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Predictive Tools for in-Line Isothermal Extrusion of 6xxx Aluminum Alloys †

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Abstract: During the last fifty years, the metal forming of aluminum alloys grew up significantly, leading to a more competitive market on which production rate and overall quality are kept higher as possible. Within the aluminum industries, extrusion plays an important role, since many industrial products with structural or even aesthetic functions are realized with this technology. Especially in the automotive industry, the use of aluminum alloys is growing very fast, since it permits a considerable weight loss and thus a reduction of the emission. Nevertheless, the stringent quality standards required don't allow the use of extruded aluminum alloys produced for the common building applications. An important parameter that can be used as an index of the quality of the extruded product is the emergent temperature: if the temperature at the exit of the press is kept constant within a certain limit, products with homogeneous properties and high-quality surface are obtained and the so called "isothermal extrusion" is achieved. As extrusion industries are spread all over the world with different levels of automation and control, a universal but simple in-line tool for determining the best process condition to achieve isothermal extrusion, is of particular interest. The aim of this work is to implement this model, that allows to evaluate the thermal gradient which have to be imposed on the billet. Several experiments have been carried out on an industrial extrusion press, and the outer temperature was recorded and compared with the simulated one to demonstrate the model consistency.

Keywords: Extrusion; aluminum; on-line simulation.

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1. Introduction

Throughout the extrusion, the exit temperature of the profile changes because of the thermodynamic characteristics of the process: predominantly, the temperature of the material increase, causing a nonuniformity of the alloys properties and of the dimension of the profile along the product length. The microstructure of the final length that has been extruded, may be characterized by grains with greater dimension than the ones in the other extremity – affecting consequently the mechanical properties – and, if the exit temperature exceeds the alloy melting temperature, the product surface will be marked by surface defects [1,2]. Therefore, it is crucial that the exit temperature of the profile is accurately monitored and, if possible, kept constant.

For these reasons isothermal extrusion has been developed [3,4]. The billets can be taper-heated, so their temperature changes lengthways – the billet head, the first fraction of material that is deformed, is warmer than the billet foot. Additionally, through a suitable process control, the extrusion speed can be progressively decreased: the regulation on the ram speed is done considering the exit temperature of the product, which is acquired at the outlet of the press [5,6]. Moreover, a constant temperature profile can be obtained through a cooling of the die, usually done by means of liquid nitrogen [7–9].

Extrusion speed variation technique allow to control the amount of heat generated while with nitrogen cooling systems the exceeding heat is removed: considering the billet taper heating, a proper temperature gradient is able to balance the amount of heat generated during the extrusion process and so the exit temperature of the product will be constant [10]. Once defined the best extrusion speed for the selected die, this practice permits to obtain an isothermal extrusion keeping the speed constant and so without compromising the plant productivity and the product quality.

During an extrusion process, the amount of generated heat is characterized by two contributes, one related to the friction phenomena and one associated to the material deformation. Furthermore, conductive and convective phenomena are established: these phenomena are responsible for heat transfers through the press-system.

Many simulation models were proposed to predict the extrusion process. Abdul-Jawwad et al. [11] used the statistical design of experiments (DOE) and find that initial billet temperature, ram speed, extrusion ratio, profile average thickness and number of die cavities influenced the resulting profile exit temperature. The integral profile approach [12–14] assumes a temperature profile surrounding the heat source to be given by the expression ΔT=a+bx+cx^2 , where a, b, c are constants determined by boundary conditions and ΔT is the temperature differential driving the heat conduction and x represents the distance from the heat source. Other works are based on the numerical analysis [14]. Furthermore, Takashi and Yoneyama [15] focus their attention on a simple model to achieve isothermal extrusion.

On the lights of the literature findings the main goal of this study is the formulation of a model that on-line, considering all the process variables, is able to define the billet temperature taper resulting in an isothermal extrusion procedure.

2. Materials and methods

Aiming an exhaustive description of the thermodynamic processes that characterize the alloy during the extrusion, it is necessary to highlight the variables related to the extrusion process. The geometrical ones are: billet initial diameter (d_B), billet initial length (L_B), container inner diameter (D_C). The following parameters are central for any extrusion process: extrusion ratio (R); circumscribing circle diameter; shape factor; form factor.

In a generic time step t, the variables correlated to the material deformation are the:

- mean equivalent flow stress $\bar{\sigma}$;
- temperature T;
- strain ε;
- mean equivalent strain rate $\bar{\dot{\varepsilon}}$.

