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SIMULATION OF STEADY-STATE EXTRUSION THROUGH A HOLLOW DIE USING HYPERXTRUDE FE SOFTWARE

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Abstract

Die design for light-metal extrusion relies on the experience of the die designer. Die performance is only known after the die is manufactured and tested on the extrusion press. The die designer needs a tool that can provide an insight into metal flow through the die at the design stage. The extrusion process engineer needs the same tool to set optimum process parameters for the highest possible productivity and product quality. Computer simulation based on the finite element (FE) method can be such a tool, if software, material model, material data, boundary conditions and simulation parameters are all appropriate to represent the real process. The majority of commercial FE codes are based on the updated Lagrangian approach. Using these codes to simulate the industrial extrusion process with large billet and tooling sizes is time-consuming. HyperXtrude is an FE code based on the Arbitrary Lagrangian-Eulerian (ALE) approach and needs far less time to simulate the process in the steady state. The present study was aimed at assessing the capabilities of HyperXtrude to simulate the extrusion process through a porthole die to produce a rectangular tube. The effects of billet temperature, heat transfer between billet, die and air, and ram speed on the extrusion pressure and extrudate temperature were investigated. The extrudate temperature was found to keep rising during steady-state extrusion and the amplitude in the range of 40–90°C depending on the billet temperature. Being different from the heat transfer coefficient between the billet and die, the heat transfer coefficient between the die and surrounding air strongly influenced the extrudate temperature and extrusion pressure. Increasing ram speed led to monotonous increases of the workpiece temperatures inside the container and die welding chamber, while the effect on the pressures inside the container and die welding chamber was complicated by heat generation.

Key words: extrusion, finite element method, aluminium

1. INTRODUCTION

In the light-metal extrusion process, die is the heart, as it largely determines the process efficiency and material recovery. The extrusion technology to a great extent concerns the die technology. The die designer must ensure not only the shape and dimensions of the extrudate, but also the most effortless metal flow and sufficient die life. In the past, the design of the die for the commercial extrusion process was based on the experience of the die designer, because analytical calculation tools available were only applicable for simple extrudate shapes. A porthole die used to produce a hollow extrudate is too complex for any analytical methods such as the upper bound method or the slab method to deal with. It is usually quite difficult to design a hollow die first time right. As a result, more cycles of die correction and trial are needed, before the die can be put into use for the production of light-metal profiles. Obviously, die trials are non-productive and must be minimized, ideally to zero. To reach the target of

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"first time right", the die designer needs a quick, reliable, predictive tool to know how metal flows through the die. The same tool is needed by the extrusion process engineer who must set the process under an optimum condition for the highest possible productivity and product quality after a minimum number of trial extrusion runs.

In recent years, numerical simulation using finite element method (FEM) has been increasingly applied to the extrusion process, thanks to the fast development of computer hardware and software. Extensive work has been carried out to optimise the die design, for example, to optimise the die bearing length for improved extrudate surface finish (Kloppenborg et al., 2008; Miles et al., 1997), and to select proper die layout and pocket geometry for unified metal flow (Fang et al., 2009). Most of the investigations carried out so far deal with the transient state of the extrusion process, concerning the first billet only. It is impractical to extend the simulation to the steady state, because of the long computation time needed for simulation using FE codes based on the Lagrangian approach (Donati & Tomesani, 2005; Liu et al., 2007a, 2007b & 2008). Actually, the extrusion process in the steady state is also of interest for the die designer who needs to know the shape and dimensions of the extrudate as well as the pressure on and temperature of the die and for the extrusion process engineer who needs to know the effect of process parameters on the extrudate temperature and extrusion pressure till the end of repeated cycles. There is a lack of the knowledge of the steady-state extrusion process through complex dies, contributing to a larger number of trial extrusion runs. Moreover, in simulation research using the codes based on the Lagrangian approach, the extrusion die has been almost exclusively assumed to be rigid. In reality, plastic deformation occurs to the die, leading to the change of the dimensions and shape of the extrudate and even to die failure (Arif et al., 2003). It is of critical importance for the die designer to capture the deformation of a complex die and know its effect on the shape and dimensions of the extrudate beforehand.

