A Comprehensive Model for Predicting Profile Exit Temperature of Industrially Extruded 6063 Aluminum Alloy
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A Comprehensive Model for Predicting Profile Exit Temperature of Industrially Extruded 6063 Aluminum Alloy

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The effects of extrusion parameters on the resulting profile exit temperature of industrially extruded 6063 aluminum alloy have been studied using statistical design of experiments (DOE). Two operating parameters (initial billet temperature and ram speed) and three geometrical parameters (extrusion ratio, profile average thickness, and number of die cavities) were investigated. A statistical model was obtained for predicting profile exit temperature with very close agreement between predicted and measured values. Present results indicated that the main contribution towards profile exit temperature comes from plastic work promoted by high extrusion ratios, high initial billet temperatures, and high ram speeds. Further contributions are promoted by parameters affecting friction and redundant work components. In addition to single-factor effects, profile exit temperature was revealed to be affected by a set of complex two-factor and three-factor interactions between the different operating and geometrical parameters. The most remarkable two-factor interactions were shown to exist between extrusion ratio and number of die cavities and between initial billet temperature and ram speed. Complex three-factor interactions have been shown to exist between extrusion ratio, initial billet temperature, and ram speed. These interaction effects are quantified in the present model and are further qualitatively discussed in terms of their effects on the resulting profile exit temperature.

Keywords Aluminum; DOE; Extrusion; Modeling; Statistical; Temperature.

INTRODUCTION

Profile exit temperature is of prime interest in the industrial extrusion of aluminum alloys, especially the heat-treatable ones. This comes from the fact that profile exit temperature at the “press mouth” determines several quality features of the produced sections. They include the degree of extrudate responsiveness to the subsequent quenching (either air or water quench) and aging treatments [1–3], the surface quality of the parts produced [1, 4–10] as well as the resulting grain structure [4, 7, 8, 11–16] and hence the overall range of surface and mechanical properties. Extrusion pressure and temperature are also strongly interrelated [3, 4, 17, 18]. From another angle, being able to predict, and indeed control, profile exit temperature is a key requirement for the isothermal extrusion, a mode of operation which has recently gained a considerable interest [9, 19]. Profile exit temperature is, however, controlled by the complex thermomechanical cycle of the extrusion process represented by the several process parameters, geometrical features of the profile, and the collective interactions between these factors. Even though the industrial extrusion of aluminum alloys is both a mature subject and a straightforward operation, it is constantly being subject to great variability within its process parameters, tool and die designs, and the vast variety of sections produced [4, 6, 17]. This makes its practice far from being optimal (or near optimal) when the combined goal of acceptable productivity levels, general product qualities, and ease of process control is being considered. The topic of this article (i.e., extrusion and profile exit temperature) has been the subject of extensive research efforts [1, 4–6, 9, 10, 13–21]. The bulk of these studies have used mathematical models, primarily the finite element method (FEM) [4, 6–10, 16, 20, 21] to predict and/or relate extrudate temperature to some process or design parameters, with some experimental verifications for these models [1, 4, 6, 7, 9, 10, 21], while others considered experimental results only [13, 18]. Extrusion temperature has been related to almost all practical process parameters including variations in the ram speed [1, 6, 8–10, 17, 21], extrusion ratio [1, 8, 17, 18], and initial billet temperature [1, 8, 17, 18]. A few studies have considered some design aspects including the presence of more than one die cavity (i.e., multihole dies) [4, 7]. Mathematical models are considered to be very useful in the design and development stage of new sections and their corresponding dies as related to metal flow, the possible microstructures, and surface features of the produced extrudate. They are normally time consuming and are carried out for a set of “fixed” parameters and must be repeated if any of these parameters are to be changed. Numerical results are only applicable to the specific case(s) studied or to very similar cases, even though they may represent good guidance as to the general behavior of the particular parameters which have been investigated. On the other hand, experimental studies alone are useful in explaining certain phenomena and providing general trends, but any numerical values obtained from these studies are not usually applicable to other situations with different
experimental setup in addition to the general trend of “changing-one-factor-at-a-time” used in these studies, which is far from being capable of representing the complex nature of industrial extrusion. In addition, a common limitation of these two types of studies is their inability to quantify interaction effects. This is especially important in the prediction and control of extrusion temperature, as this is the result of a set of complex thermal events (generation/loss), including [6] the following:

1. Heat generation due to deformation;
2. Heat generation due to friction and shear mechanisms involved;
3. Heat loss to the tooling;
4. Heat loss from tooling to the ambient surrounding;
5. Heat conduction between the billet and extrudate.