The flow stress and strain rate mean equivalent definition is assumed to simplify the studied problem: actually, inside the deformation zone, the value related to the flow stress and to the strain rate changes both in time and in space. For this reason, an average flow stress and strain rate values are estimated. In order to estimate the mean equivalent stress flow, it is generally applied the Zener-Hollomon-Sheppard [16]:

$$\bar{\sigma} = \frac{1}{\alpha}\ln\left\{\left(\frac{Z}{A}\right)^{\frac{1}{n}} + \sqrt{\left[\left(\frac{Z}{A}\right)^{\frac{2}{n}} + 1\right]}\right\} \qquad Z = \dot{\bar{\varepsilon}}\exp\left(\frac{\Delta H}{G\cdot T}\right) \tag{1}$$

Where: Z, Zener's parameter; ΔH, deformation activation energy; G , gases universal constant; α,n, A constants related to the processed material. The latter can be found in literature for many aluminum alloys.

Given the deformation temperature, to apply the Zener-Hollomon-Sheppard expression, it is required firstly the calculation of the mean equivalent strain rate that for the extrusion is [16]:

$$\dot{\varepsilon} = \frac{6\mathrm{v_{RAM}} \cdot \mathrm{d}_0^2 \cdot \tan\alpha \cdot \ln\mathrm{R}}{\mathrm{d}_0^3 - \mathrm{d}_\mathrm{E}^3} \tag{2}$$

where: $\mathrm{v_{RAM}}$ s the ram speed, $\mathrm{d_0}$ is the billet initial diameter, $\mathrm{d_E}$ is the extruded diameter, R is the extrusion ratio and α the dead-metal zone semi angle.

The developed model is logic-based on a billet discretization approach: once evaluated the deformation zone volume, known the billet dimensions after the upsetting phase, the billet is divided into some control sub-volumes equal to the volume of the deformation zone calculated as:

$$\mathrm{V_{DZ}} = \frac{\pi}{24} \cdot \mathrm{L_{DZ}} \left(\frac{\mathrm{d}_0^3 \cdot \mathrm{d}_\mathrm{E}^3}{\tan\alpha} \right) \tag{3}$$

So therefore the number of sub-volumes is

$$\mathrm{n_{discr}} = \frac{\mathrm{V_{billet}}}{\mathrm{V_{DZ}}} \tag{4}$$

Through this discretization approach, at each algorithm time step it is always controlled the same volume of material able to fulfil the deformation zone.

2.1. Thermodinamics model

In this study the following thermal phenomena are considered in different part of the process.

In the container:
- friction between the external billet surface and the inner container;
- heat dissipation towards the container if its temperature is lower than the billet one;
- heat generation during the billet upsetting

In the deformation zone:
- friction and deformation heat generation in correspondence of the deformation zone;

In the die:
- friction heat generation between the material and the die;
- heat dissipation towards the die;

Outside the extrusion machine:
- heat dissipation towards plant environment.

2.1.1 Container

The heat generate during the upsetting is calculated as the heating due to the material plastic deformation:

$$\Delta T = \frac{\beta\bar{\sigma}(L_B - L_{0)}}{\rho c_p L_B} \tag{5}$$

Where β is the fraction of the deformation energy converted into heat (generally 0.95); ρ, material density; $\mathrm{c_P}$, material specific heat; $\mathrm{L_B}$ billet initial length; $\mathrm{L_0}$, billet final length.

In a direct extrusion process, the material is pushed towards the die which has a fixed position inside the press: because of this motion, the external billet surface crawls along the inner container surface. As a result, some heat is generated. Considering the discretized billet, the friction interaction, as well as the cooling one, must be referred to each control sub-volume: the overall worth of the phenomenon is consequently function of the position of the sub-volume with respect to the deformation zone. The temperature increase due to this friction phenomenon is, in the discretized volume:

$$\Delta T_{f,c} = \frac{m_c \cdot BTF \cdot \bar{\sigma} \cdot 4L_{CV}}{\sqrt{3} \cdot \rho \cdot c_p \cdot d_0} \tag{6}$$

Where m_c, billet-container friction coefficient; BTF fraction of the generated heat which flows inside the billet, assumed as 0.8.