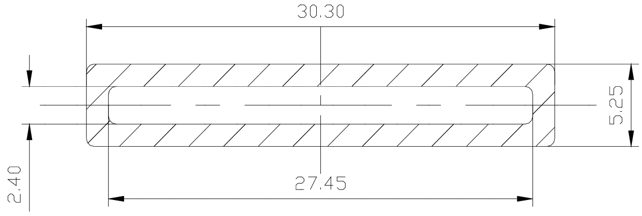
In the present study, the steady-state extrusion process through a porthole die to produce a rectangular tube was simulated using the commercial FE software HyperXtrude (version 7.0) based on the Arbitrary Lagrangian-Eulerian (ALE) approach, which had been expected to need far less computation time. The effects of process variables (billet temperature and ram speed) and boundary values (heat transfer coefficients) on the extrudate temperature and extrusion pressure were investigated, because the combination of these parameters dictates the amount of heat generated and dissipated during the process and thermal management holds the key to the extrusion process.

2. NUMERICAL MODEL

2.1. Geometry model and mesh

Figure 1 shows the rectangular tubular extrudate with a wall thickness of 1.4 mm and the porthole die used in the present study to extrude the thin-wall tube. Detailed dimensions of the billet and extrusion tooling are given in table 1.

(a) Rectangular tubular section



(b) Geometry of the porthole die

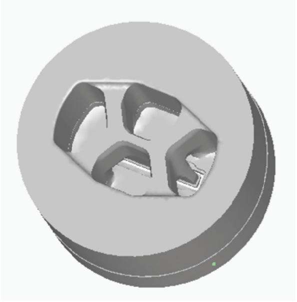
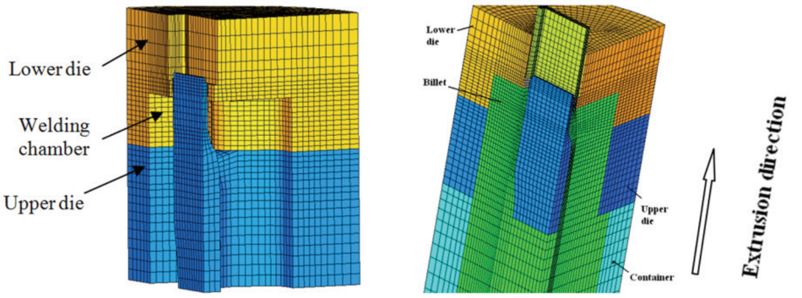


Fig. 1. Geometry of the tubular section and the porthole die used to produce the extrudate.

Table 1. Dimensions of the billet and extrusion tooling.

Billet length (mm)	100
Billet diameter (mm)	50
Container diameter (mm)	50
Extrusion ratio	21.6
Bearing length (mm)	8

Because the billet, extrusion tooling (container, die and follower pad) and extrudate were all symmetrical, only a quarter of the objects were modelled to save simulation time. The mesh generated in the lower die, upper die, container and billet consisted of 61,889 hexahedral elements, as shown in figure 2.



(a) mesh of the porthole die **(b) mesh of the die, billet and container**

Fig. 2. *FE mesh for steady-state extrusion simulation.*

2.2. Material model

The most common aluminium alloy for extruded products, AA6063, was used as the billet material in the present FEM simulation. The modified Sellars–Tegart model having a hyperbolic sine form to correlate the effective flow stress with strain rate and temperature was considered appropriate to describe its hot deformation behaviour:

$$\bar{\sigma} = \frac{1}{\alpha}\sinh^{-1}\left\langle\left[\frac{Z}{A}\right]^{1/n}\right\rangle \tag{1}$$

where $\bar{\sigma}$ is the flow stress, α, A and n are the temperature-independent constant, and Z is the Zener-Hollomon parameter, defined as:

$$Z = \dot{\varepsilon}\exp\left(Q/RT\right) \tag{2}$$

where $\dot{\varepsilon}$ is the effective strain rate, Q the activation energy for deformation, and T the absolute temperature, and R the universal gas constant. The constants used for the 6063 alloy are as follows: $\alpha = 4\times10^{-8}$ m^2, $n = 5.385$, $A = 5.91052\times10^9$ s^{-1}, $Q = 1.4155\times10^5$ kJ/mol and $R = 8.314$ $J/(mol\ K)$ (Sheppard, 1999).

The container and die made of the H13 tool steel were also modelled in order to examine the thermal exchange between the billet and die. Table 2 shows the physical properties of both the billet and tooling.

Table 2. *Physical properties of the AA6063 and H13 tool steel.*

Property	AA6063	H13
Density (g/cm^3)	2.78	7.76
Heat capacity (J/kg·K)	900	460
Heat conductivity (W/m·K)	198	24.3

2.3. Boundary values and process parameters

In the numerical simulation of the extrusion process, friction factor is the most difficult parameter, mainly because it is experimentally immeasurable during extrusion and simulative tests such as block-on-cylinder, or ball-on-disc or ring compression tests do not exactly represent the complex tribological conditions during extrusion at elevated temperatures with and without the involvement of oxides at the container wall and die bearing, respectively. In the present simulation, the simple Coulomb friction model was used.

$$\tau_{\text{crit}} = \mu\sigma_{\text{n}} \tag{3}$$

where μ is friction coefficient and σ_{n} the normal stress.