From another angle, a common challenge to the fitness of any model in the extrusion process is that some design and operation parameters in the industrial extrusion are normally dictated by some factors which are beyond the choice of the designer and/or researcher. For example, the number of die cavities is normally dictated by a compromise between the extrusion ratio, the specific shape of the cross-section, the length of the run-out table, and the minimum/maximum speed of the puller. The initial ram speed is also normally chosen based upon profile thickness, initial billet temperature, required productivity levels, and the puller speed. Some factors also cannot be included in mathematical models as independent parameters, an example of which is the “shape complexity” factor (22 and 23). From the above discussion, it is obvious that despite the great importance of mathematical models, these are not adequate alone to cover the extrusion process collectively for the design and operation stages. The literature clearly lacks a “comprehensive” model for the prediction of extrusion temperature which possesses the following features:

1. Is capable of quantitatively evaluating the effects and contributions of both operating parameters such as ram speed, initial billet temperature, and geometrical parameters such as extrusion ratio, profile complexity, and number of die cavities;
2. Is capable of quantifying the effects of both individual parameters, mentioned above, as well as their interaction(s);
3. Covers wide ranges for process and geometrical parameters and accurately predicts profile exit temperature regardless of the specific section of the extrudate;
4. Is suitable for both the design stage as well as press operation and control;
5. Can be used by researchers, production engineers, and press operators;
6. Is applicable to other extrusion studies/plants with minor modifications;
7. Is quick and simple to use.

In the present study, statistical modeling, using factorial design of experiments (DOE), has been applied to the direct industrial extrusion process of aluminum alloy 6063 as an example of a widely used material for commercial extrusion applications [4, 24]. The objective of this study is to obtain a statistical model that will help predict profile exit temperature with the features listed above.

**Material and Experimental Procedure**

**Material**

The material used in this study was AA 6063 alloy, the composition of which is shown in Table 1. Eight-inch (~200 mm) diameter and 500 mm long billets (H 0 temper) were used for extrusion trials.

**Selection of Extrusion Parameters and Parameter Values**

Extrusion runs for the present study were carried out on a commercial BredaTM-type press with a 2200 ton capacity and an eight-inch internal diameter. All tooling parts including container, dies, die holder, etc. were kept at temperature of 450°C before the start of each extrusion run. A five-factor two-level DOE plan has been adopted and a specialized statistical software, Design Expert®, was used for the design and analysis of the experiments. Each of the five factors (parameters) has two values (known as levels): the high (H) and the low (L). These two levels cover the range within which the particular parameter can vary. A $2^5-1$ DOE was used (where n is the number of factors = 5) with a total of 16 extrusion runs. The preliminary experimental setup in terms of coded values ($H = 1$ and $L = -1$), taken from the software, is shown in Table 2. The sequence of experiments presented in Table 2 was generated by the Design Expert® software for randomizing purposes. Ideally, in the 2-level DOE, each experiment (in this case extrusion run) would include a list of pre-planned experimental runs where parameters would have fixed values of either the $H$ or the $L$ levels. In actual industrial extrusion situations, it is possible to allocate fixed values to operating parameters, but it would be practically impossible to find extruded sections together with their corresponding extrusion dies having the same “fixed” values of all geometrical parameters. Based on this, fixed values (levels) have been allocated to operating parameters, while in the case of geometrical parameters, a range of values has been chosen for each the $H$ and $L$ levels, respectively. In this case, for geometrical parameters, the values employed for analysis are the average of the used values within each range. Choice of the parameters to be investigated in this study and their values/ranges has been based on previous literature, consultation with personnel from industrial extrusion plants, and the first author’s experience (who formerly held the position of extrusion die shop manager). These included the following:

1. Extrusion ratio (ER);
2. Number of cavities in the die (NOC);
3. Chemical composition of alloy 6063 (wt%).

<table>
<thead>
<tr>
<th>Al</th>
<th>Cu</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Mn</th>
<th>Ni</th>
<th>Cr</th>
<th>Ti</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bal.</td>
<td>0.01</td>
<td>0.55</td>
<td>0.5</td>
<td>0.19</td>
<td>0.015</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Table 1.**—Chemical composition of alloy 6063 (wt%).
3. Average thickness of the profile (THK); 4. Initial billet temperature (BLT); 5. Ram speed (RS).