In correspondence of the billet-container interface, in addition to the heat generation, it is established a heat transfer phenomenon due to the different temperature of the container with respect to the billet one. To simplify the problem, for each sub-volume translation towards the die, the overall thermal balance was split into two subsequent phases, the material heating due to the friction and then the heat transfer phenomena. Considering the i− th step the temperature increase due to the upsetting is:

$$T_{i,c} = (T_{i,0} + \Delta T_{f,c} - T_{liner}) \cdot e^{\frac{L_{CV}}{R_{liner} \cdot \rho \cdot V_{CV} \cdot c_p \cdot v_{RAM}}} + T_{liner} \tag{7}$$

Where: $T_{i,0}$ is the control sub-volume temperature at the step start; T_{liner} is the temperature of the internal part of the container, R_{liner} is the liner thermal resistance.

The above described calculations must be reiterated as much are the control sub-volume steps necessary to reach the deformation zone: actually, when a cylinder gets the position immediately ahead the deformation zone, no further steps are accounted to it.

2.1.2 Deformation zone

The phase that mainly increase the material temperature is the deformation process. Moreover, still within the deformation zone, but inside the material, internal friction phenomena are established: they also cause some amount of heat, contributing to the alloy temperature increase. The temperature increase due to the plastic deformation process of the material is:

$$\Delta T_d = \frac{\beta \bar{\sigma} lnR}{\rho c_p} \tag{8}$$

Instead, the thermal power generated by the internal friction phenomena is valuable as:

$$\Delta T_{if} = \frac{\bar{\sigma} \cdot lnR \cdot cot\alpha \cdot R \cdot A_E \cdot L_{CV}}{\sqrt{3} \cdot \rho \cdot c_p \cdot V_{CV}} \tag{9}$$

Where: A_E equivalent section of the extruded product.

Given the control sub-volume initial temperature, i.e. its final temperature while leaving the container, and all the temperature increases within the deformation zone, it is possible to define the final temperature of the material outgoing this region, therefore:

$$T_{DF} = T_{i,c} + \Delta T_d + \Delta T_{if} \tag{10}$$

2.1.3 Die zone

The interaction between the material and the die is also based on the crawling among two bodies: consequently, it is established a friction phenomenon that generates some heat. Moreover, the die temperature is lower than the profile one: actually, the die is warmed by the heat coming from the liner and the adjacent deformation zone, but it is also cooled down by the environment. Consequently, a heat transfer between the profile and the die is established.

The temperature increase due to this friction phenomenon is:

$$\Delta T_{f,d} = \frac{m_D \cdot BTF \cdot \bar{\sigma} \cdot SF \cdot d_E \cdot L_{DIE}^2}{\sqrt{3} \cdot \rho \cdot c_p \cdot V_{CV}} \tag{11}$$

Where L_{DIE} is the longitudinal length of interaction between the profile and the die; SF, extruded profile shape factor.

The longitudinal length of interaction is function of the die assembly, that is related to the desired profile geometry. Considering the profiles geometry, the great difference is represented by a solid, semi-hollow or hollow profile: from the die design point of view, a hollow profile is the more challenging one to be produced and so will be the estimation of the die interaction length.

As for the material-container interaction, splitting the total thermal balance into two subsequent steps, it is now necessary to define the temperature decrease as a result of the heat dissipation towards the die:

$$T_c = (T_{DF} + \Delta T_{f,d} - T_{DIE}) \cdot e^{\frac{L_{DIE}}{R_{DIE} \cdot \rho \cdot V_{CV} \cdot c_p \cdot v_E}} + T_{DIE} \tag{12}$$

Where: $T_{i,0}$ is the control sub-volume temperature at the step start; T_{DIE} is the temperature of the die, R_{DIE} is the die thermal resistance.

2.1.3 Outside the extrusion machine

Despite the extrusion process is fully developed inside a press, its boundary conditions are also important. From this point of view, it is necessary to consider the interaction between the material and the plant environment when: the billet is loaded inside the container and the extruded product leaves the die.

These two interactions are based on a convective heat transfer phenomenon that in both the cases is the cause of the material cooling. The material cooling during the loading phase is crucial especially when the isothermal extrusion based on a temperature tapered billet is chosen. Furthermore, the extruded product cooling at the die exit is central when the heat treatment of the material is expected to be done directly in-press: specifically, the possible problems are referred to the cooling step related to the homogenization phase. Taking into account the thermal exchange in this part of the process, known the profile temperature at the cooling phenomenon end, its initial temperature is:

$$T = (T_x - T_\infty) \cdot e^{\frac{h \cdot \pi \cdot SF \cdot d_e \cdot L_{CV} \cdot R_t}{\rho \cdot V_{CV} \cdot c_p}} + T_\infty \tag{13}$$

Where, T_x is the Initial billet temperature T_0 at the beginning of the process and T_C at the end, h is the convective heat transfer coefficient.