In the present research, process parameters, *i.e.* the initial billet temperature and ram speed were taken as variables, and the heat transfer coefficients between the billet and die and between the die and surrounding air were taken as variable boundary values. The parameters used are given in table 3.

For each simulation, only a few hours were needed using a Windows XP PC with 2 GB RAM and 3.0 GHz Intel Core processor to reach the converged results.

Table 3. *Process parameters and boundary values.*

Fraction coefficient	0.4
Initial billet temperature (^{0}C)	430, 450, 500, 550
Die initial temperature (^{0}C)	430
Heat transfer coefficient between billet and die (W/m^2·K)	500, 1000, 2000, 3000, 4000, 5000, 6000
Heat transfer coefficient between die and air (W/m^2·K)	0, 50 100, 200, 300
Ram speed (mm/s)	1, 2, 3, 4, 5, 6, 7, 8

3. RESULTS AND DISCUSSION

3.1. Effect of the initial billet temperature

In the optimization of extrusion process parameters, it is important to avoid a high extrusion pressure because of a too low billet temperature and also to avoid hot shortness or localized recrystallisation and grain growth because of a too high billet temperature. At a given initial die temperature, the extrusion pressure and extrudate temperature are influenced by the initial billet temperature. Figure 3 shows examples when the initial die temperature was set at 430°C and the ram speed was 3 mm/s. It can be seen that the extrusion pressure decreases rapidly with increasing billet temperature from 430 to 550°C, while extrudate temperature increases. At a billet temperature of 550°C, the extrudate temperature can reach 591°C, which is below the solidus of the 6063 alloy (615°C). At a lower billet temperature, the temperature increase is much more significant. For example, at a billet temperature of 430°C, the temperature increase can be as much as 90°C.

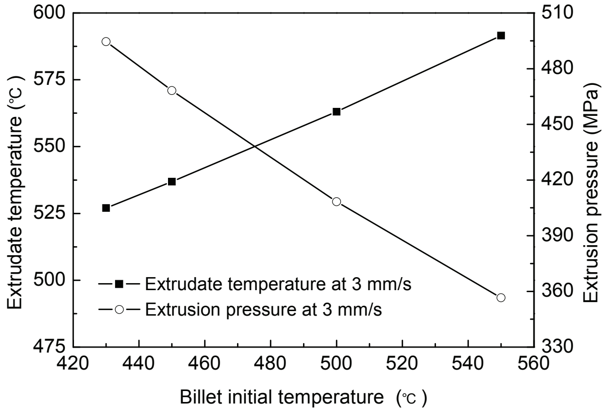


***Fig. 3.** Effect of the initial billet temperature on the extrusion pressure and extrudate temperature.*

3.2. Influence of heat transfer coefficient

The heat transfer between the billet and die, as well as between the die and surrounding air is usually not so important for the extrusion process at the transient stage, due to the short time. As a result, no data could be found in the literature about the effect of this boundary value. For extrusion in the steady state, however, longer extrusion time must be considered and this parameter becomes interesting. The effect of the heat transfer coefficient between the billet and die was determined when the heat transfer coefficient between the die and air was fixed at 50 W/m^2·K. The results are shown in figure 4.

As shown in figure 4, when the heat transfer coefficient between the billet and die increases from 500 to 6000 W/m^2·K, the extrudate temperature decreases only a few degrees (less than 10°C). With increasing heat transfer coefficient, more heat is transferred from the billet to the die. However, the deformation heat continuously generated during the extrusion process makes the temperature gradient between the billet and die very small, which is not the case for the transient-state extrusion. For the same reason, the extrusion pressure increases slightly (less than 10 MPa) with increasing heat transfer coefficient between the billet and die, as shown in figure 4. However, when the heat transfer coefficient between the die and air was varied, at a given heat transfer coefficient of 2000 W/m^2·K between the billet and die, the results were totally different, as shown in figure 5. This may represent the situation when intensive die cooling is applied.

