A CO-SIMULATION APPROACH BASED ON CLOSE-LOOP FEEDBACK CONTROL FOR ALUMINUM ALLOYS PROFILE EXTRUSION

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The conventional simulation for aluminum alloys profile extrusion (AAPE) is an open-loop control system in which the control parameters cannot be adjusted during the simulation process. To address this issue, we use the novel co-simulation method by coupling two kinds of code: using Abaqus code to model the extrusion process and a Python code to model the control unit. Then, a fully coupled feedback closed-loop co-simulation of AAPE is presented in this work. By using the numerical model of the closed-loop control system, the profile outlet temperature is controlled to be balanced and uniform. Moreover, a gradient-heated aluminum billet is simulated in this paper. For this special scenario, it is important to model the AAPE control system by considering the interaction of the die with the aluminum alloys components, resulting in a more accurate representation.

Keywords: co-simulation, aluminum alloys, extrusion, FEM, MPC.

1. Introduction

AAPE is a process for creating profiles by pushing heated aluminum alloys through a die. The quality of the extruded profile and the process parameters, including material morphology, internal stress, and temperature are closely interconnected, all of which vary during the extrusion process, making it difficult to predict the extrusion status. Of all the parameters, the extrusion temperature at the outlet essentially affects the mechanical properties, material microstructure, and surface smoothness of the profile. As a result, isothermal AAPE [1-6] has been well investigated by many researchers. For isothermal AAPE, the critical step of extrusion control is to maintain a relatively balanced profile temperature. The ram speed regulation system enables the amount of heat generated during the extrusion to be controlled. Marthinsen et al. [7] used the Zener-Hollomon equation and Feltham's equation to determine the relationship between the extrusion temperature

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and extrusion speed. J. Zhou [8] used the Finite Element Method (FEM) to simulate and verify isothermal AAPE through continuous ram speed variation. Additionally, through an appropriate control method, the extrusion speed is regulated by using the exit temperature as a feedback control parameter [9,10]. The Model Predictive Control (MPC) [11,12] method is used to design closed-loop control strategies for isothermal AAPE.

The finite element method has been proven to be a powerful tool for predicting temperature variation during the aluminum extrusion process. FEM can also simulate the closed-loop control process of isothermal AAPE if co-simulated with a feedback control system. Co-simulation [13] is an innovative simulation technology that couples several distributed parallel simulation tools in an integrated environment to manage the data flow and synchronization between them. P. Kathirgamanathan and T. Neitzert [14] constructed an iterative procedure to determine the optimal conditions of the isothermal process using an optimization routine such as MATLAB's lsqnonlin and using ABAQUS to solve the extrusion flow at each iteration. Amin Farjad Bastani [15] conducted transient FEM simulations of the AAPE using the FEM software Altair HyperXtrude 9.0 and a 2D FEM software ALMA2π.

In actual AAPE, aluminum alloys bars are preheated by gradient heating [16,17], which will produce an unobservable vortex from a temperature field in the bars, and the internal temperature field will bring nonlinear disturbance to the predicted parameters. The novel concept of this research is to use the Finite Element Method to acquire the internal temperature field and combine MPC using a co-simulation approach. The main advantage of this approach is that it can simulate actual AAPE with a preheated bar and closed-loop controller. With the help of this approach, the optimum preheating and control strategy can be studied through co-simulation results analyzing.

2. Materials and Methods

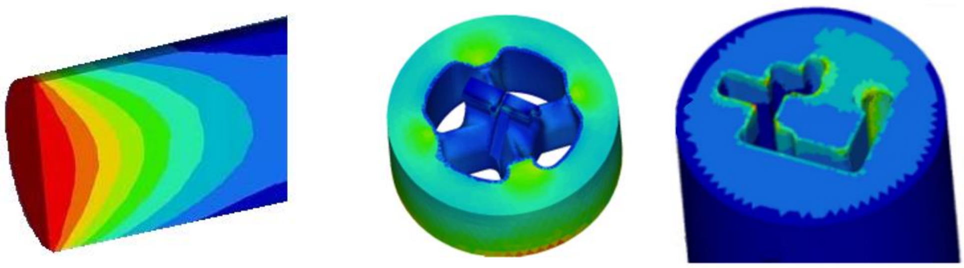
As shown in the Fig. 1(a), for the purpose of the isothermal extrusion, aluminum billet is gradient heated before extrusion to make the aluminum alloy temperature earlier enter higher than the later, so as to compensate for the temperature rise caused by the extrusion process. The internal temperature field of the bar heated by gradient heating is in the form of vortex, which cannot be measured in actual production, however we [18] have discussed the vortex form temperature field is an essential problem to the temperature prediction. The gradient heated bar enters the die part marked as Fig. 1(b) under the thrust of the extruder, and is extruded from the outlet marked as Fig.1(c) through three steps of splitting, welding and forming.

