A Review of Modeling and Control for Aluminum Extrusion

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Abstract. In aluminum extrusion, hot billets are compressed to flow through a die for creating an arbitrary shape. This paper discusses the main research fields of aluminum extrusion, and gives a brief review of the modeling and control for aluminum extrusion. Numerous models have been developed to achieve isothermal extrusion, which can be divided into four types: FEM based model, analytical model, experiment-derived model and real-time model. Control of aluminum extrusion process is critical to improving the quality and quantity of the extrudate. The main goal of the control is to keep the exit temperature of extrudate constant, the so-called “isothermal extrusion”. Only real-time model-based control is feasible to achieve “real” isothermal extrusion.

Introduction

In recent decades, aluminum extrusion profiles have been extensively used around the world. The aluminum extrusion process is illustrated in Fig. 1. The billet (4) in the container (1) is pushed through the die (5) of the desired cross-section by the ram (2) and dummy pad (3). The dummy pad between the ram and the billet can be reused, and its function is to keep them separate. Firstly, the force in extrusion increases rapidly as the billet upsets to fill the container. After upset, a deformation zone (4a) and a dead metal zone (4b) are formed at the front of the billet. The deformation zone provides a source of metal for the extrudate (6). With the extrusion process, the billet goes into the deformation zone, and the length of billet becomes short. After most of the aluminum billet has been extruded, the metal flow in the deformation zone is already too distorted, so that extrusion is no longer feasible. Therefore, the remaining billet is removed, and the whole extrusion process is repeated [6].

![Figure 1. Schematic of the direct aluminum extrusion process. (8) Temperature measure area (d) the distance between the exit of the die and the temperature measure area.](image-url)
Hot extrusion is a method of reducing the cross-sectional area of a metal or alloy block by forcing it through the die at a high pressure and a recrystallization temperature. Aluminum extrusion is a hot extrusion process in which aluminum billet and extrusion tools such as containers and die require preheating. In extrusion process [10, 22], heat is generated by three sources: the deformation of the billet, the friction of the billet against the container, and the shearing at the dead metal zone. Some of the generated heat is transported towards the die and container. Some heat remains in the extruded metal causing an increasing in temperature of the extrudate. And the other part increases the temperature of the portion of the billet which has not been extruded. In the extrusion process, the heat transfer process through the billet is complicated, and it is difficult to obtain the complete analytical solution of the heat transfer differential equation.

Since the temperature of the deformation zone is unpredictable, the temperature variation of the extruded product is changed at constant speed extrusion, resulting in differences in the microstructure and mechanical properties and dimensional tolerances of the extrudate in the length direction. In industrial practice [15], temperature management plays an important role in the extrusion of aluminum. The profile temperature at the die exit is the most influential parameter in aluminum extrusion process control because it largely determines the mechanical properties, surface quality and microstructure of the extrudate. As showed in Fig 1, according to the mechanical structure of press, the proper position of the multi-wavelength pyrometer (9) is the die platen (7), which is at a distance of 2 to 3 meters from the extrusion die [4, 23]. It is difficult to control since the exit temperature is delayed by more than 30 seconds.

The Main Fields of Research on Aluminum Extrusion

The goal of aluminum extrusion is to ensure that the consistency of the mechanical properties and dimensional accuracy of extrudate. The quality of the product is closely related to the strain distribution, the temperature distribution, the metal flow velocity distribution [12] and other factors in the deformation process of the extrusion process. It is difficult to accurately grasp the real metal flow behavior in the high pressure, high temperature and high friction of the sealed extrusion container.

In a given extrusion process, the extrusion material, extrusion ratio, and profile cross section have been determined, the main factors that affect the metal flow behavior include: extrusion pressure, extrusion speed, container temperature, billet temperature, die temperature and structure. According to different objectives, the current studies of aluminum extrusion focus on:

(1) Metal flow behavior. The purpose is to study the influence of various factors on metal flow behavior [26, 32, 34], including pressure force model [2], physical model [1, 7, 13, 14], numerical analysis method [28, 42, 43] and friction models [22, 39-41].

(2) Metal constitutive equation [35, 36]. Constitutive equation is a model that reflects the relationship between flow stress and strain, strain rate and temperature of aluminum at high temperature. The accuracy of the model directly affects the simulation, modeling and control of the aluminum extrusion process.