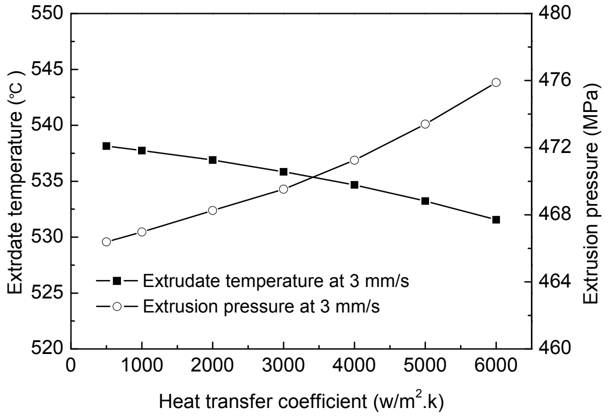


***Fig. 4.** Effect of the heat transfer coefficient between the billet and die on the extrudate temperature and extrusion pressure.*

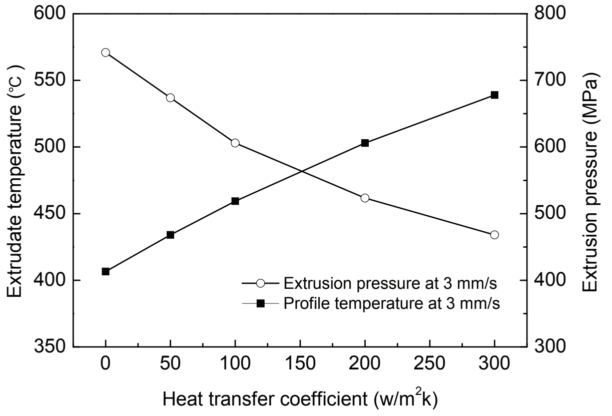
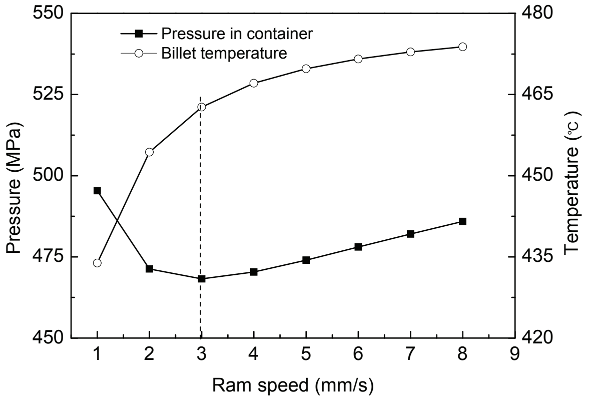


***Fig. 5.** Effect of the heat transfer coefficient between the die and air on the extrusion pressure and extrudate temperature.*

3.3. Effect of extrusion speed

Once the extrusion ratio is fixed, ram speed is the only process parameter determining the extrusion speed. In the present research, the pressures and temperatures at the contact interface between the billet and dummy block and at the contact interface between two metal steams that rejoin inside the welding chamber to form a weld seam were analysed. The effect of ram speed on the pressures and workpiece temperatures at these two locations, i.e. inside the container and inside die welding chamber, is shown in figure 6. As can be seen, during steady-state extrusion, increasing ram speed leads to a monotonous increase of the billet temperature inside the container, from 433 to 478°C. However, the extrusion pressure first decreases when ram speed increases from 1.0 to 3.0 mm/s, following by a continuous increase. It suggests that the softening of the billet material caused by the rapid increase of temperature due to increasing ram speed is stronger than strain-rate hardening. When ram speed increases further from 3.0 mm/s (indicated by a dash line in figure 6a), the strain-rate hardening of the billet material becomes dominant and the extrusion pressure increases steadily.

(a) inside the container



(b) inside the welding chamber

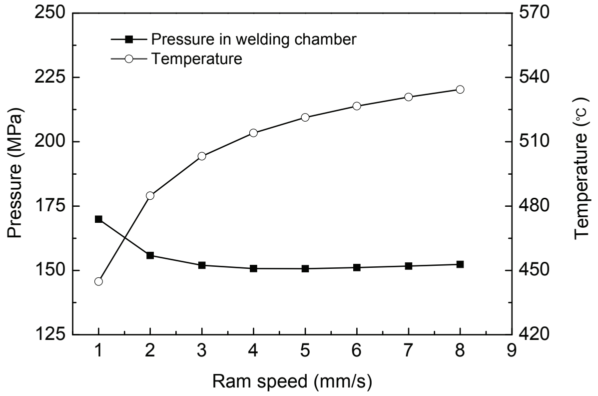


Fig. 6. Effect of ram speed on the pressures and temperatures at interfaces between the billet and dummy block inside the container and between two metal steams inside the welding chamber.