In order to simulate the whole extrusion process, the three-dimensional models of aluminum billet, die and export profile are established, and a finite element simulation model is established by using Abaqus. Isothermal extrusion is aimed at keeping the temperature constant in part (c) of Fig.1. Let the input of extrusion control be extrusion speed x and the output be temperature y. With the increase of velocity, the outlet temperature increases, and vice versa.
According to the temperature rise model of Δy established by Cheng Meng [19]

$$P_e = x(t)D/\lambda \tag{1}$$

$$\eta = h/D \tag{2}$$

$$\Delta y(t+1) = 3.5\times 10^{-6} \times P_{0r} - \Delta y(t)(1-e^{1.6\sqrt{\eta\lambda/Dx(t)}}) \tag{3}$$



(a) (b) (c)
(a) gradient heated aluminum billet, (b) split die, (c) profile outlet.
Fig. 1. FEM modelling of AAPE:

$y(t+1)$ is the temperature rise at the current time, $y(t)$ is the temperature rise at the previous time, $x(t)$is the extrusion speed at the previous time, and $x(t+1)$ is the current extrusion speed, Table 1 summaries the AAPE input and output description.

Table 1

AAPE input and output description

Symbol	Description	Unit
P_{0r}	Unit extrusion force on the section of plastic deformation zone	MPa;
P_e	Picric number	
λ	Thermal conductivity	mm / s
η	Ratio of stroke of extrusion shaft to inner diameter of extrusion cylinder	
$x(t)$	Extrusion speed of the previous moment	mm / s
h	Extrusion shaft stroke	m
ρ	Unit mass	kg /m^3

$$P_{0r}=(x(t+1)- x(t))\rho \tag{4}$$

Because the change of outlet temperature is as follows:

$$y(t+1)=y(t)+\Delta y(t+1) \tag{5}$$

Replace 5 with

$$y(t+1)=y(t)+3.5\times10^{-6}\times\rho\times\Delta x(t+1)-\Delta y(t)(1-e^{1.6\sqrt{\eta\lambda/Dx(t)}}) \tag{6}$$

The control objective is to keep the outlet temperature constant. If the expected constant value of outlet temperature is y_H, the control objective is as follows:

$$y(t+1)\approx y_H \tag{7}$$

3. Development of a closed-loop control strategy

In this paper, a closed-loop controller based on predictive controller is adopted. The controller calculates the sequence of control variables (x) in a future time domain (t) to make the corresponding predictive output $y(t+1)$ as close as possible to the desired output y_H. The structure of the predictive controller used in this paper is shown in Fig.2.

1. Let the output of model prediction be y_m and the error be e, $e(t)=y(t)-y_m(t)$. Suppose that the prediction output after error correction is:

$$y_p(t+1)=y_m(t+1)+he(t)=y_m(t+1)+h(y(t)-y_m(t)) \tag{8}$$

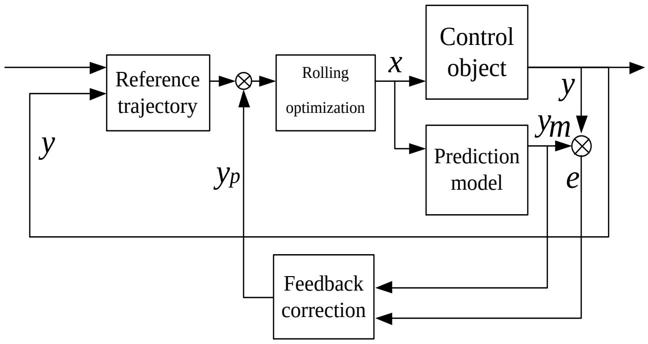


Fig. 2. Controller structure for MPC control strategy.

h is an adjustable parameter, and the value of h determines the robustness and immunity.