(3) Die design and optimization [21, 25, 31, 33]. The main objectives of the studies are to obtain the desired size of the profile, to extend the die design life and optimize the extrusion process parameters.

(4) Temperature distribution for aluminum extrusion process [16, 29]. The main goal of the study is to master the temperature distribution of aluminum extrusion process changes to maintain a constant extrudate temperature, so as to ensure that the extruded product performance and dimensional accuracy in the length direction with consistency.

(5) Modeling and control for extrusion process [2, 4, 5, 6, 8-10, 15, 17-20, 24, 27, 30, 37, 38].

In this paper, only modeling and control for isothermal extrusion are discussed and reviewed.
Modeling and Control for Isothermal Extrusion

Numerous models have been developed to achieve isothermal extrusion, which can be divided into four types: FEM-based model [11], analytical model, Experimental-derived model and real-time model. All FEM models [3] relate various extrusion parameters with exit section temperature achieving high prediction accuracy and representing FEM as a powerful tool for extrusion simulation. The main disadvantage of the comprehensive FEM models are excessive computational times required that makes the application in on-line closed-loop control impractical. The analytical model is a model derived from the extrusion process mechanism under the given assumptions, which is characterized by the need to determine the boundary conditions. Experimental-derived model usually is developed by using statistical methods, neural networks [5; 8; 20] and other methods, with data collected through a group of orthogonal experiments. The real-time model is usually a parametric model or a state equation. The process data are used to identify and correct parameters using system identification.

FEM-based Model

Bastani et al. [3] used Altair HyperXtrude 9.0 (3D finite element software) and ALMA2π (2D finite element software) to study the extrusion process parameters on the impact of extrusion quality. The process parameters studied included front billet temperature, initial billet temperature gradient, ram speed and container cooling rate. They defined three phases of the extrusion cycle: start, middle and the end of the ram stroke. They got the optimum combination of isothermal extrusion process parameters and represented it as an "isothermal maps" at each phase of the extrusion cycle.

Zhang et al. [9] used HyperXtrude to study the aluminum extrusion process of thin-wall hollow. They investigated the effect of extrusion speed on the metal at the exit of the extrusion die, including the metal flow, temperature distribution, extrusion force, and weld pressure. The results showed that there existed an optimal stem speed for the flow velocity distribution. Extrusion speed and extrusion profile temperature and extrusion pressure were positively correlated. The increase in extrusion speed could improve the welding quality of extruded profiles. The appropriate extrusion speed could be determined by a comprehensive comparison and analysis of simulation results. It is unclear whether the research results could give a useful guideline for determining initial billet and die temperature.

Zhou et al. [15] have used DEFORM 3D to simulate the 7075 alloys isothermal extrusion process. They set two target temperatures for the two different compositions of the 7075 alloy and established the velocity profile associated with the ram displacement. The simulation results were verified by experiments. The results showed that the prediction of the temperature change at the conventional extrusion speed could be obtained by computer simulation, and the extrusion velocity curve of the isothermal extrusion could be determined in advance. Using the preset extrusion speed profile, the exit temperature of the profile could remain in the range of 10°C. The isothermal extrusion speed was constantly changing compared to conventional extrusion at constant extrusion speed, increasing the average extrusion speed of each billet. The pressure on the die surface during isothermal extrusion remained almost constant, helping to maintain the uniformity of the profile geometry. The predictions of extrusion pressures, die temperatures, and profile temperatures were in agreement with the experimental measurements of laboratory-scale equipment.

Analytical Model

Akeret [23] presented a numerical method for analysis of temperature distribution. The billet in the container has to be divided into cells in a suitable way. He assumed the temperature of any given cell remained constant, and presented a simple model for the simulation of the extrusion process with a stepwise movement of the billet. The deformation zone at the die entry is simulated by a heat source in the foremost cell. He compared the calculated emergent temperatures with the experimental results, and the rising or falling trend of the curve, as predicted by calculation, was confirmed by experimental results.
Cuellar Matamoros [10] proposed a semi-analytical model where flow, velocities, pressure, and strain were solved analytically and only temperature distributions were determined numerically. The main challenge and priority at deriving a first-principles dynamic model of the extrusion process that is suited for control purposes lie in achieving reasonable computation times. As compared to the usual Finite Elements Method for the modeling of extrusion processes, the semi-analytical approach allowed for a considerable reduction in computation times. The model was validated with data from an industrial aluminum extrusion press. The validated model was then used to design various open-loop optimal control strategies according to different performance criteria. In subsequent investigations, a simplified model was derived and then compared to the semi-analytical model. The billet and tooling were divided into various discs. Material and heat balances were formulated for each zone. The number of discs, representing the undeformed part of the billet, decreased as the extrusion proceeded. After a length equivalent to the width of a disc was extruded, its temperature was assumed to remain constant over time, and the heat balance was formulated for the remaining zone. The equations of the simplified model for the various bodies involved were listed in the appendix.