Profile average thickness has been incorporated in the present study as a simple and easily determined measure of shape complexity effects. Shape complexity has been defined using several formulas, but a recently acceptable definition of this factor represents a function of the ratio of the profile perimeter to that of an equivalent round profile with the same cross-sectional area [22 and 23]. A closer look at this definition reveals that profile thickness plays a major role in the shape complexity, as generally thick sections would have low shape complexity-factor values, while thin sections would have larger values for this parameter. It could be argued here that, for the sake of simplicity, profile average thickness could be used to investigate the effect of shape complexity on the resulting profile exit temperature. The values/ranges employed in the experiments and the values used for analysis are shown in Table 3.

Table 4 presents the actual values employed for the sixteen extrusion runs in Table 2. As explained earlier, the values used for analysis are shown in Table 3.

Table 3.—High and low values (ranges) and values used for analysis of extrusion parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High (Range)</th>
<th>Value used for analysis</th>
<th>Low (Range)</th>
<th>Value used for analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusion ratio</td>
<td>(≥65)</td>
<td>74</td>
<td>(&lt;40)</td>
<td>30</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>(3–6)</td>
<td>6</td>
<td>(1–2)</td>
<td>1.5</td>
</tr>
<tr>
<td>Billet temperature (°C)</td>
<td>460</td>
<td>460</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Average profile thickness (mm)</td>
<td>(≥3)</td>
<td>4.4</td>
<td>(&lt;1.5)</td>
<td>1.4</td>
</tr>
<tr>
<td>Ram speed (mm/s)</td>
<td>8</td>
<td>8</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 4.—Actual values employed for the sixteen extrusion runs.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>ER</th>
<th>NOC</th>
<th>THK (mm)</th>
<th>BLT (°C)</th>
<th>RS (mm/s)</th>
<th>Exit temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>90.8</td>
<td>8</td>
<td>3</td>
<td>400</td>
<td>5</td>
<td>508</td>
</tr>
<tr>
<td>14</td>
<td>90.8</td>
<td>8</td>
<td>3</td>
<td>460</td>
<td>8</td>
<td>522</td>
</tr>
<tr>
<td>5</td>
<td>72.6</td>
<td>8</td>
<td>1.7</td>
<td>400</td>
<td>8</td>
<td>513</td>
</tr>
<tr>
<td>12</td>
<td>72.6</td>
<td>8</td>
<td>1.7</td>
<td>460</td>
<td>5</td>
<td>518</td>
</tr>
<tr>
<td>1</td>
<td>60.8</td>
<td>1</td>
<td>3</td>
<td>400</td>
<td>8</td>
<td>508</td>
</tr>
<tr>
<td>10</td>
<td>60.8</td>
<td>1</td>
<td>3</td>
<td>460</td>
<td>5</td>
<td>512</td>
</tr>
<tr>
<td>11</td>
<td>72.5</td>
<td>2</td>
<td>1.25</td>
<td>400</td>
<td>8</td>
<td>512</td>
</tr>
<tr>
<td>15</td>
<td>72.</td>
<td>2</td>
<td>1.25</td>
<td>400</td>
<td>5</td>
<td>512</td>
</tr>
<tr>
<td>8</td>
<td>33.4</td>
<td>4</td>
<td>3.6</td>
<td>460</td>
<td>5</td>
<td>508</td>
</tr>
<tr>
<td>9</td>
<td>33.4</td>
<td>4</td>
<td>3.6</td>
<td>460</td>
<td>5</td>
<td>513</td>
</tr>
<tr>
<td>13</td>
<td>36.5</td>
<td>4</td>
<td>1.2</td>
<td>400</td>
<td>8</td>
<td>508</td>
</tr>
<tr>
<td>16</td>
<td>36.5</td>
<td>4</td>
<td>1.2</td>
<td>460</td>
<td>5</td>
<td>512</td>
</tr>
<tr>
<td>7</td>
<td>11.7</td>
<td>1</td>
<td>8</td>
<td>400</td>
<td>8</td>
<td>508</td>
</tr>
<tr>
<td>6</td>
<td>11.7</td>
<td>1</td>
<td>8</td>
<td>460</td>
<td>5</td>
<td>512</td>
</tr>
<tr>
<td>2</td>
<td>37.3</td>
<td>2</td>
<td>1.4</td>
<td>460</td>
<td>8</td>
<td>508</td>
</tr>
<tr>
<td>4</td>
<td>37.3</td>
<td>2</td>
<td>1.4</td>
<td>400</td>
<td>5</td>
<td>508</td>
</tr>
<tr>
<td>Average (H)</td>
<td>74</td>
<td>6</td>
<td>4.4</td>
<td>460</td>
<td>8</td>
<td>508</td>
</tr>
<tr>
<td>Average (L)</td>
<td>30</td>
<td>1.5</td>
<td>1.4</td>
<td>400</td>
<td>5</td>
<td>508</td>
</tr>
</tbody>
</table>