The Reference trajectory is

$$y_r(t+j)=\alpha^j y(t)+(1-\alpha^j)\, y_H \tag{9}$$

where, $\alpha=\exp(-jT/T_r)$.

2. T_r is the time constant of the reference trajectory and T is the sampling period.

3. The prediction model is shown in Equation (5), and the rolling optimization is carried out. In this paper, a quadratic loss function J_p is defined as the "gap" between the prediction output and the reference output of the model.

$$\min\ J(k)=\sum_{i=1}^{P}\omega_i[y_P(k+i\mid k)-y_r(k+i)]^2 \tag{10}$$

where, ω_i is a non-negative weighting coefficient, which represents the proportion of the deviation of each sampling time in the objective function J_p. The goal of optimization is to find a group of control variables $[x(t), x(t+1) \ldots, x(t+p-1)]$ to minimize J_p.

4. According to Equation (5), the display solution of control quantity x can be derived.

$$x^*(t) = \frac{1}{g_1}[\alpha y(t) + (1-\alpha)w - y(t) + \sum_{i=1}^{N} g_i x(t-i) - \sum_{i=2}^{N} g_i x(t-i+1)] \quad (11)$$

5. If there are constraints on the control quantity, then:

$$x(t+1) = x_{max} \quad (12)$$

6. The algorithm takes the control quantity x of the next time to be optimized as the optimization object. The objective function is then used to obtain the optimal control quantity for the time t+1 through rolling optimization. The optimal control quantity x is then applied to the extrusion control system to control it. The process is repeated by incrementing t by one, turning to the 3rd step until the end of the control.

4. Schema of the design

4.1 Illustration of co-simulation process.

In this paper, Abaqus 2020 and Python 2.7 are used to build a co-simulation system. The architecture of the co-simulation system is shown in Fig.3. Abaqus is used as the finite element simulation software, and Python is used to develop the aluminum extrusion prediction model and controller simulation program. The data interaction method used in this work is presented in detail in Bbl. A and Yang D B et al. [19]. The data interaction between Abaqus and Python is based on Python extended Abaqus scripting interface program.

The script interface bypasses the GUI of Abaqus/CAE and directly interacts with the kernel to realize the functions of repetitive operation, creating and modifying model database, accessing output data have and so on. The ODB database stores the simulation process data of Abaqus temporarily and reads the data of the ODB result database of Abaqus through the script interface. Controller gets the status data of FEM simulation, and then runs the control algorithm. The control parameters are calculated and submitted to FEM simulation through inp file. The profiling temperature acquisition is automatically carried out by the Extrusion Management System (EMS) press control software [20].

4.2 Step length setting

A proper time step length has to be selected before the start of the co-simulationwhich will affect the convergence and accuracy of the solution. If the time step length is unreasonable, and irregular oscillation will be formed in the element with intermediate nodes, then resulting in unreal temperature results. The setting of the time step length is related to the size of the finite element mesh element, and Bi represents the ratio of convective and conductive thermal resistance.

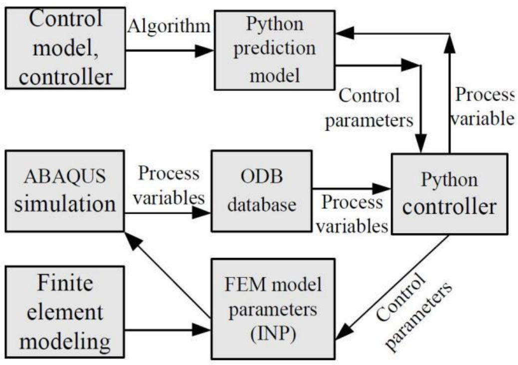


Fig. 3. Block diagram for co-simulation system.

$$B_i = s\Delta x / R \quad (13)$$

Δx is the cell width, s is the heat transfer coefficient, R is the average thermal conductivity.

Let F_O be a dimensionless time Fourier number, which quantifies the relative ratio of heat conduction to heat storage for a cell with a width of Δx.

$$Fo = \frac{R\Delta t}{\rho c(\Delta x)^2} \quad (14)$$

In (14), c is specific heat and ρ is the average density, Δx is the nominal cell width, and R is the average thermal conductivity. The time step is determined by Bi.