Experimental-derived Model

Abdul-Jawwad et al. [4] used a statistical design of experiments (DOE) to investigate the effect of extrusion parameters on the resulting profile exit temperature of an industrial press 6063 aluminum alloys. They studied five operating parameters, including two operating parameters: initial billet temperature and ram speed, and three geometrical parameters: extrusion ratio, profile average thickness, and number of die cavities. Based on the experimental data, they obtained a statistical model for predicting the exit temperature of the profile, which was very close to the predicted value and the measured value. In this model, the single factors influencing the profile exit temperature were high extrusion ratio, high initial billet temperature and high ram velocity. They found that the profile exit temperature was affected by a complex set of two-factor and three-factor interactions between different operating and geometrical parameters. The most important two-factor interactions were between the extrusion ratio and the number of die cavities and between the initial billet temperature and the ram speed. The three-factor interactions were between the initial billet temperature, the ram speed and the extrusion ratio.

Branimir Lela et al. [19] used functional data analysis (FDA) to derive a linear regression mathematical model for the prediction of profile exit temperature. They recorded the extrudate temperature, ram speed, and extrusion pressure in actual industrial condition. Relationships between ET and RS can be formed as ET(t)=β1(t)+ β2(t)∙α1(t)+ α2(t) ∙β2(t) ∙RS(t), where ET is the extrusion temperature, RS the ram speed, and α1, α2, β1, β2 the regression coefficient functions. They determined α1, α2, β1, β2 by fitting least squares criterion extended for FD. Simulation of the mathematical model showed that its predictions were in good accordance with the measured data on the extrusion pressure. They calculated the adequate ram speed curve for isothermal extrusion.

MENG et al. [17] performed an orthogonal extrusion experiment to study the effects of billet temperature, ram speed, and die temperature. They used a regression-based mathematics model to predict the extrudate temperature of 6063 aluminum alloys.

Lucignano et al. [8] took different approaches and used artificial neural network methodology for the development of a mathematical model capable of predicting exit section temperature but did not consider isothermal extrusion.

Boris GOTLIB et al. [24] created a model of pipes isothermal extrusion. The intelligent control system of the extrusion process provides isothermal extrusion conditions by speed regulation of compression ram in the extrusion process. In this system, intelligent control was used in hybrid controller which connects neural networks and fuzzy logic technology. For technological reasons all types of pipes were divided into three groups according to the geometrical sizes of a matrix and a needle. Basic technological parameters of the process have the following factors: diameter of container, temperature of isothermal extrusion, the initial temperature of the billet and container and
the ram velocity. At the first stage of the hybrid system, three neural networks were used to calculate of parameters which were included in the basic isothermal extrusion model. In this case fully connected three-layered feed-forward back propagation neural networks type were used. At the second stage of the hybrid system, they used methods of fuzzy sets theory. As all groups have a partial intersection of their initial parameters, for this reason, membership function for each group was created. They utilized trapezoid functions of two variables as a membership function. Such system architecture gives an opportunity for the most exact approximation of all necessary parameters. Using such system architecture, one can achieve the system control goals at most and implement the model of the process that is built on the knowledge base in the real-time control process.

**Real-time Model**

Tibbetts and Ting-Yung [6] proposed a mathematical model based on the physical phenomena of the extrusion process. The model was based on axisymmetric extrusion, from circular billet to round rods. The model contained the following equations and functions: project temperature state, ram position, ram speed, heat conduction, boundary heat loss, advection, heat generation, extrudate temperature, extrusion load, maximum strain rate. In this model, the boundary heat loss terms and the heat generation terms could not be given by the assumptions. The boundary heat loss terms could be formed by three gradient functions: the container wall, the die face, and the dummy pad. The heat generation terms are also composed of three functions: deformation, friction, and shearing sources. Therefore, the model had coefficients $c_f$ and $c_h$, where $c_f$ represents the magnitude of the boundary conditions and $c_h$ represents the scaling of the flow stress about deformation, friction and shearing source. They assumed the flow stress kept a constant. The $c_f$ and $c_h$ could be identified by process data. They used this model to develop parameter identification and open-loop control methods. They also proved that parametric and control variables enter the model equations, making open-loop optimization problems and identification convenient to deal with. An example of factory test data was provided. They chose a specific objective function for the open-loop design.

