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# Quality prediction of longitudinal seam welds in aluminium profile extrusion based on simulation

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**Abstract**

The paper presents the analysis of different quality criteria of longitudinal seam welds that appear in aluminium profiles during extrusion using porthole dies. The physical background and limitations of the most widely used criteria are discussed. A new improved dimensionless welding quality criterion that takes into account the unbalances of metal flow is proposed by the authors. It is based on analysis of simulation results obtained by QForm Extrusion FEM software and experiments. The authors also introduced a comparative classification of longitudinal seam welds based on the practical application of profiles. It allows the user to characterise the quality of a seam weld depending on its specific application and make a decision regarding its suitability for certain technical requirements. The proposed criterion has been approved by industrial experiments for different types of profiles. Particularly its numerical critical value has been found for AA 6082 alloy. The quantitative correspondence between welding types and values of developed criterion is also defined.



*Keywords:* profile extrusion; welding criteria; simulation; seam welds; QForm Extrusion; welding; Al-alloys; QForm; quality; AA 6082; FEM; aluminium.

## 1. Introduction

Profile extrusion process belongs to processes of metal forming allowing to obtain products of various cross-sectional shapes. In most cases it is difficult or impossible to obtain long-length profiles with the required properties by other methods of metal forming. Extruded profiles are increasingly used in automotive, railway, aerospace and other industries, therefore they are subjected to strict requirements in terms of dimensions and properties. This paper discusses features of aluminium profile extrusion process through porthole dies.

One of the main disadvantages of the considering process in addition to the increased deformability of mandrel cores is the presence of longitudinal seam welds in the product, which under certain process conditions may have critically low quality compared with base metal and that is why cause the formation of longitudinal cracks and delamination.

At present there is no reliable universal tool for predicting the quality of longitudinal seam welds. It is caused by a number of factors including a wide range of extruded products, the need of experimental study for each profile and alloy, the use of CAE software with rough assumptions etc.

## 2. Features of extrusion process and their role in the formation of high-strength welding seams at plastic deformation

The nature of the action of external forces applied to the deformable metal or alloy during extrusion determines the main form of the stress state at the plastic zone – triaxial non-uniform compression. This type of stress state is most favorable since large compressive stresses reduce the possibility of formation of tensile stresses in certain sections of the plastic zone causing fracture. Therefore, even fragile


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materials can be processed by extrusion with high extrusion ratio. However, this process requires the application of high loads. In order to reduce them as well as to ensure the required properties after heat treatment, extrusion is carried out at high homological temperatures.

All of the mentioned features inherent to the extrusion process have a beneficial effect on the formation of durable weld bondings during plastic deformation. High plastic strains contribute to the intensive renewal of the welded contact surfaces. The extrusion ratio for hot direct extrusion process of aluminium profiles is usually not less than 10, and for some processes it can exceed 1000 that has not yet been achieved by other metal forming processes. High hydrostatic pressure in the plastic zone during extrusion contributes to the combining of metal streams, creating high compressive stresses on the surfaces to be welded which are necessary for their convergence to a distance close to the interatomic one.

Finally, high homological temperatures (as a rule $T_{extr} \geq 0.7T_{melt}$) usual for aluminium profile extrusion process contribute to the growth and strengthening of bonds due to more intense diffusion processes.

Based on the foregoing it can be concluded that extrusion process creates preconditions for obtaining durable weld bondings during plastic deformation. Therefore, it is no coincidence that extrusion is widely used in industry to produce hollow aluminium profiles of complex shape i.e. where the quality of the welding seams is one of the most important characteristics of the resulting products.

Nowadays, despite all the favorable factors in aluminium profile extrusion the issue of the formation of a high-quality welding bonds remains relevant and the requirements are only tightened.

