Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 31
ISSUE 2
December
2008

3D finite element analysis of metal flow in hot aluminium extrusion of T-shaped profile with various offset pockets

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Received 13.09.2008; published in revised form 01.12.2008

Analysis and modelling

ABSTRACT

Purpose: The present paper has therefore investigated influence of offset pocket design on metal flow behaviour in hot aluminium extrusion of a T-shaped profile.

Design/methodology/approach: A series of finite element simulations have been carried out by offsetting the centre of pocket cross-section and examining exit velocity distributions of the profile cross-section for each case.

Findings: That the offset pocket has influence on the metal flow during extrusion process. Small distance between the edge of the pocket and the edge of the die leads to slow flow velocity but if the distance is large the metal can flow through easily, hence higher velocity. With the information from the analyses, the new pocket was proposed. The velocity difference across the cross-section of the extrude was smaller compared to the original pocket. The extrudate is straight and not bent. Offsetting pocket can therefore be used to control metal flow to the die.

Practical implications: The appropriate design of pocket will help in regulating the metal flow and lead to a single bearing length or even zero length bearings. This is more favorable than a flat die with varying bearing lengths as a pocket die could be more easy to machine or correct especially extrusion of a thin walled profile. The pocket is usually required for extrusion of complex geometries. The fundamental understandings of pocket design are currently inadequate. It depends heavily on the experience of the die designer. Limited work has been done towards systematically examining influences of the pocket geometries and offsets on metal flow.

Originality/value: The present paper has therefore investigated influence of offset pocket design on metal flow behaviour in hot aluminium extrusion of a T-shaped profile of which its cross-sectional width varies. Its shape factor is 6.76 . The thermal effect has also been incorporate. An appropriate pocket die design for a T-shaped profile has later been proposed.

Keywords: Extrusion; Finite element model; Aluminium; Die design; Pocket design; Metal flow

1. Introduction

Aluminium extrusion is a hot forming process in which a hot aluminium billet is pressed through a die of required shapes. This process is widely used to manufacture products such as heat sinks, structural frames and furniture accessories. Product quality and extrusion productivity of the extrusion process depend highly on performance of an extrusion die. Die design and die making are the most important aspects of the entire extrusion process. A good die design must be able to maintain uniform exit velocity throughout a profile cross-section, in order to avoid twisted, bent, or out of tolerance extrudates. Balance of flow is critically important for sections with varying thickness. In general, thicker wall sections flow faster than thinner ones and areas near the centre of the die flow faster than areas near the container wall.

Traditionally, the control of flow has been achieved using variable bearing lengths. The length of the bearings over which the aluminium passes are adjusted locally so that the frictional forces act to balance any asymmetry of the velocity. The disadvantage of this method is that the bearings generate heat due to friction, which limits the extrusion speeds attainable before poor surface quality or localised tearing of the extrudate occurs. For this reason, it is beneficial to use the shortest bearings possible [2].

To enable the use of short bearings, material flow can also be controlled primarily using a shaped pocket (or feeder) in front of the die. The appropriate design of pocket will help in regulating the metal flow and lead to a single bearing length or even zero length bearings. This is more favorable than a flat die with varying bearing lengths as a pocket die could be more easy to machine or correct especially extrusion of a thin walled profile. The pocket is usually required for extrusion of complex geometries. The fundamental understandings of pocket design are currently inadequate. It depends heavily on the experience of the die designer. Limited work has been done towards systematically examining influences of the pocket geometries and offsets on metal flow.

Many orks have employed finite element method to simulate extrusion process. Lee and Im [1] performed a three dimensional analysis of extrusion to investigate the deflections of extruded products exiting from the flat dies with various bearing lengths. While Li et al. [2,3] performed two dimensional finite element analysis to investigate the effects of pocket geometric parameters on metal flow during extrusion under isothermal condition. Peng and Sheppard [4] managed to carry out three dimensional finite element simulation of extrusion process with thermal effect incorporate. They studied the influence of the pocket on material flow in multi-hole extrusion with the circular cross-section profile of which shape factor is low. The pocket, however, is usually utilised in extrusion of a thin walled profile with varying cross-sectional width.

The present paper has therefore investigated influence of offset pocket design on metal flow behaviour in hot aluminium extrusion of a T-shaped profile of which its cross-sectional width varies. Its shape factor is 6.76 . The thermal effect has also been incorporate. A series of finite element simulations have been carried out by offsetting the centre of pocket cross-section and examining exit velocity distributions of the profile cross-section for each case. An appropriate pocket die design for a T-shaped profile has later been proposed.