(1) When $Bi<1$, F_O is used to calculate the time step Δt.

$$\Delta t = \beta \frac{\rho c(\Delta x)^2}{K} \quad (15)$$

(2) When $Bi>1$, The product of Bi and F_O is used to calculate the time step Δt.

$$\Delta t = \beta \frac{\rho c \Delta x}{h} \quad (16)$$

It is an important task to keep synchronism of numerical simulation and control simulation. We run Abaqus finite element simulation after a certain number of steps, then suspend it and retain the calculation thread without using CPU resources, at this time python script is running to obtain and process all kinds of information in the analysis process, use callback function to obtain monitoring information, and pass it to the controller for control simulation. The optimal control parameters are submitted to Abaqus through inp file, and Abaqus resumes the simulation.

5. Experimental Verification and Analysis

The steps of Co-simulation are shown in Fig.4. The numerical analysis of extrusion needs thermal stress analysis. In this paper, the structure thermal indirect coupling analysis method is adopted, that is, the model of a single physical field is solved in a specific order, and the results of the previous analysis are applied as the boundary conditions of the subsequent analysis. In the thermal stress analysis of this paper, the node temperature obtained from the temperature solution will be used as the volume load in the structural analysis. The thermal node temperature is applied to the structural element. In order to get better structural results, the structural element is different from the thermal model mesh. Structural loads are mapped from thermal analysis, then establish thermal and structural database and result file.

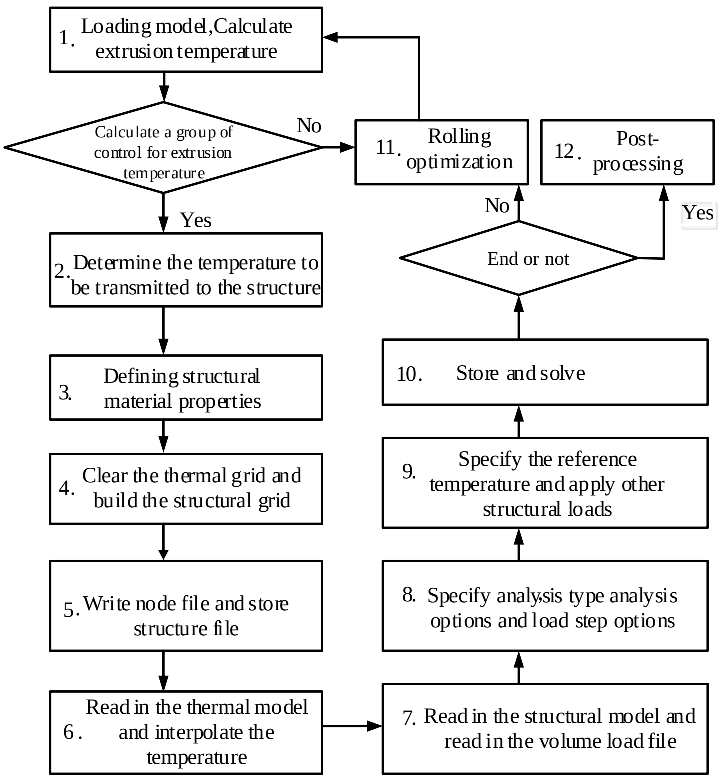
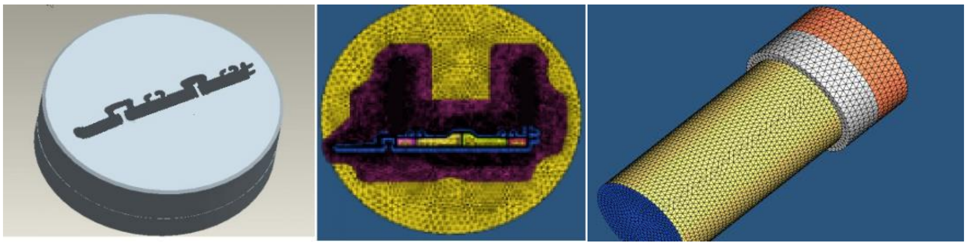


Fig. 4. Co-simulation process.

5.1 Extrusion process parameter setting

As shown in the Fig.5, in this paper, the three-dimensional models of aluminum billet, die and export profile are established, and the finite element simulation model is established by Abaqus, the experimental parameters of co-simulation are set as Table 2, where the preheating temperature are set as gradient heated [21] with 1hour.



(a) Aluminum billet (b) porthole die (c) profile export.