## 3. Welding quality criteria in profile extrusion

### *3.1. Existing criteria*

There are many studies evaluating the quality of extrusion welding seams using various CAE software [1] for simulation of metal forming processes. According to [2] and [3], all the most well-known welding criteria (Tab. 1) are based on the pressure in the welding chamber and the higher it is, the better bonding is formed.

Table 1. Most widely used welding quality criteria.
1) Akeret; 2) Plata-Piwnik; 3) Donati-Tomesani; 4) J-criterion; 5) Bourqui.

| | Equation | Nomenclature |
|---|---|---|
| 1) | $P_m = \max(p_i) > C$<br>$P_{mn} = \max\left(\frac{p_i}{\sigma_s}\right) > C$ | $p_i$ – pressure in welding chamber<br>$C$ – critical value<br>$\sigma_s$ – flow stress |
| 2) | $Q = \int_t \frac{P}{\sigma_s} dt \geq C$ | $P$ – pressure in welding chamber<br>$t$ – time of flow in welding chamber |
| 3) | $K = \int_t \frac{P}{\sigma_s} dt\, v = \int_l \frac{P}{\sigma_s} dl \geq C$<br>$K_{ad} = \frac{1}{w} \int_A \frac{P}{\sigma_s} dA \geq C$ | l – point path of flow in welding chamber<br>$v$ – absolute velocity of the point<br>$w$ – welding seam thickness<br>$A$ – area of the contact surface |
| 4) | $J = \int_t k_0 \left\lvert\frac{\sigma_m}{\bar{\sigma}}\right\rvert \dot{\varepsilon} \cdot e^{\left(\frac{RT}{Q_D}\right)} dt \geq C$ | $\sigma_m$ – mean stress (welding pressure [4])<br>$k_0$ – coefficient related to material and surface conditions of metal for bonding<br>$\dot{\varepsilon}$ – strain-rate<br>$R$ – universal gas constant<br>$T$ – temperature<br>$Q_D$ – activation energy |
| 5) | $\frac{P_w}{P_s} > 0.5$ | $P_w$ – pressure below the web<br>$P_s$ – pressure above the web |

From a physical point of view, this means that a certain pressure is at least a necessary condition for the formation of bonds, defining the convergence of divided streams to each other by the distance required for bonding formation.

### *3.2. Applicability of existing criteria*

According to [5]-[8], the critical values for the Plata-Piwnik (PP) and Donati-Tomesani (DT) criteria should be determined experimentally for a typical design and alloy, and the criteria as such can be used before actual trial only in order to compare the quality of the seams within each concrete profile. Such approach does not carry much practical significance since the main purpose of using any criterion as well as simulation is to predict the properties of the product before conducting a real experiment.

In this study as well as in [5]-[7] it is shown that there are some inaccuracies in predicting the quality of welding seams when using all the presented criteria. Thus, considering two different profiles (Fig. 1; Experimental data is provided by ASAŞ Alüminyum Sanayi ve Ticaret A.Ş., Istanbul, Turkey; and Fig. 2; Experimental data is provided by Saturn Ltd., Russia) it can be clearly seen that both DT and PP criteria selectively match the real results: DT for the first project, PP for another one. Range of the scale for both simulation results is adjusted in order to show the properly welded seams by red colour. Therefore, higher value of criterion corresponds to better quality for presented results.

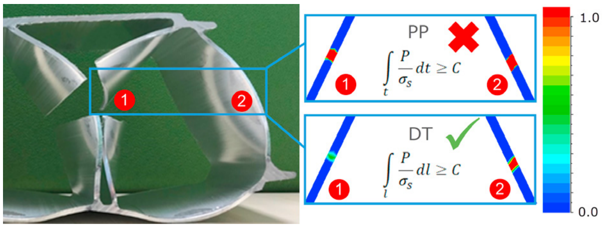



Fig. 1. Comparison of practical result of welding quality test performed using cone punch (left) and welding quality calculated using PP and DT criteria (right) by means of QForm (DT shows reliable result).