Pandit et al.[18] developed a cyclic learning control for extrusion. This control scheme improves the control of the temperature of the extrudate, from extrusion cycle to extrusion cycle, by iteratively optimizing an appropriate performance index. This control strategy has the disadvantage of requiring too many iterations until isothermal extrusion is attained. In industrial practice, various types of profiles were extruded batch wise in the same press. To achieve isothermal extrusion, the iterative learning control may require more learning cycles than what are available for a certain profile.

**Discussion on Modeling and Control for Aluminum Extrusion**

To achieve the industrial application of isothermal extrusion, aluminum extrusion modeling and control need to face the following issues:

1. **Accurate measurement of profile outlet temperature.** As mentioned above, the profile temperature is not detected until at least 30 seconds from the mold. During this movement, the profile exchanges heat with the environment, causing the profile temperature to fall. As a result, the temperature detected by the thermometer is related to the extrusion speed of the previous time, and has a large hysteresis and a large temperature change.

2. **Effect of extrusion pressure and extrusion speed on temperature rise.** In the extrusion process, approximately 85% to 95% or more of the plastic deformation work is converted to heat, which causes a temperature rise in the extrusion profile. Extrusion pressure and extrusion speed are usually used as control inputs for the design of control algorithms, since both are closely related to plastic deformation work.

3. **Temperature variation of the deformation zone in the extrusion process.** The exit temperature of the profile is the deformation zone temperature plus the extrusion temperature rise, only on the
basis of mastering the deformation zone temperature, it is possible to correctly calculate the control parameters to achieve isothermal control.

(4) The temperature changes of aluminum billet in the extrusion process, which is the basis of the optimization of aluminum billet preheated parameters.

(5) Acceptable calculation time. Each extrusion cycle time in five minutes to ten minutes. The calculation of the model has to be completed in a limited time.

(6) Real-time identification and calibration of model parameters. The parameters of the model are influenced by parameters such as alloy material, mold type, extrusion tool, aluminum billet preheating temperature and so on, and these factors will always change.

The comparison of models is shown in Table 1. FEM-based model, analytical model and experimental-derived model have closely related the assumptions which the model was developed. Among the three models, only “open loop” control can achieve ‘close to’ isothermal conditions. The temperature change during the extrusion process can be accurately obtained through the FEM-based model, but requires a lot of calculation time. This model can get a preset extrusion speed curve, to achieve approximate isothermal extrusion. Experimental-derived model and analytical-model need less time, but these two models can only get less accurate temperature distribution, which is not enough to reach isothermal extrusion. Note that the problem of isothermal extrusion of aluminum should be investigated from the systems and control engineering point of view. Closed-loop control is a crucial control method. The structure and parameters of the real-time model are usually obtained by analyzing the process data and using the system identification method. The problem is that it is difficult to obtain a precise profile exit temperature and deformation zone temperature.

Table 1. Comparison of models

<table>
<thead>
<tr>
<th>Model type</th>
<th>Model performance</th>
<th>Control Method</th>
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<tbody>
<tr>
<td></td>
<td>computation times</td>
<td>accuracy</td>
</tr>
<tr>
<td>FEM-based model</td>
<td>massive</td>
<td>precise</td>
</tr>
<tr>
<td>Analytical model</td>
<td>more</td>
<td>coarse</td>
</tr>
<tr>
<td>Experimental-derived model</td>
<td>less</td>
<td>coarse</td>
</tr>
<tr>
<td>Real-time model</td>
<td>least</td>
<td>coarse</td>
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</table>

Conclusions

In this paper, the main fields of research on aluminum extrusion are discussed, and four types of models for aluminum isothermal extrusion are summarized: FEM-based model, analytical model, Experiment-derived model and real-time model. The practical difficulty in achieving isothermal extrusion in the industry is that it cannot obtain the temperature change of the billet and extrudate in a limited time and the measurement of the die exit temperature has a great lag. The real-time model can solve the above problems after an accurate measurement of the exit temperature, so that it is possible to realize “real” isothermal extrusion in the industrial press.

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