Fig. 5. An experiment example

Table 2

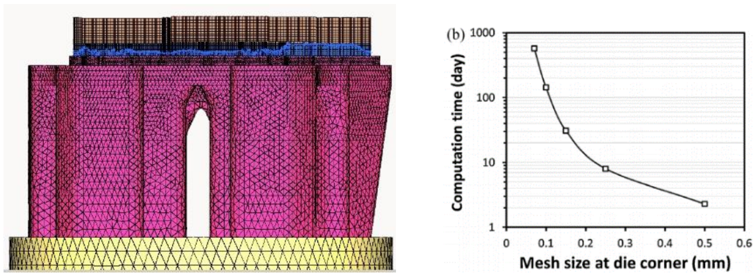
Extrusion parameter's setting table.

Parameter	Setting
Material	AA 6063
Inner diameter of extrusion cylinder	258mm
Preheating temperature	400-500°C
Extrusion cylinder temperature	450°C
Mold temperature	480°C
Extrusion ratio	39.12

According to the input and output model of the extrusion control system, the controller is designed by using the system proposed in this paper, and the adaptive control algorithm is programmed by using the complex control algorithm software package to realize the isothermal extrusion control of aluminum profile. In the experiment, the set value of outlet temperature δ = 510 °C. The preheating strategy is To validate the feedback close loop control AAPE, isothermal AAPE experiments were carried out with varying controlled ram speed.

5.2 Mesh size setting

The effective of co-simulation models are closely related to the mesh size, if the mesh size respecting the time step are appropriate, accurate simulation will be achieved in terms of the field affects. AAEP FEM simulations with different mesh sizes were carried out in this paper. The co-simulation of AAEP was carried out in a Linux workstation with 16GB of RAM and four 3.16 GHz Intel Xeon processors.



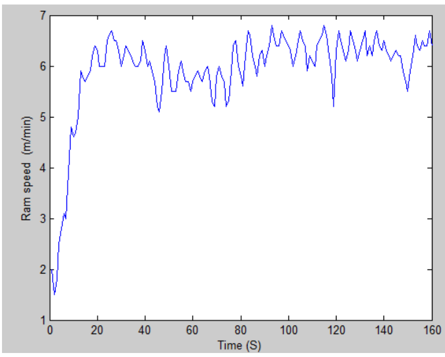
(a) Mesh size setting example; (b) Computation time versus mesh size.

Fig. 6. Co-simulation mesh size setting.

Fig.4b shows that decreasing mesh size dramatically increase computation time for an entire extrusion cycle simulation from a few days using 0.5 mm mesh size (within the mould) to more than one year with 0.07 mm mesh size, but it is can be observed that the compute error related to the mesh size is decreased when using small elements. As shown in Fig.6b, considering the accurate results need, 0.25 mm as mesh size of the mould corner is used for our co-simulations.

5.2 Validation of the co-simulation approach.

We validated our new proposed co-simulation approach by comparing outlet temperature with constant ram speed AAPE simulation. As Fig.7 shows, controlled by feedback close loop controller, ram speed is varying in our study different to the constant ram speed in conventional AAPE which is shown in Fig.8, the appropriate stem speed in Fig.8 is determined according to an effective guideline proposed by Cunsheng Zhang[22].



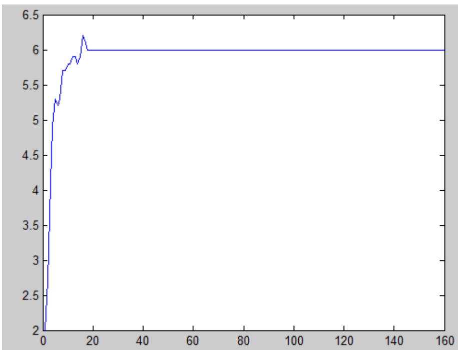


Fig. 7. The controlled input curve. Fig. 8. Constant input curve.

Time series of the outlet temperatures are shown in Fig.9 and Fig.10. Compare Fig.9 with Fig.10, it is observed that outlet temperatures in Fig.10 is more stable than in Fig.9, the highest temperatures in Fig.9 are exceed 530°C, and the change range of temperatures is rather big. However, the temperatures in Fig.10 are no more than 513°C, most temperatures are close to the optimal target of 510°C and the change range of temperatures is rather small. That mean isothermal extrusion is validated with feedback close loop control.