2. Validation of parameters used in finite element simulations

In order to experimentally validate the parameters chosen for the finite element models of extrusion process, a simple finite element model has been set up to simulate the extrusion experiment given in [8]. The profile considered was of rectangular cross-section, dimensions of which are shown in Fig. 1.

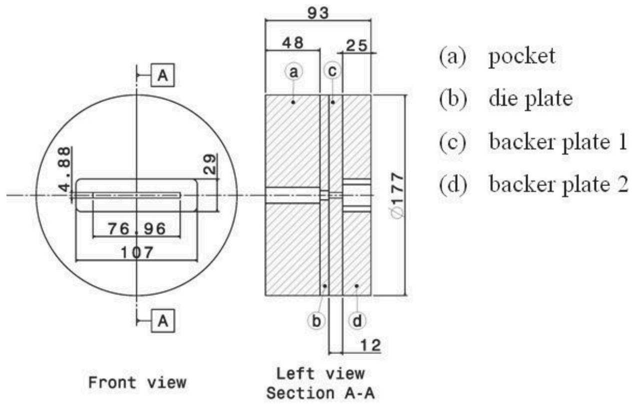

Fig. 1. Dimension of die and profile used for validation

The billet material used here was AA6063 with rigid-viscoplastic behaviour. The billet and tooling temperature were set at 480 ºC to enable the investigation to focus on the metal flow at anisothermal conditions. The friction between the container and the billet contributes significantly to the complexity of the extrusion. At the interface, the friction resistance approaches the shear resistance of the hot material during deformation. A fraction or all of the displacement of the billet occurs by shear in its surface layers leaving a fragment of the billet deposited on the wall of the container. In practice, aluminium alloys are extruded with, if not at all, only a small amount of graphite applied to the die face. Unlubricated aluminium extrusion is desirable since it prevents impurity pick up from the tools. Furthermore, it ensures that the material making up the extrudate surfaces comes from pure material within the billet.

The conditions at the billet/container interface during extrusion has a direct effect on metal flow, the stresses acting upon the tools and the material, the load and energy requirements as well as the extrudate temperature. Studies have shown the friction coefficient ranging between 0.8 and 1 based on experimental observations and they have indicated that the friction coefficient is approximately a constant during the extrusion regardless of the initial extrusion temperature. Clearly neither of these methods of establishing the value of friction is satisfactory and for design purposes, the friction is usually assumed to be 0.85 [5]. The physical properties of the billet and tooling used in the simulation are listed in Table 1.

Table1.
Physical properties of the workpiece and tooling

Properties	AA6063
Heat capacity (N/mm^2 ºC)	2.433
Thermal conductivity (N/s ºC)	180.2
Heat transfer coefficient between workpiece and die/container/ram (N/s mm ºC)	5
Heat transfer coefficient between die/container/ram and air (N/s mm ºC)	0.02
Emission	0.7

The plastic behaviour of the aluminium is defined via the flow stress. It describes the relation between the effective stress ($\bar{\sigma}$)

and the equivalent viscoplastic strain rate ($\dot{\bar{\varepsilon}}$). The Zener-Hollomon law [6] is used here, i.e.

$$\dot{\bar{\varepsilon}} = A\left(\sinh\left(a\bar{\sigma}\right)\right)^n \exp\left(-H/RT\right) \qquad (1)$$

Plastic properties for AA6063 alloy are listed in Table 2

Table 2.
Plastic properties for AA6063 alloy [7]

Aluminium alloy	a	n	A (s^{-1})	H (J/mol)	R (J/mol K)
6063	0.04	5.4	6 x 10^9	1.4 x 10^5	8.314

The ram pressure throughout the extrusion cycle obtained from FE and experiment is shown in Fig. 2. It can be seen that the findings agree well once the process is in steady state, i.e. after the peak pressure is reached. As a result, the parameters proposed, including the material and friction parameters, are used throughout the study.

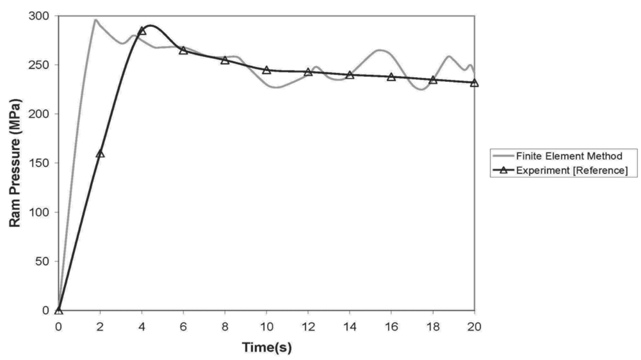

Fig. 2 A comparison of ram pressure between experimental and finite element findings

3. Finite element simulations

3.1. Geometries of the profile and the pocket

A T-shaped profile has dimensions as shown in Fig. 3. The width of web is twice larger than that of the flange.