2.2 Implementation and validation of the models

Two different models have been derived. Actually, the main problem related to the extrusion process modelling is how to consider the material deformation with respect to the number of holes that characterize the die. Each schematization of a direct extrusion process and consequently each formulation, is based on a billet extrusion through which is produced a single profile; consequently, there is not any expression, that considers a multi-holed die. In the first approach, fixed the extrusion ratio, the holes characterizing the die are not considered: through the extrusion process, the billet is deformed into a single profile, defined by its section and shape factor. The second approach is meaningful only in presence of a multi-hole die. In this case, considering the number of die holes, the billet section is equally divided into subsections: as a result, from the original billet the same number of equivalent sub-billets are obtained. Each sub-billet, through the associated deformation zone, defines a single profile represented once more by its section and shape factor.

Data acquisitions were arranged to obtain all the necessary inputs required by the algorithm; it was considered:

- the acquisition of the air temperature at the die boundaries;
- the acquisition of the air temperature inside the press exit tunnel.

During the production, the profile temperature acquisition is done automatically by the press controller software (EMS-Extrusion Management System and N5Nitrogen by ATIE1) [17]: however, the needed temperatures were acquired by means of thermocouples ad-hoc placed inside the press working-structure.

The automatic acquisition of the profile temperature is done by a pyrometer fixed on the press structure. The pyrometer is placed over the press exit tunnel outlet and pointed down to the profile exiting the machine. The boundary temperature characterizing the container is always known and almost constant: this is due the heat up modality of the container itself. The die is directly heated up once before it is positioned inside the press: usually, it is preheated around 400°C. During the extrusion process, the heat generated by the liner and the material deformation adjacent the die, increases once more its temperature. By means of a thermocouple placed close to the die, the temperature is acquired. An additional set of acquisition allowed to define the air temperature inside the press exit tunnel: two thermocouples were placed sideways in the lower half of the tunnel, while another one was fixed on the vault of the tunnel upper half.

The validation of the models was done comparing experimental temperatures data with the estimated ones. A couple of solid profiles and a couple of hollow ones were chosen.

3. Results and discussion

The algorithm with multiple profile represents the extrusion process better than the single one and for this reason only these results are reported. The goodness of the predicted temperatures was qualitatively defined arranging them to the related experimental values inside a chart. The predicted and measured temperature for different profiles, solid and hollow, with more than one holes is reported in Figure 1 and 2. The predicted temperature is in good agreement with the measured one in all the cases.

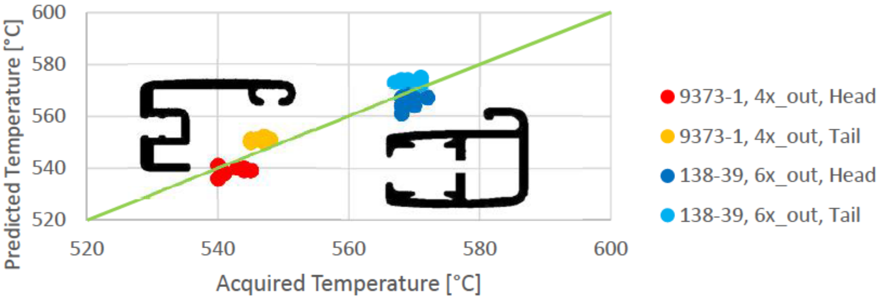


Figure 1. Solid profile temperature prediction for extrusion with 4 and 6 holes

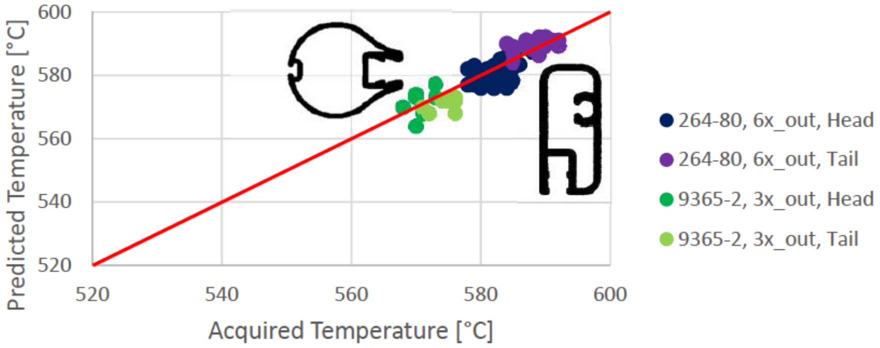


Figure 2. Hollow profile temperature prediction for extrusion with 3 and 6 holes

The multiple profile approach shows a great prediction capability: actually, all the prediction errors range among ±1.5%. As reference, the measurement accuracy of an industrial pyrometer is usually within ±1-2%. Using the algorithm with a single profile all the predicted value are underestimated and the error is around 7%.