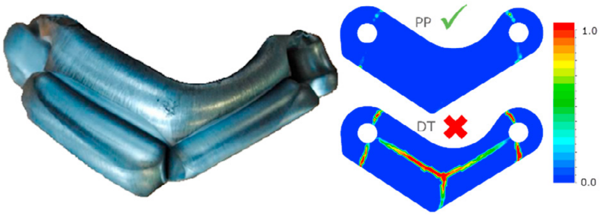



Fig. 2. Comparison of real profile front end after extrusion and welding quality calculated using PP and DT criteria by of QForm (PP shows reliable result).

Also, from [6] and [7] it can be seen that the nature of the error has the random character. Nevertheless, it was stated in [3] that J-criterion has much higher accuracy compared with the criteria PP and DT. Fundamentally, this criterion differs from the PP criterion by a proportional dependence on the strain-rate ( $\dot{\varepsilon}$ ) and a direct exponential dependence on temperature ($e^T$). This means that with a change of strain rate or temperature, the quality of welding should correspondingly change: getting higher with increase of these parameters and getting lower with decrease.

Everything else being equal, under extrusion conditions a change in the strain-rate can be achieved by changing the extrusion velocity. Furthermore, according to [8], with an increase of extrusion velocity, the welding quality decreases due to a decrease in the duration of the contact between streams under high pressure; therefore, the assumption accepted in J-criterion should not have experimental evidence.

As shown in [9]-[10], a change in temperature in the operating range (505-580) °C slightly affects the welding quality and with a further decrease in temperature outside the described interval the negative effect intensifies but does not contribute the dominant impact. At the same time, based on the numerical data described in [3], the component $e^{\left(\frac{RT}{Q_D}\right)}$ changes by less than 1% in the temperature range (450-600) °C; therefore, for this criterion the thermal index does not make a significant contribution to weld bonding formation.

*3.3. Hypothesis about characteristic values*

As it is demonstrated in [3] and used in [4], during extrusion the absolute value of the mean stress in the welding chamber is close to the value of contact pressure; therefore, the $\sigma_m$ parameter can be used for calculation as an analog for $P$. Then, analyzing the formulation of PP and DT criteria and taking into account the fact that they are dimensional, it can be assumed that for each alloy there is a characteristic time (PP) and a characteristic length (DT) that are the minimum necessary for the formation of a high-quality bonding. Finally, both criteria can be rewritten in normalized form:

$$\overline{PP} = \frac{1}{t_{al}} \left| \int_t \frac{\sigma_m}{\sigma_s} dt \right| \geq 1; \quad (1)$$

$$\overline{DT} = \frac{1}{l_{al}} \left| \int_l \frac{\sigma_m}{\sigma_s} dl \right| \geq 1; \quad (2)$$

From where, the characteristic time ($t_{al}$) is the minimum time required for the formation of a high-quality bonding for a particular alloy to be in the welding chamber at mean stress ($\sigma_m$) equal to flow stress ($\sigma_s$). Then, the characteristic length ($l_{al}$) is the minimum path length required for the formation of a high-quality bonding for a particular alloy in the welding chamber at mean stress ($\sigma_m$) equal to flow stress ($\sigma_s$).

It is obvious that with an increase of extrusion velocity, the length of the flow path in the welding chamber remains almost unchanged, therefore, the triaxiality ($\frac{\sigma_m}{\sigma_s}$) is the only parameter that is taken into account by DT criterion. But as is known from the practice and mentioned before, with an increase of extrusion velocity the quality of welding decreases due to a decrease in the duration of the contact between streams under the pressure. In this regard, further the only PP criterion is investigated. The choice was made also because in their studies [6]-[8], [11] Donati and Tomesani, moving on to integration over the path, introduced the velocity as a correction parameter for PP criterion, which avoids summing up the triaxiality for dead metal zone under the webs where its value reaches maximum [2] and the velocity is zero. Whereas when using QForm CAE software [1], there is no need to use correction parameter, since the summation occurs along the traces that have already entered the profile bypassing dead metal zones.