The extrusion flat die has a uniform bearing length of 5 mm. The pocket has the same shape and firstly with the same centre as the flat die as shown in Fig. 4. Therefore, the pocket angle is the same around the die aperture. This pocket was also used as a reference pocket.

To study the effects of offset pockets on the metal flow, the pocket in Fig. 4 which has the same centre as the flat die was displaced vertically so that its centre is eccentric. Four cases were generated as detailed in table 3. The study did not consider to shift the centre of the pocket left or right due to the fact that the profile is symmetric about the vertical axis.

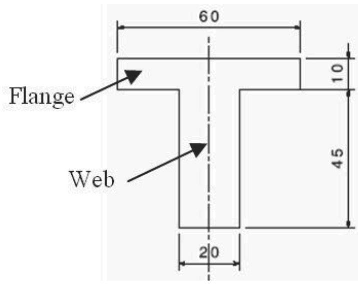

Fig. 3. Dimensions of T-shaped profile

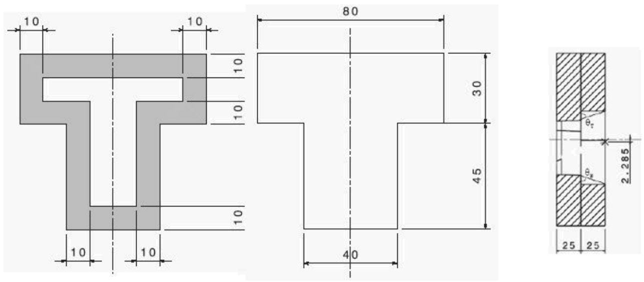

Fig. 4. (a) Dimensions of T-shaped pocket and pocket angles

Table 3.
Details of each offset pocket case

Direction / Distance	Downward	Upward
3 mm	Case 1	Case 3
5 mm	Case 2	Case 4

3.2. Development of finite element model

With the die and pocket geometries described in the previous section, the finite element model was established for steady state extrusion. Fig. 5 shows the configuration of the extrusion process components. Since the T shaped is symmetry about the vertical axis, only haft of the T shaped was modeled and meshed in three-dimension.

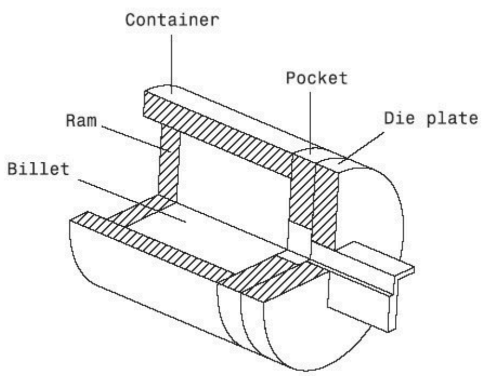

Fig. 5. Configuration of the extrusion process components

The container has the diameter of 131 mm. For simplicity, the ram speed is constant at 6 mm/s. Assuming that the tooling and container are rigid. The material parameters, temperature, shear friction coefficient used here are the same as those used in section 2 which were already validated.

4. Results and discussion

4.1. Extrusion of T-shaped profile with standard pocket

The contour line of flow velocity across the section during steady state operation is present in Fig. 6. It is obvious that the velocity distribution is inhomogeneous. The velocity of the web is generally greater than the that of the flange. The far left and right of the flange (label H in Fig. 6) experiences the slowest velocity. This is due to the fact that the width of the flange is smaller. Also the middle area of the flange has higher velocity than both left and right.

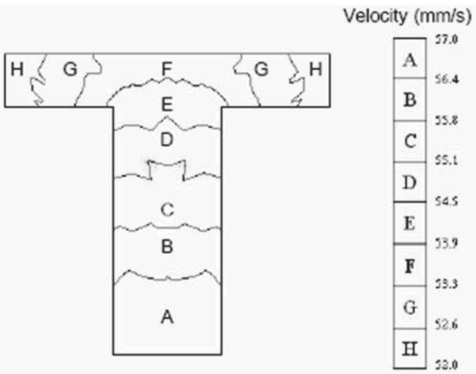

Fig. 6. Distribution of exit velocity across T-section

Fig. 7 shows the plot of exit velocity at various locations across the profile cross section. The graph shows the velocity at location (0-1) is relatively high while at locations (3-4) and (5-6) the velocity is relatively low. The inhomogeneity of the flow velocity across the section leads to upward bent extrudate as shown in Fig. 8. It can be said that using a single bearing length with a pocket centre to a die aperture is not suitable for a varying thickness profile. This simulation case was employed as a reference case in order to compare its result with those obtained from the offset pockets. The next section, the pocket would be offset from the centre of the die aperture.