**Temperature Measurement**

Profile exit temperature was measured using a WILLIAMSON PRO120-20™ multi-wavelength pyrometer with a measuring range of 200–600°C. Temperature measurement point was chosen at a distance of about two meters from the press mouth, which represents the point at which actual quenching, either by air fans or water spray jets starts, and hence represents a true press quench. Temperature readings were taken after a steady state has been established (evidenced by a relatively constant profile temperature).

**RESULTS AND DISCUSSION**

Table 5 shows the measured profile exit temperature together with the different parameters’ values used for statistical analysis.

Table 5.—Measured profile exit temperature together with parameters’ values used for statistical analysis.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>ER</th>
<th>NOC</th>
<th>THK (mm)</th>
<th>BLT (°C)</th>
<th>RS (mm/s)</th>
<th>Exit temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>74</td>
<td>6</td>
<td>4.4</td>
<td>400</td>
<td>5</td>
<td>508</td>
</tr>
<tr>
<td>14</td>
<td>74</td>
<td>6</td>
<td>4.4</td>
<td>460</td>
<td>8</td>
<td>522</td>
</tr>
<tr>
<td>5</td>
<td>74</td>
<td>6</td>
<td>1.4</td>
<td>400</td>
<td>8</td>
<td>513</td>
</tr>
<tr>
<td>12</td>
<td>74</td>
<td>6</td>
<td>1.4</td>
<td>460</td>
<td>5</td>
<td>518</td>
</tr>
<tr>
<td>1</td>
<td>74</td>
<td>1.5</td>
<td>4.4</td>
<td>400</td>
<td>5</td>
<td>508</td>
</tr>
<tr>
<td>10</td>
<td>74</td>
<td>1.5</td>
<td>4.4</td>
<td>400</td>
<td>8</td>
<td>512</td>
</tr>
<tr>
<td>11</td>
<td>74</td>
<td>1.5</td>
<td>1.4</td>
<td>460</td>
<td>8</td>
<td>530</td>
</tr>
<tr>
<td>15</td>
<td>74</td>
<td>1.5</td>
<td>1.4</td>
<td>400</td>
<td>5</td>
<td>512</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>6</td>
<td>4.4</td>
<td>460</td>
<td>8</td>
<td>506</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>6</td>
<td>4.4</td>
<td>400</td>
<td>5</td>
<td>495</td>
</tr>
<tr>
<td>13</td>
<td>30</td>
<td>6</td>
<td>1.4</td>
<td>400</td>
<td>8</td>
<td>502</td>
</tr>
<tr>
<td>16</td>
<td>30</td>
<td>6</td>
<td>1.4</td>
<td>460</td>
<td>5</td>
<td>501</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>1.5</td>
<td>4.4</td>
<td>400</td>
<td>8</td>
<td>473</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>1.5</td>
<td>4.4</td>
<td>460</td>
<td>5</td>
<td>472</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>1.5</td>
<td>1.4</td>
<td>460</td>
<td>8</td>
<td>520</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>1.5</td>
<td>1.4</td>
<td>400</td>
<td>5</td>
<td>495</td>
</tr>
</tbody>
</table>
From Table 5, it is obvious that it would be difficult to relate profile exit temperature to any single parameter (factor) in isolation of other factors. This, at a first glance, indicates the existence of complicated interaction effects acting beside the effects of individual process parameters. These will be explained in the following sections after the overall statistical model has been introduced.