## 4. Classification of welding quality types in aluminium profile extrusion

Generally, in technical literature it is customary to divide longitudinal welding seams into welded and non-welded after extrusion. From a practical point of view such approach is not complete since the requirements for the quality of weld bondings vary significantly depending on the type and application of the final product. So, for automotive, railway and other profiles which will be used for loaded constructions, the increased requirements are applied on the welding seams. Whereas for decorative profiles the main requirement is the absence of a visual defect after painting.

Therefore, in this paper it is proposed to divide all types of weld bondings in aluminium profile extrusion according to the obtained properties into:

- structural welding – the formation of a seam with cohesive properties
- mechanical welding – the formation of a seam with autohesive properties (with keeping the structural interface between the streams), which are characterized by the presence of a visible welding line
- absence of welding

Such classification allows to uniquely characterize the quality of welding seams and make a decision about their suitability depending on the requirements.

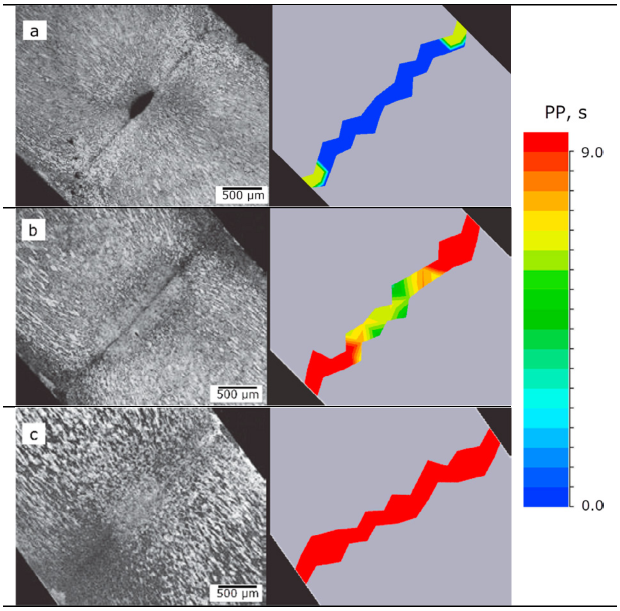
## 5. Study

### *5.1. Determination of characteristic time*

In work [10], microstructural analysis was performed for samples obtained by extrusion through porthole die with different heights of the welding chamber (Tab. 2 left). It can be clearly seen that presented microstructural analysis completely correlates with the classification of all welds into 3 types according to their properties. So, (a) corresponds to the absence of welding, (b) to mechanical welding with preservation of the structural interface between the streams, (c) to structural welding. Similar results were obtained by simulation in QForm Extrusion using PP criterion, where it shown a similar nature of the prediction of welding seam properties (Tab. 2 right).

Table 2. Cross-sectional microstructures [10] and simulation result using PP criterion for AA 6082 profiles extruded through die sets with different height of the welding chamber: a – 2mm; b – 10mm; c – 15mm.

| Experiment | Simulation | Scale |
|---|---|---|




Based on the presented results, namely according to the maximum value of presented scale, characteristic time ($t_{al} = 9s$) for normalized $\overline{PP}$ criterion (1) was assumed for the AA 6082 alloy.

### *5.2. Validation of the selected model*

To further check the reliability of normalized $\overline{PP}$ criterion (1) as well as the accepted critical value, another extrusion project was calculated for an industrial AA 6082 profile with known characteristics of welding seam quality (Fig. 3). Experimental data was provided by Gulf Extrusions Co. LLC., Dubai, UAE.