4.2. Extrusion of T-shaped profile with offset pocket

By shifting the centre of the pocket to various positions along the vertical axis, four cases were studied as described in Table 3. Figure 9 shows comparisons of exit velocities at various locations across the T-section for all five cases including the reference case.

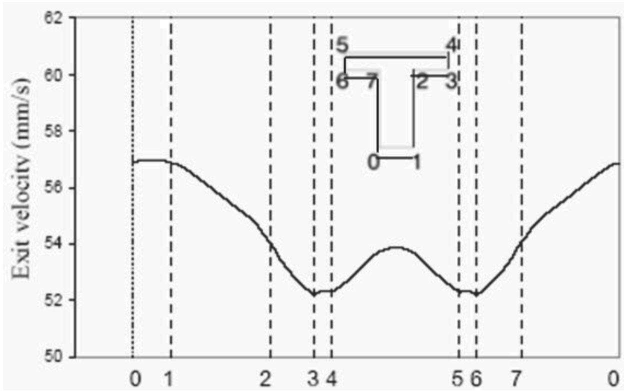

Fig. 7. Graph showing the exit velocity at various locations of the T-section profile

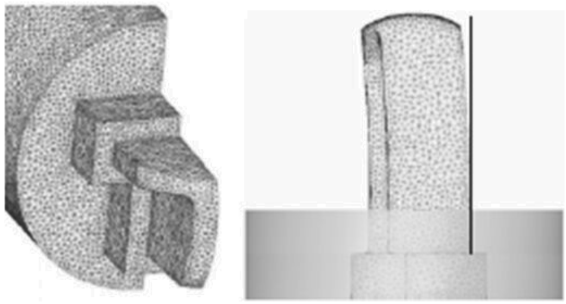

Fig. 8. The T-shaped profile at the die exit

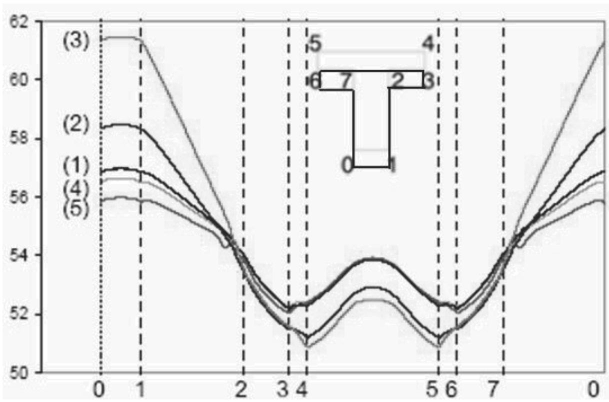

Fig. 9. Graphs of exit velocity at various locations: (1) reference case (centered pocket), (2) case 1 (downward 3 mm), (3) case 2 (downward 5 mm), (4) case 3 (upward 3 mm), (5) case 4 (upward 5 mm)

Results show that shifting the centre of the pocket upward leads to slower exit velocity at the location (0-1) compared to those of the reference case. This is because the edge of the pocket at the location (0-1) came closer to the die aperture. The material volume surrounds that edge decrease. The pocket angle is also smaller. This causes difficulty for metal to flow into the die. The reverse effects occurred if the pocket centre displaced downward as seen in the Fig. 9. The similar effects were also evident at the flange area. However, the exit velocity at the far left and right of the flange location (3-4) and (5-6) does not change much because the distance between the edge of the pocket and the flat die does not change for all cases considered here. The contribution to the change in velocity for this locations (3-4) and (5-6) are from the change occurred at location (2-3) and (6-7).

The velocity at location (1-2) and (7-0) results from the distance changed in location (0-1) and (2-3).

From these analyses, shifting the pocket centre upward for this T shapedd profile results in small velocity difference. While shifting the pocket centre downward results in large velocity difference. Apart from translating the pocket centre up or down the centre of the pocket can also be changed by increasing the distance between the edge of pocket and the edge of the die aperture in some locations. By doing so, the pocket angle will also be changed. The studies show that the smaller the distance between the two edges, the smaller the pocket angle. It can also be said that small pocket angle results in slower velocity in that location.

