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Prediction of longitudinal seam weld quality in multi-chamber aluminium extrusion

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Abstract. In the extrusion of complex multi-chamber profiles, the longitudinal seam (L-seam) weld quality is significantly affected by the thermo-mechanical history and the 'local' formation conditions under which the weld is produced during the extrusion process. The L-seam welds can lead to non-uniform mechanical properties and variations with regard to the mechanical integrity of extruded products. Therefore, effective prediction and analysis of seam weld quality is crucial to quality insurance of extrusion products for advanced applications. This study deals with the prediction of L-seam weld quality and associated mechanism analysis in the extrusion of multi-chamber aluminium profiles to advance the understanding of how the 'local' thermo-mechanical history and conditions influence the weld quality. To this end, carefully controlled industrial-scale extrusion experiments were conducted to analyze the L-seam formation behaviour. Additionally, a finite element (FE) model was developed to investigate the thermo-mechanical history during the formation of L-seam welds. The model was also employed to predict the L-seam weld quality, incorporating several welding quality criteria, namely Q, K, and J criteria. Examination of the thermo-mechanical history within the welding chamber reveals a compromise in the welding quality at the centre of the L-seam compared to near the surfaces. Moreover, the findings highlight that the J-criterion can provide the most consistent predictions for the L-seam quality, providing a more accurate reflection of the thermo-mechanical history during the solid-bonding process than the Q and K criteria. The findings can contribute to the development of process guidelines and quality assurance strategies for producing multi-chamber aluminium extrusion profiles.

Introduction

Extrusion provides opportunities for producing complex multi-chamber sections, offering high functionality in terms of lightweight, structural integrity, etc [1]. However, meeting demanding industrial quality standards necessitates a thorough understanding and effective control of the mechanisms influencing longitudinal seam welds. In the extrusion of multi-chamber sections, the material undergoes division into multiple streams by die bridges, subsequently rejoining in the welding chamber to form longitudinal seam (L-seam) welds extending in the extrusion direction [2]. The weld quality of different L-seams can vary significantly particularly for complex-shaped cross-sections, due to the unique and inhomogeneous material flow characteristics. The welding-induced non-uniform mechanical properties on extruded profiles pose significant challenges, especially for structural applications such as the crashworthiness of automotive battery protection systems.

At present, experimental techniques are widely used to evaluate the quality of L-seam welds in extrusions, including tensile tests and fatigue tests [2–6], as well as wedge and bulge expansion tests [8]. While these methods provide valuable initial insights, their limitations include significant cost, time consumption, and inability to trace formation history, particularly for complex profile shapes. Consequently, both analytical and numerical investigations are crucial for establishing a more comprehensive understanding of the factors influencing L-seam quality, particularly the impact of thermo-mechanical extrusion history.

For theoretical analysis of L-seam welds, several criteria have been proposed to evaluate L-seam quality, including pressure-dependent criteria [8, 9], the pressure-time criterion (Q-criterion) [11], the pressure-time-flow criterion (K-criterion) [12], and the pressure-material surface-strain rate criterion (J-criterion) [7].

The Q, K and J criteria are briefly described as follows:

Q-criterion is defined by Eq. (1) [11]:

$$Q = \int_0^t \frac{\sigma_m}{\bar{\sigma}} dt \qquad \text{(Eq. 1)}$$

where t represents time, σ_m is the mean stress, and $\bar{\sigma}$ is the effective stress.

K-criterion is expressed by Eq. (2) [12]:

$$K = \int_0^t \frac{\sigma_m}{\bar{\sigma}} v\, dt \qquad \text{(Eq. 2)}$$

where, v represents the material flow speed.

J-criterion is expressed by Eq. (3) [7]:

$$J = \int_0^t k_0 \frac{\sigma_m}{\bar{\sigma}} \dot{\bar{\varepsilon}} \exp\left(\frac{RT}{Q_D}\right) dt \qquad \text{(Eq. 3)}$$

where $\dot{\bar{\varepsilon}}$ is the effective strain rate, Q_D is the activation energy, R is the universal gas constant, and k_0 is the material and surface condition constant.

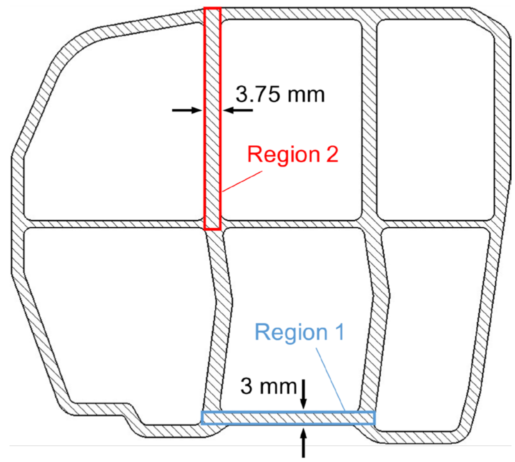
From the provided equations, it is noticed that the J-criterion differs from the Q and K criteria because of its dependence on strain rate and temperature, suggesting that a higher temperature and strain rate can improve the L-seam quality. However, Donati and Tomesani [13] reported that higher extrusion velocity can reduce L-seam quality due to the reduced welding time. Therefore, there is still a need for more experimental and theoretical studies to assess the J-criterion. Furthermore, Donati and Tomesani [12] reported that the K-criterion predicts L-seam quality better than the Q-criterion. Additionally, Kniazkin and Vlasov [14] proposed a modified Q-criterion (combined with the FE method) that offers improved accuracy compared to the K-criterion. Nevertheless, the exploration of the modified Q-criterion remains limited, necessitating experimental validation.

