die, the change of sheared billet length is slight at varying ram velocity, which shows good agreement with Hatzenbichler's report [19]. It can also be observed that in case of pyramid die, more billet around 20 mm should be sheared off in comparison with the porthole die. One of the reasons is that the port-bridge with conical shape and smaller width cannot provide strong resistance for the material flow in the billet center, and higher flowing velocity causes the skin flowing downward more rapidly.

5 Conclusions

In this paper, the pyramid die extrusion process of a rectangular AA6005 tube was comprehensively studied by performing different types of finite element analysis. The effects of ram velocity on material flow behavior, extrudate temperature, extrusion force, transverse weld, longitudinal weld, and back end defect were overall investigated. Additionally, the conventional porthole die extrusion for the same profile was also studied to provide comparison.

It was concluded that with higher ram velocity, the *VRD*, extrudate temperature, extrusion force, and welding pressure during pyramid die extrusion increases obviously, while the length of transverse weld tends to decrease. And the effect of ram velocity on the appearance of back end defect is slight based on the billet track analysis. By comparing with the porthole die, pyramid die shows the advantages in providing higher welding pressure, reducing extrusion force, and transverse weld length. However, with respect of material flow, exit temperature, and back end defect, the pyramid should be further optimized to obtain good performance. Finally, it should be pointed out that this paper is a preliminary study on the pyramid die extrusion, and more experimental work should be carried out in future to gain detailed information.

Fig. 14 Evolution of billet skin during pyramid die extrusion at ram velocity of 1.0 mm/s. **a** *t*=110 s, **b** *t*=150 s, **c** *t*=190 s, **d** *t*=220 s



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

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