During extrusion through a porthole die to produce a tubular extrudate, the properties of the weld seams to a large extent determine the quality of the extrudate. For a sound weld seam, the pressure inside the welding chamber is of critical importance. From figure 6, it is clear that the pressure inside the welding chamber is much lower than that inside the container, partly because a large proportion of pressure is consumed by the energy to overcome the resistance to flow before the metal arrives at the welding chamber. While the pressure inside the container increases slowly as ram speed increases beyond 4 mm/s (from 468 to 486 MPa), the pressure inside the welding chamber remains relatively stable (at about 152 MPa). The temperatures of the workpiece inside the container and welding chamber increase with increasing ram speed. With an increasing ram speed from 1 to 8 mm/s, the temperature inside welding chamber increased from 445 to 534°C (figure 6b), leading to reduced flow stress, and furthermore the contact time between the two metal streams inside the welding chamber decreased from 3.2 to 0.4 s. Undoubtedly, all these factors would influence the weld quality. It is however believed that the ratio of the contact pressure at the interface to the local flow stress of the billet material plays a dominant role in determining the weld quality (Li et al., 2008). An overall effect of increasing ram speed on the weld quality is likely to be positive, which is to be experimentally verified.

4. CONCLUSIONS

In this work, the steady-state extrusion process was successfully simulated using the HyperXtrude software based on the ALE approach. Simulation was highly efficient and could be completed with a few hours. The effects of the initial billet temperature, heat transfer coefficients and ram speed on the extrusion pressure and extrudate temperature were determined. The following conclusions have been drawn.

(1) During steady-state extrusion, the workpiece temperature keeps rising. The extrudate temperature is much higher than the initial billet temperature. Depending on the initial billet temperature, the extrudate temperature rise varies from 40 to 90°C.

(2) The heat transfer coefficient between the billet and die has little influence on the extrudate temperature and extrusion pressure. On the contrary, the extrudate temperature and extrusion pressure change significantly as the heat transfer coefficient between the die and surrounding air increases from 0 to 300 $W/m^2 \cdot K$.

(3) Increasing ram speed leads to a monotonous increase of the billet temperature inside the container. However, with increasing ram speed, the pressure inside the container first decreases, before a continuous increase, which suggests that the softening of the material caused by the rapid increase of temperature is stronger than strain

rate hardening. Increasing ram speed does not increase the pressure inside the welding chamber, but it does increase the workpiece temperatures inside the container and welding chamber to favour the forming of sound weld seams.

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SYMULACJA STACJONARNEGO WYCISKANIA PRZEZ MATRYCĘ MOSTKOWĄ Z WYKORZYSTANIEM PROGRAMU MES HYPERXTRUDE

Streszczenie

Projektowanie matryc do wyciskania metali lekkich opiera się na doświadczeniu projektanta. Efektywność matrycy jest widoczna dopiero po jej wyprodukowaniu i po wykonaniu prób wyciskania. Dlatego projektanci matryc potrzebują na różnych etapach projektowania narzędzi, które dostarczą im informacji o schemacie płynięcia metalu przez matrycę. Takiego samego narzędzia potrzebują inżynierowie w produkcji aby móc dobrać optymalne parametry procesu ze względu na własności wyrobu i wydajność. Numeryczne symulacje metodą elementów skończonych są takim narzędziem, o ile program, model materiału, warunki brzegowe i parametry symulacji są prawidłowo dobrane do danego procesu. Większość komercyjnych programów MES opiera się na sformułowaniu updated-Lagrangian. Zastosowanie tych programów do symulacji procesów przemysłowych charakteryzujących się dużą długością kęsa jest bardzo czasochłonne. Program MES HyperXtrude opiera się na sformułowaniu Arbitrary Lagrangian-Eulerian (ALE) i wymaga znacznie krótszych czasów obliczeń. Celem niniejszej pracy jest ocena możliwości programu HyperXtrude w zakresie symulacji procesu wyciskania rur o przekroju prostokątnym przez matrycę mostkową. Badano wpływ temperatury kęsa, warunków wymiany ciepła między kęsem a pojemnikiem i otaczającym powietrzem oraz prędkości tłoka na naciski oraz na temperaturę wypraski. W czasie stacjonarnego wyciskania temperatura wypraski wzrastała w zakresie 40-90°C, zależnie od temperatury wsadu. Zaobserwowano znaczny wpływ współczynnika wymiany ciepła między wypraską i otaczającym powietrzem, który jest znacząco różny od współczynnika wymiany ciepła z pojemnikiem. Zwiększenie prędkości tłoka prowadzi do ciągłego wzrostu temperatury wewnątrz pojemnika i w komorze zgrzewania. Wpływ tej prędkości na naciski w pojemniku i w komorze zgrzewania jest złożony ze względu na generowanie ciepła odkształcenia.

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