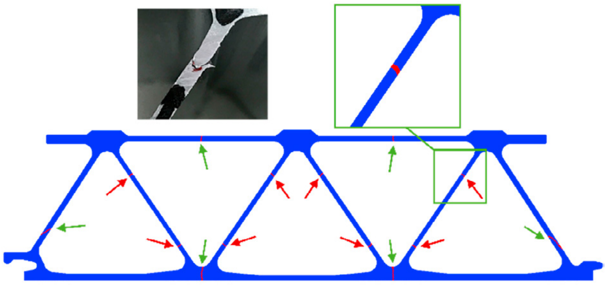


Fig. 3. Welding seams location in profile section. Welding line is marked by red. Problematic seams are indicated by red arrows; other seams are indicated by green arrows.

In practice, it turned out that all internal weld bondings have reduced quality. Welding lines were visible to the naked eye and when a minimum load was applied, the profile was stratified along problematic seams. In this case, the lowest quality of the considered internal seams had side ones (one of them is illustrated on Fig.3). However, the results obtained by calculation of normalized $\overline{PP}$ criterion did not reveal a real defect (Fig. 4). For 3 points selected for different weld bondings (with quality problem and without) criterion has shown the value over than 1, moreover for practically poor-quality welding seam criterion had demonstrated better quality than for high-quality bonding, that is completely wrong. This leads to suggestion that the criterion does not take into account at least one more parameter specific for the particular process, which generally determines the quality of weld bonding.


Fig. 4. Result of welding quality calculated using normalized $\overline{PP}$ criterion (1).

### *5.3. Proposed criterion*

Analyzing simulation results for the project under consideration, a significant imbalance of metal flow was revealed (Fig. 5). In this case, the most difference in flow was created between the streams forming poor-quality seams. As is known, such unbalanced flow of the profile is mostly determined by metal flow in ports, which in turn directly affects the formation of longitudinal bondings in the profile.

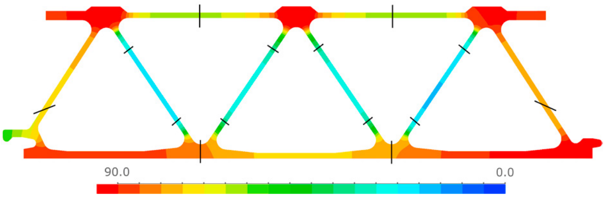



Fig. 5. Distribution of absolute velocity (mm/s) in the profile section. Positions of welding seams are indicated by black lines.

In order to take into account such an influence, a hypothesis about mutual slippage of metal streams was put forward, and the concept of imbalance factor was introduced as a parameter that takes into account the non-uniformity of streams velocities during the formation of weld bonding:

$$K_{ij} = \frac{V_i}{V_j}; \qquad (3)$$

Where $i, j$ – numbers of streams forming particular welding seam (Fig. 6), $V_i, V_j$ – average streams velocities calculated in profile section provided that $V_i > V_j$.

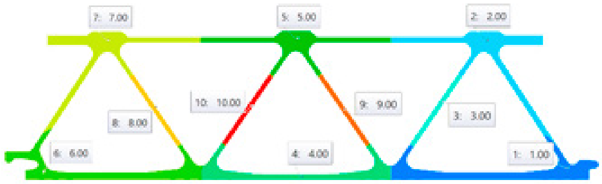



Fig. 6. Stream numbers presented in profile section.

The values of calculated average velocities and imbalance factors are presented in Tab. 3 and Tab. 4.