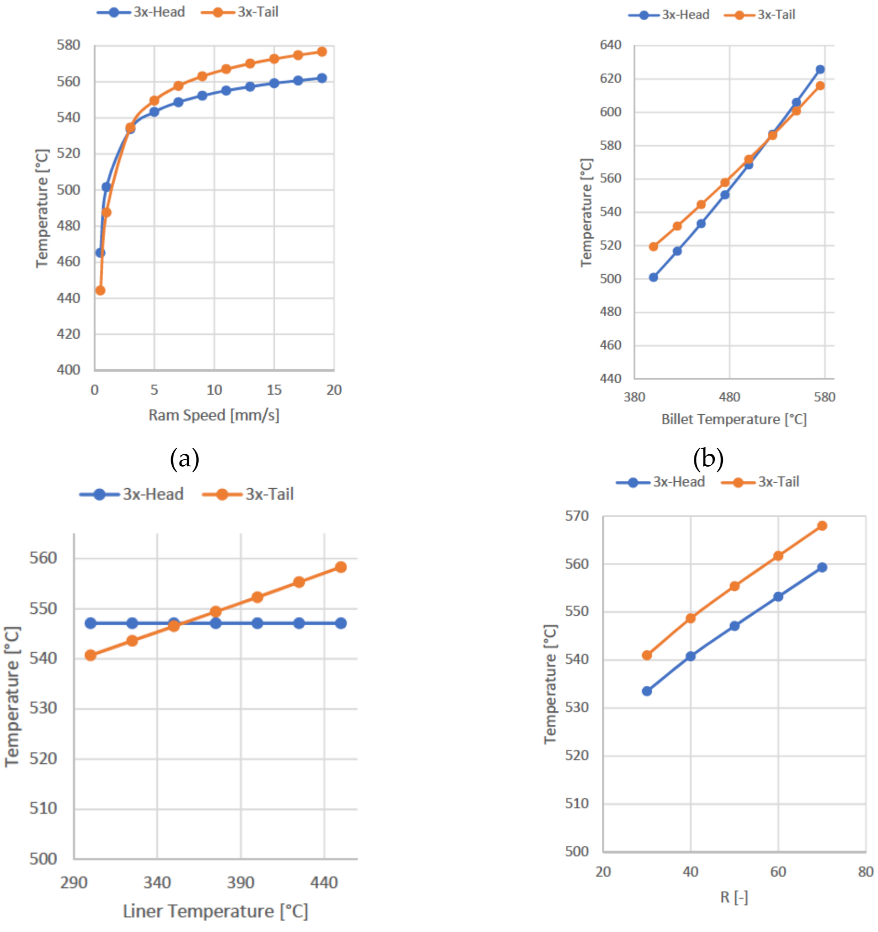
3.1. Analysis of Sensitivity

By means of a sensitivity analysis, it was studied the process variables influence on the profile head and tail temperatures, measured in correspondence of the pyrometer measurement point.

The parameters outlined are:

- v_{RAM}, ram speed;
- T_{IN}, initial billet temperature. The billet was considered as homogeneously-heated;
- T_{LINER}, average liner temperature;
- R, extrusion ratio.

The selected model involves 3 holes in the die.



(a) (b)

(c) (d)

Figure 3. Process variables influence on the profile head and tail temperature: (a) ram speed; (b) billet temperature; (c) liner temperature; (d) reduction ratio.

The main result of these analyses refers to the container involvement into the definition of an isothermal extrusion condition (Figure 3): actually, every extrusion parameter that affects the heating and the cooling phenomena between the billet and the liner has a critical value by means of which an isothermal extrusion can be achieved. Consequently, the heating and the cooling phenomena that take place downstream the container, i.e. the material-die interaction and the material environment interaction, cannot be accounted to get an isothermal extrusion, because they increase or decrease the whole material temperature in the same measure. Therefore, this condition is achieved only when at the end of the material-container interactions the billet tail temperature will be almost equal to the initial billet head temperature.