**Overall Statistical Model**

Figure 1 presents a half normal probability plot for the proposed model based on statistical analysis (different factors have been indicated by alphabetical letters as shown in the figure). In simple terms, this plot shows which factors (interactions) have the greatest effects on the resulting exit temperature. A factor lying away from the lower left corner of the plot indicates a strong effect, while a factor lying at or near this corner indicates a nil or a very minor effect. From this plot it can be seen that, for single parameters, extrusion ratio has the strongest effect on profile exit temperature followed by ram speed, initial billet temperature, profile average thickness and then number of die cavities. The fact that extrusion ratio has the strongest effect on profile exit temperature is due to the fact that this parameter (ER) represents the total effective strain of the extrusion parameter [1, 8, 17, 22, 23], hence reflecting the overall plastic work required. The strongest double interaction is seen to exist between initial billet temperature and ram speed, while the strongest triple interaction exists between the extrusion ratio, initial billet temperature, and ram speed. A moderate effect is noticed for the interaction between extrusion ratio and number of die cavities. Even some of these interaction effects can be expected from general metal forming principles, pertinent to the extrusion process, their relative importance (in terms of numerical values) would be difficult to obtain without such a model. In addition this model has revealed that some interaction effects (especially that between initial billet temperature and ram speed) are more important than individual process parameters contributing to these interaction effects.

The statistical model representing the numerical values of the different effects in Fig. 1, in terms of coded values, is presented below in Eq. (1). This model is useful in predicting profile exit temperatures when the different parameters are substituted in terms of their coded values (1 for \(H\) and \(-1\) for \(L\)), and where only the \(H\) and \(L\) levels are used. A more general model where actual values could be used is presented in Eq. (2). It could be seen that the coefficients of the different parameters and interactions have changed and that some coefficients have changed signs from positive to negative and vise versa. The change in coefficients’ values and signs is due to the differences between the actual values and the coded values of the different parameters (for example the \(H\) values for ER and THK are 74 and 4.4, respectively, while they have the same coded value of 1). More details on this subject can be found elsewhere [25].

### Exit Temperature

\[
\begin{align*}
\text{Exit Temperature} &= 506.31 + 9.06^* \text{ER} + 3.56^* \text{NOC} - 5.06^* \text{THK} \\
&+ 5.06^* \text{BLT} + 5.19^* \text{RS} - 3.69^* \text{ER}^* \text{NOC} \\
&+ 2.19^* \text{ER}^* \text{THK} - 0.94^* \text{ER}^* \text{BLT} - 1.31^* \text{ER}^* \text{RS} \\
&+ 6.44^* \text{BLT}^* \text{RS} - 3.81^* \text{ER}^* \text{BLT}^* \text{RS}
\end{align*}
\] (1)

### Exit Temperature

\[
\begin{align*}
\text{Exit Temperature} &= 1303.51162 - 9.39520^* \text{ER} + 5.45707^* \text{NOC} \\
&- 6.82197^* \text{THK} - 1.98889^* \text{BLT} - 142.09596^* \text{RS} \\
&- 0.074495^* \text{ER}^* \text{NOC} + 0.066288^* \text{ER}^* \text{THK} \\
&+ 0.023611^* \text{ER}^* \text{BLT} + 1.61616^* \text{ER}^* \text{RS} \\
&+ 0.34331^* \text{BLT}^* \text{RS} \\
&- 3.85101E - 003^* \text{ER}^* \text{BLT}^* \text{RS}
\end{align*}
\] (2)

Figure 2 shows actual profile exit temperatures against their predicted values. It is obvious that, in spite of the fact that average values were used for geometrical parameters for analysis purposes, there is a very close agreement between actual and predicted values.

This reflects the robustness of statistical models as being insensitive to marginal variations in parameters’ values while producing accurate predictions within practical acceptance limits. As quantitative evaluation of the different effects has been introduced in this section, qualitative discussion of these effects will be presented in the following sections in the light of the above model.