Table 3. Average velocities for each stream.

| Stream № | $V$, mm/s | Stream № | $V$, mm/s |
|---|---|---|---|
| 1 | 86.22 | 6 | 80.26 |
| 2 | 78.96 | 7 | 97.17 |
| 3 | 20.73 | 8 | 21.71 |
| 4 | 73.76 | 9 | 28.76 |
| 5 | 75.56 | 10 | 28.85 |

Table 4. Imbalance factors for each welding seam.

| $ij$ | $K_{ij}$ | $ij$ | $K_{ij}$ |
|---|---|---|---|
| 12 | 0.92 | 76 | 0.99 |
| 14 | 0.86 | 86 | 0.27 |
| 25 | 0.96 | 87 | 0.27 |
| 31 | 0.24 | 94 | 0.39 |
| 32 | 0.26 | 95 | 0.38 |
| 46 | 0.92 | 104 | 0.39 |
| 75 | 0.95 | 105 | 0.38 |

Based on the available data about the quality of weld bondings for the real profile, it was found that with a quadratic dependence of the value of welding quality criterion on the imbalance factor, the best convergence with experiment is observed (Fig. 7). Hence the final form of the modified (1) dimensionless criterion is:

$$\overline{PP_{mod}} = \frac{1}{t_{al}} \left(K_{ij}\right)^2 \left| \int_t \frac{\sigma_m}{\sigma_s} dt \right| \geq 1; \qquad (4)$$

Quantitative comparison between normalized $\overline{PP}$ (1) and proposed (4) criteria for 3 particular points selected from weld bondings with different quality is presented in the Tab. 5:

Table 5. Quantitative comparison of welding quality values calculated using normalized $\overline{PP}$ and proposed criteria.

| Point № | $\overline{PP}$ | $\overline{PP_{mod}}$ | Practical result |
|---|---|---|---|
| 1 | 1.45 | 0.296 | Not welded |
| 2 | 3.278 | 0.221 | Not welded |
| 3 | 3.115 | 3.112 | Welded |

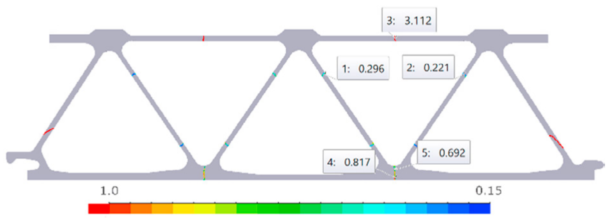



Fig. 7. Result of welding quality calculated using proposed criterion (4).

According to simulation results, criterion values of points 4 and 5 (aren't presented in Tab. 5) correspond to mechanical welding.

## 6. Discussion

According to presented study the physical meaning of proposed criterion (4) is as follows: high-quality weld bonding is formed for metal streams mutually passing the characteristic time if hydrostatic pressure inside the welding chamber is greater than or equal to the flow stress of the alloy provided that the average flow velocities of converged streams are equal. Moreover, the characteristic time can be quite simply defined by means of simulation for each alloy using the inverse method in the presence of a certain amount of experimental data. Thus, for the alloys with decreased extrudability, an increase of the characteristic time is assumed, and for alloys with increased extrudability, a decrease.

Finally, based on demonstrated experimental data, the quantitative correspondence between the types of welding quality and the values of the proposed criterion can be formalized as follows:

- $\overline{PP_{mod}} \in [1; \infty)$ – structural welding
- $\overline{PP_{mod}} \in (0{,}15; 1)$ – mechanical welding
- $\overline{PP_{mod}} \in [0; 0{,}15]$ – absence of welding

## 7. Conclusions

As a summary, the presented research allows to draw the following key conclusions:

1. Existing quality criteria do not have universality, describing only some of the necessary conditions of bonding formation.
2. The pressure in the welding chamber is necessary but not sufficient parameter for predicting the quality of longitudinal welding seams.
3. There is an effect of imbalance of the converged streams on the welding quality. This effect can be taken into account using the imbalance factor.
4. The characteristic time used in the modified criterion is a characteristic of a particular alloy.
5. The characteristic time for AA 6082 alloy is 9 seconds.
6. Proposed criterion can be used to predict quality of longitudinal welding seams during extrusion of hollow and solid profiles with limitations determined by accuracy of general calculation using FEM.
7. Described classification of the welding types together with the corresponding values of the proposed criterion make it possible to uniquely determine the suitability of the seam depending on the requirements.

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