3.2. Billet temperature taper definition

Defined by means of a proper model the temperature increase trend related to a billet extrusion, the next step is focused on the determination of the billet temperature taper. It is essential when an isothermal extrusion condition must be reached without a variation of the extrusion process parameters. Moreover, the potential of this approach is the possibility to obtain an isothermal extrusion at the maximum extrusion speed allowed by the die design, thus increasing the productivity of the press.

The taper temperature is defined by a reiterative cycle: the inputs of this process are the profile initial extrusion temperatures, considering a homogenously-heated billet, and the desired isothermal target temperature. With respect to each curve development, the logic behind the cycle is to decrease locally the billet initial temperature where the predicted final temperature is higher than the target one, and vice versa. The process is iterative since every material temperature increase during the billet extrusion is function of the mean equivalent flow stress that is non-linearly function of the mean equivalent

strain rate which again is non-linearly function of the initial billet temperature. Given the previously examined profiles and known each process inputs, through the algorithm it was estimated the temperature taper. The predicted values were related to the real ones.

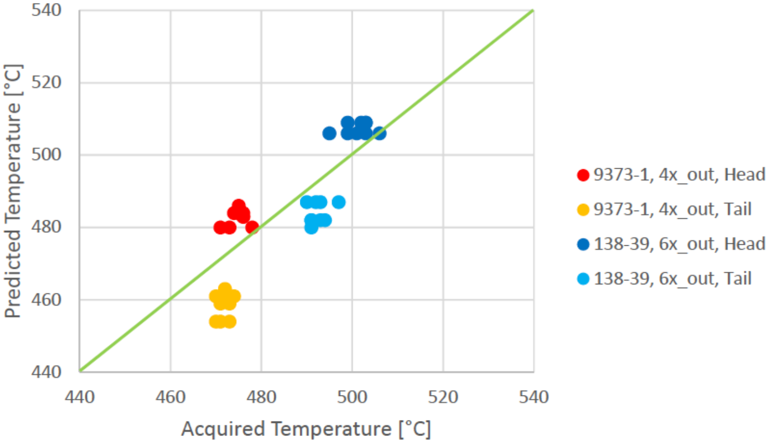


Figure 4. Solid profile temperature taper for extrusion with 4 and 6 holes: predicted and measured

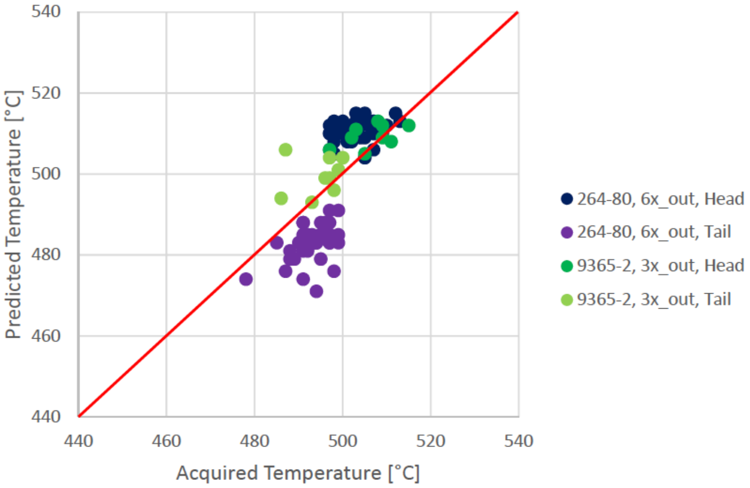


Figure 5. Hollow profile temperature taper for extrusion with 3 and 6 holes: predicted and measured

As results of the temperature taper estimation analysis, the algorithm overestimates the billet head temperature (⇨ +1.5%) and underestimates the tail one (⇨ -2%), thus the estimated taper is slightly steeper than the real one. However, considering the actual process errors, the ones related to the algorithm estimations can be reasonably accepted too.

4. Conclusions

The realized model (in particular the multiholes one) is in good agreement to the real extrusion process that considers the actual die outlets. The error of the predicted extrusion temperature (or taper temperature) is less than the pyrometer accuracy. Moreover the model is faster than a F.E.M. simulation guarantying a high on-site repeatability and it is translatable into the extrusion-press-controller software language.

Finally, the evidence that adjusting some process variables, the isothermal extrusion can be achieved even without employing the related conventional practices was found: actually, it exists a critical constant ram speed, a homogeneous billet temperature and a liner temperature by means of which the extrusion results isothermal.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

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