**Single-Parameter Effects**

**Extrusion Ratio, Ram Speed, and Billet Temperature.** These three parameters seem to have direct effects on profile exit temperature, as single factors, Fig. 1, which is in agreement with previous studies listed in Section 1 and hence will not be elaborated further.
Profile Thickness and Number of Die Cavities. The effects of profile average thickness and number of die cavities are shown in Figs. 3(a) and (b), respectively. It is interesting to see that profile average thickness, which has not been studied as an important single factor in previous studies, seems to have considerable negative effect on profile exit temperature, Eq. (2), implying that a small decrease in profile thickness would result in a significant increase in the resulting profile exit temperature. Changing thickness while having other parameters fixed, then extruding a thinner profile, is expected to result in a less homogeneous metal flow and an increase in both the extent of the shear zone within the deformation zone in front of the die and the total length of this shear zone within the cross-section of the deformation zone. Even though the effective strain, and hence the plastic work, will not be affected in this case, the amount of redundant work is expected to increase tremendously. The more difficult axial flow of the metal is also expected to exert radial stresses resulting in an increase in frictional forces between the forming sections and the die land as well as between the forming billet and the container wall. Increasing the redundant and frictional work components would be expected to have a corresponding increase in profile exit temperature. It has been also argued that both the flow stress and the mean strain rate increase with more complex flow patterns (26).

Figure 3(b) indicates, roughly, an increase of about 1.5 to 2°C per die cavity. The direct effect of increasing the number of die cavities is a more complex metal flow [4, 7]. Peng and Sheppard [4] investigated metal flow patterns in single and multihole (cavity) dies using FEM with experimental evaluations. Their findings indicated the presence of dead metal zones within the circumferential extremities of the dies as well as in the areas between the different die cavities. This has led to the creation of a corresponding number of shear zones with severe deformation patterns. Their simulation and experimental results indicated a larger angle between the circumferential dead metal zone and the die in the case of multihole dies, which is expected to increase the extent of metal flow complexity. Although this has been related to the distance of the outer die cavity and the billet edge [4, 26], in practice an increase in the number of die cavities normally requires a distribution approaching the limiting circumscribing circle of the die. Increasing the number of die cavities is expected to contribute towards increasing profile exit temperature through the more complex metal flow patterns and their effects on the total work of deformation.

Figure 3.—Effect of single process parameters on profile temperature: (a) profile average thickness and (b) number of die cavities.
Two-Factor Interactions

Interaction effects become important when the nature of the relationship between two or more factors changes as one of these factors moves from its low to high level and vice versa. In our case, for example, two factors which are expected to increase (or decrease) profile exit temperature as single factors may have a combined effect of decreasing (or increasing) this temperature when any of these two factors moves from its high level to its low level and vice versa. Another situation where interaction effects become important is when two or more factors having comparable effects when present at certain levels \((H\text{ or } L)\), but when any of these factors moves to another level, then some of these factors (not necessarily the ones changing their levels) would have diminishing (or dominating) effects. The most important of these interaction effects will be discussed below.

Interaction between Extrusion Ratio and Number of Die Cavities. This interaction effect is shown in Fig. 4, where it can be seen that the role of increasing the number of die cavities is to increase the resulting profile temperature more markedly at low extrusion ratios, while at high values of extrusion ratio the number of die cavities seems to have no discernable effect on the resulting profile exit temperature. The effect of extrusion ratio, as a single parameter, is to increase the total effective strain and hence the plastic work needed for deformation. In Section 1, extrusion ratio was shown to have the largest effect on profile exit temperature, Eqs. 1 and 2 and Fig. 1, indicating that plastic work of deformation is the major contribution towards temperature evolution during the process of aluminum extrusion, which is in agreement with previous research \([1, 8, 17, 18]\). In this case, the effect of increasing the less significant, frictional, and redundant work caused by increasing the number of die cavities, would only be evident at low extrusion ratios where the amount of plastic work is relatively small. This is further illustrated in the temperature-contour graph in Fig. 5, where the curves become almost flat at high extrusion ratios indicating a diminishing effect of the number of die cavities at this level of extrusion ratios.