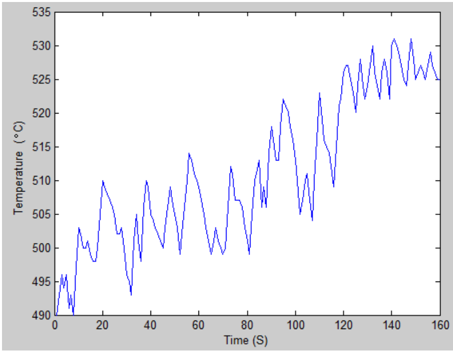


Fig. 9. The outlet temperature curve without control.

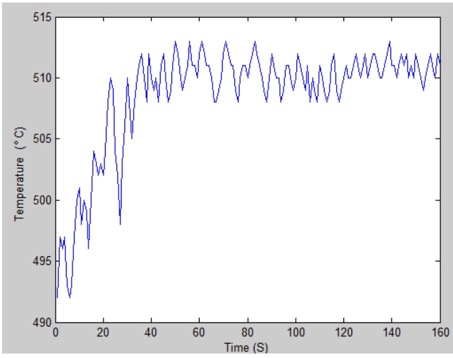


Fig. 10. The outlet temperature curve of co-simulation.

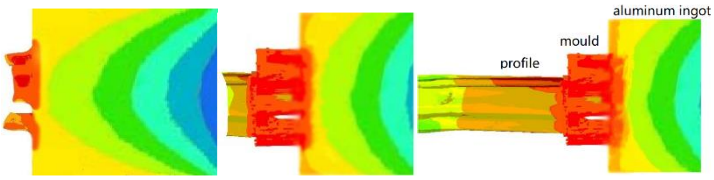
After the co-simulation, the results of post-processing are shown in Fig.11. Temperature description of Fig.10 is shown in Table 3.

Table 3

Temperature description in post-processing.

Color	Description	Temperature
	Red	530°C
	Orange	520°C
	Gold	510°C
	Yellow	500°C
	Yellowgreen	490°C
	Springgreen	480°C
	Green	470°C
	Navyblue	460°C
	Turquoise	450°C
	Royalblue	440°C
	Orengerd	430°C

■	Blue	420°C



(a) (b) (c)

(a) 20s, (b) 120s, (c) 2min

Fig.11. Temperature distribution of co-simulation results

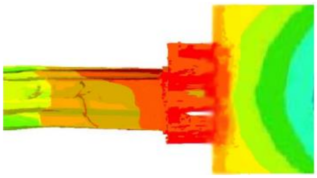
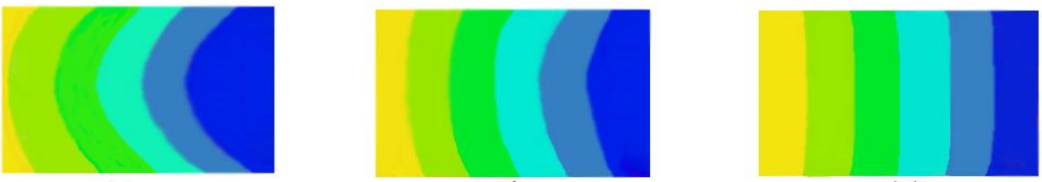


Fig.12. Temperature distribution during the continuous extrusion of simulation without control

Fig.11 illustrates the AAPE process in co-simulation. Different with the conventional AAPE simulation, the gradient heated aluminum billet is simulated as actual heated from 400°C-480°C like Fig.1(a) shows. We set the optimal target for outlet temperature control in isothermal extrusion as 510±10 °C, especially prevent the temperature from exceeding 520°C causing recrystallize [23] for aluminum which affects the quality of the products. Fig.11(a) depicts the split behaviours during start up, Fig.11(b) during the forming and Fig.11(c) during the continuous extrusion. Compare Fig.11(c) with Fig.12, it is observed that more uniform temperature distribution is achieved in our study.

5.3 Results and discussion

In order to study the optimum preheating strategy by using the co-simulation approach, we compared average ram speed and average outlet temperature results of three co-simulations. The settings of these co-simulations are only different in gradients heated times. As Fig.7 shows, (a)(d)(g) represent the simulated results under gradients heated of 1hour, (b)(e)(h) represent the simulated results under gradients heated of 2hours, (c)(f)(i) represent the simulated results under gradients heated of 3hours. The simulated results including the evolution of exit temperature, the ram speed.