5. Improvement of the pocket design

The new design of the pocket was proposed based on the analyses in section 3.1 and 3.2 to achieve uniform velocity across the T-section of extrudate with the aim to regulate the flow. Since the web of the T-shaped profile is twice larger than the flange width. With the standard pocket and a single bearing length, the velocity of the web area was greater than the velocity of the flange. By moving the centre of pocket upward results in a slower velocity in the web and a little higher velocity on the flange. Therefore, the new pocket would be designed by shifting the pocket centre upward 7 mm so that the velocity location (0-1) would be reduced more. The critical location would be the location (3-4) and (5-6) where the velocity is slowest. In addition, shifting pocket up causes a little effect on the velocity at these location. However, the change in velocity is instead affected by the change occurred at the location 2 and 7. It is seen in Fig. 9 in the previous analyses that the velocity decreases from point 2 to point 3 and from point 7 to point 6. This is because point 2 and point 7 are close to the centre of the die than point 3 and 6 respectively. The new pocket are design to regulate the velocity along locations (2-3-4) and (5-6-5) by decreasing the velocity at point 2 and point 7 and increasing velocity at the location (3-4) and (5-6). These can be done by reducing the distance, in both x and y directions, between the edges of pocket and the die at location 2 and 7 and increase distance between the pocket and the die radially around point 3 and point 6. At the midpoint of the flange the velocity is quite high. It can be reduced by reduced the distance between the edges of the pocket and the die at the edge nearby the midpoint. The proposed pocket design is shown in Fig. 10. The plot of exit velocity at various location is shown in Fig. 11.

It has been found that the velocity at the (0-2) location is more uniform and velocity difference at location (2-3) and (6-7) reduces from 3.33% for the reference case to 2.88% for the proposed pocket. In addition difference between the velocity at the mid point of the flange (4-5) and the velocity at point 4 and 5 decrease to 1.84% compared to the reference case is 2.84%. The standard deviation of the velocity across the T-section is 0.729 which is less than the reference case. The profile obtained using the new pocket design is straighter that the other cases as shown in Fig. 12.

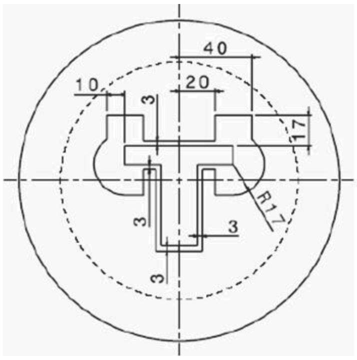

Fig. 10. The new design pocket

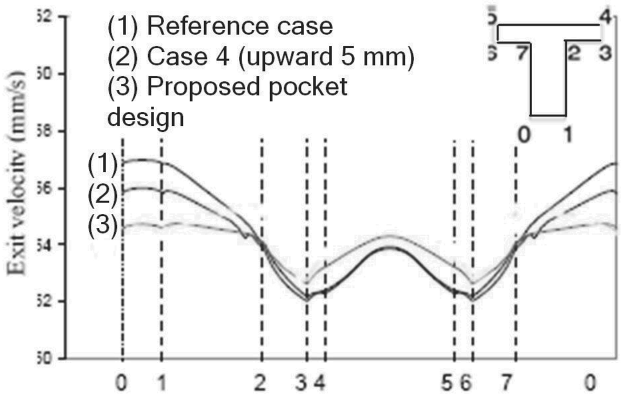

Fig. 11. Group of exit velocity at various locations

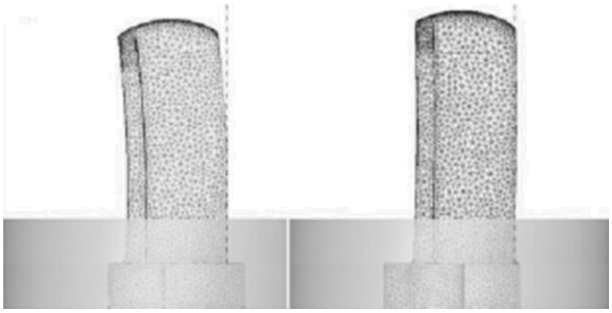

Fig. 12. Comparison of extrudates that extrude using (a) standard pocket (b) the proposed pocket

6. Conclusions

Finite element model was developed for hot aluminium extrusion to study the influence of offset pocket by performing a series of simulations for various positioned pocket. It was found that the offset pocket has influence on the metal flow during extrusion process. Small distance between the edge of the pocket and the edge of the die leads to slow flow velocity but if the distance is large the metal can flow through easily, hence higher velocity. With the information from the analyses, the new pocket was proposed. The velocity difference across the cross-section of the extrude was smaller compared to the original pocket. The extrudate is straight and not bent. Offsetting pocket can therefore be used to control metal flow to the die.

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