Interaction between Initial Billet Temperature and Ram Speed. Figure 6 shows the effect of interaction between ram speed and initial billet temperature on the resulting profile exit temperature.
Both ram speed and initial billet temperature are expected to increase profile exit temperature when considered as single factors [1, 6, 8, 9, 17, 21]. In addition to providing “direct” heat, the effect of increasing initial billet temperature is to lower the flow stress [17], while the ram speed is directly related to the effective strain rate of the extrusion process. From Fig. 6, it can be seen that the general trend at high ram speeds is a remarkable increase in profile exit temperature as the initial billet temperature increases. This may be explained by a significant increase in the amount of plastic work promoted by the profound temperature-dependant strain rate sensitivity of this material [8, 17]. At lower ram speed levels, however, profile exit temperature seems surprisingly to decrease, even though slightly, when increasing initial billet temperature. It could be argued that the softened billet, and hence the low flow stress level, reduced the amount of plastic work and the associated temperature evolution. Temperature loss to the tooling and to the ambient, which is more profound at low deformation speeds, is also expected to contribute to the resulting profile exit temperature [6, 17]. These results indicate that the amount of heat produced by the increase in plastic work, as a result of strain rate sensitivity, is far more important than the direct heat provided by a higher initial billet temperature. This is evident from extrusion runs number 3 and 7 in Table 5 where the effect of extra 60°C in the starting billet temperature was more than overcome by the effect of 3 mm/s increase in the ram speed. This also strengthens the argument that the major contribution to the resulting profile exit temperature in the extrusion process is that coming from plastic work. It should be noted, however, that at lower billet temperatures, (below about 410°C) in Fig. 6, low ram speeds may result in slightly higher profile exit temperatures than high ram speeds. A possible explanation is that at lower ram speeds there would be more heat transfer from the “hotter” container and other tooling to the forming billet, hence raising the overall temperature level. This behavior has been previously observed in FEM modeling by Fang et al. [10]. The temperature-contour graph for this interaction is presented in Fig. 7. In this figure, the temperature seems to remain unchanged when any of the two parameters is kept at its low level regardless of the value of the other parameter. The temperature seems to start increasing only when these two factors are increased simultaneously indicating that both higher initial billet temperatures and higher ram speeds are necessary to promote the increased strain rate sensitivity of this material with its consequent effects on the plastic work of deformation and the resulting profile exit temperature.

**Three-Factor Interaction between Extrusion Ratio, Initial Billet Temperature, and Ram Speed**

The effects of interactions between the extrusion ratio, initial billet temperature, and ram speed on the resulting profile exit temperature is shown in Fig. 8.

The cube graph in Fig. 8 indicates strong and rather complex interactions within these three parameters. At high extrusion ratios, the lowest profile exit temperatures are seen to be associated with low levels of initial billet temperature and ram speeds (around 510°C) increasing either parameter to its high level while keeping the other parameter at its low level is seen to result in a minor increase in profile exit temperature (about 3°C) compared to the increase in profile exit temperature when the two parameters are increased simultaneously (about 16°C). The combination of extrusion ratio and ram speed represents the effective strain rate of the extrusion process. Combining high strain rates with high forming temperature would be expected to
promote the strain rate sensitivity resulting in larger values of plastic work and thus higher profile exit temperatures. At low extrusion ratios, however, the behavior and nature of interaction between initial billet temperature and ram speed seem to be altered. At this level of extrusion ratios raising either parameter alone seems to result in a decrease in profile exit temperature of 7–9°C compared to a profound increase of about 25°C when the two parameters are increased simultaneously. It could be argued that, at low initial billet temperatures and high ram speeds, there is less likelihood that heat would be transferred to the “colder” billet from the “hotter” surroundings than at lower speeds, while at high initial billet temperatures and low ram speeds there would be a chance for heat transfer from the “hotter” billet and forming sections to the colder surroundings [10, 17]. At the same time, the effect of interaction between initial billet temperatures and ram speed is much more profound at lower extrusion ratios.

Conclusions

The effects of different extrusion parameters on the resulting profile exit temperature were studied using statistical DOE. A statistical model has been obtained for predicting profile exit temperature with very close agreement between predicted and measured values. The main contribution towards temperature evolution has been shown to come from plastic work followed by add-on contributions from redundant and frictional work components. This research has shown that profile thickness has a remarkable effect on the resulting exit temperature, through its expected effect on the metal flow patterns, and may be practically used to represent shape complexity effects. Complex interactions between the different process parameters were shown to affect the resulting profile exit temperature in addition to the main single process parameters.

Number of die cavities seems to have an appreciable effect on profile exit temperature only at small extrusion ratios. Increasing initial billet temperature leads to increasing profile temperatures only at high ram speeds, while at low ram speeds this, surprisingly, leads to lowering the resulting temperature.

The amount and nature of interaction between initial billet temperature and ram speed, in terms of its contribution towards profile exit temperature, is strongly dependant on the extrusion ratio, leading to a triple (three-factor) interaction, and is seen to be more profound at low extrusion ratio values.

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References