(a) (b) (c)

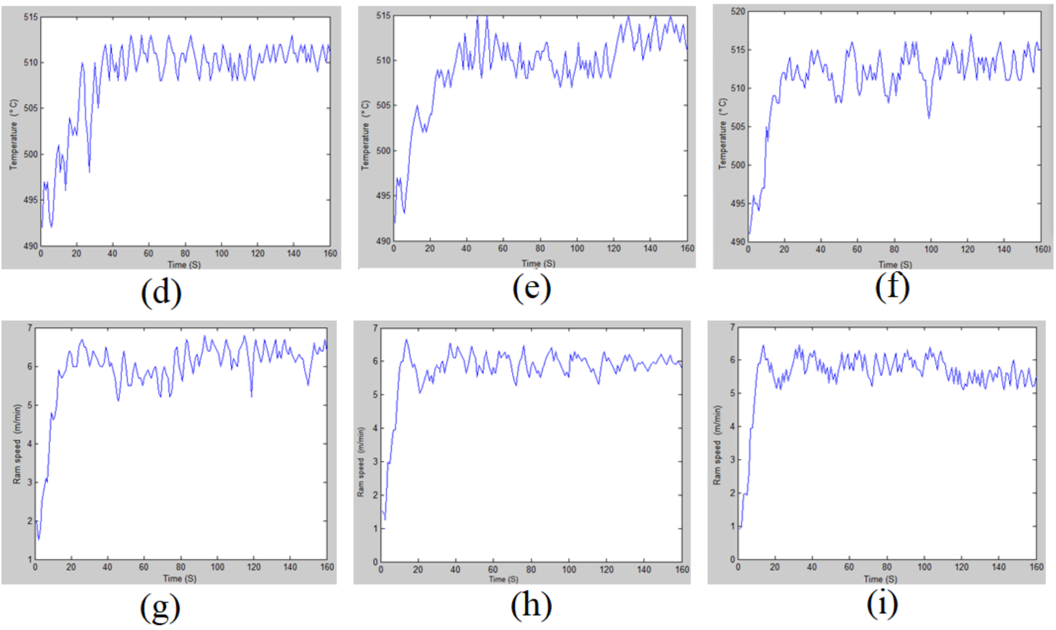


Fig.12. Evolution of exit temperature and ram speed during extrusion process under different temperature gradients heated of (a) (d) (g) 1hour, (b) (e) (h) 2hours, and (c) (f) (i) 3hours.

The average of temperature is evaluated by Eq. (17),

$$T_{avg} = \frac{\sum_{i=1}^{n} T_i}{n} \tag{17}$$

where n is the total number of selected time nodes, T_i is the temperature at time node i. According to Eq. (17), T_{avg} of 1hour gradients heated is 506.7541°C, T_{avg} of 2hour gradients heated is 509.2688°C, T_{avg} of 3hour gradients heated is 511.2625°C. The average of ram speed is evaluated by Eq. (18),

$$R_{avg} = \frac{\sum_{i=1}^{n} R_i}{n} \tag{18}$$

where n is the total number of selected time nodes, R_i is the ram speed at time node i. According to Eq. (18), R_{avg} of 1hour gradients heated is 5.89m/min, R_{avg} of 2hour gradients heated is 5.68m/min, R_{avg} of 3hour gradients heated is 5.38m/min. It is clear that the long gradients heated causes lower ram speed and higher exit temperature, that mean the preheating strategy of 1hour gradients heated is better than the others, the more co-simulations are carried out, the more superior preheating strategy will be found.

6. Conclusions

Within this work we combined the predictive control-based Python codes and Abaqus FEM codes to a co-simulation system of AAPE. One advantage of the new proposed co-simulation approach is it obtain unobservable temperature of gradient preheated aluminum bar, with the help of this approach, the optimum preheating and can be studied through co-simulation results analyzing.

The other advantage is that it allows combining a feedback close loop controller to the AAPE FEM simulation. The experiment results show it is possible to vary ram speed for isothermal extrusion by means of feedback close loop control. With the controlled ram speed, a stable outlet temperature would be maintained within a small fluctuation range. These kinds of co-simulations can be used not only to optimize for higher applicable and performance of AAPE simulation, but also for the proper design of actual control units for AAPE.

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