The understanding of the influence of thermo-mechanical history on the quality of L-seam welds during the aluminium extrusion process remains limited, despite the research available in the literature on L-seam weld quality. Furthermore, there is a need for additional analyses to enhance the accuracy of predicting L-seam weld quality. Consequently, this paper focuses on the modelling of L-seam welds and the prediction of their quality in multi-chamber aluminium profiles. The findings presented in this paper aim to provide practical guidance for both researchers and extruders seeking a better comprehension of the L-seam welding mechanism.

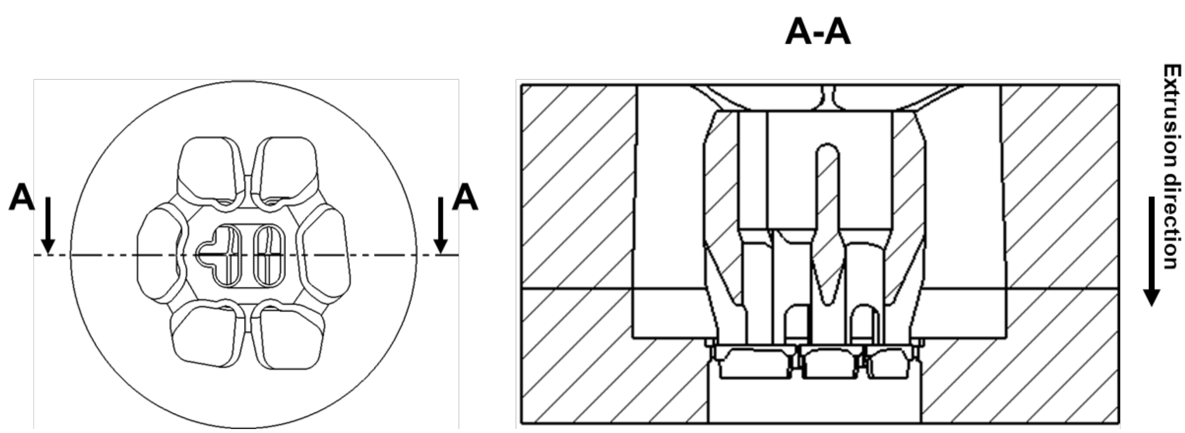
Extrusion Experiments and Modelling

Industrial-scale extrusion experiments. A series of full-scale industrial extrusion experiments were undertaken at Benteler Automotive Raufoss AS (Raufoss, Norway) using a 55 MN extrusion press for producing aluminium alloy multi-chamber profiles. Table 1 shows the process parameters used in the extrusion experiments. The geometric dimension of the extruded profile is illustrated in Fig. 1. In this figure, the die and mandrel design employed in the extrusion experiments are also illustrated, featuring a die with eight portholes. The billet material is AA6005, prepared through the DC-casting method and homogenized before the extrusion process.

To characterize and examine the quality of L-seam welds, two representative regions, marked as Region 1 and Region 2 as shown in Fig. 1, were carefully removed from the multi-chamber profile. Subsequently, the extracted samples underwent a series of preparation processes, including grinding with abrasive papers and etching with a sodium hydroxide solution. Ultimately, the L-seam welds became visible to the naked eye.



a) Multi-chamber profile



b) Die design

Fig. 1 Produced multi-chamber profile geometry and die design used in the production.

Table 1. Parameters in extrusion experiments.

Parameter	Value	Unit
Billet diameter	280	mm
Billet length	1400	mm
Billet temperature	480	°C
Temperature taper	40	°C/m
Ram speed	4.7	mm/s
Extrusion ratio	28	/
Container temperature	420	°C
Die temperature	460	°C

Numerical modelling. To enable effective analysis of the longitudinal seam weld mechanisms in extruded profiles, an FE model for the extrusion process was developed based on QForm-Extrusion 10.2.1 to reproduce the material flow behaviour in the extrusion process [15]. QForm-

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Extrusion, a commercially available FE package, enables the coupling of die deformation and accurate prediction of weld position [16]. The model comprises four groups representing the main components: billet, porthole and welding chamber, bearing, and profile (see Fig. 2). Both the extrusion tools and billet were discretized using 3D tetrahedral 4-noded elements. The material behaviour of AA6005 was represented by an isotropic viscoplastic model using the Hensel-Spittel constitutive equation (Eq. 4) [17]:

$$\sigma = A e^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{m_4/\varepsilon} \left(1+\varepsilon\right)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{m_3} \dot{\varepsilon}^{m_8 T} \quad \text{(Eq. 4)}$$

where σ is the flow stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, T is the temperature, and A and m_1-m_9 are the material coefficients (see Table 2).

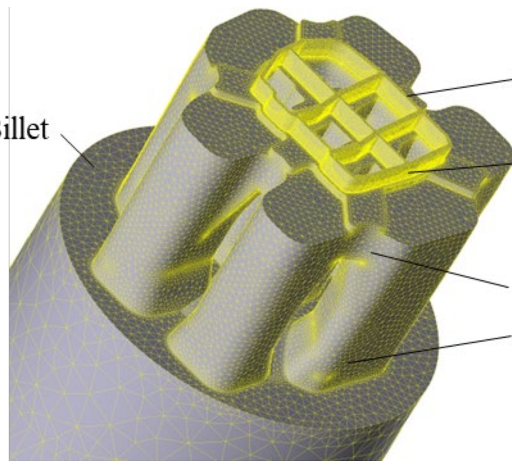


Fig. 2 Numerical model.

Table 2. Hensel-Spittel parameters [15].

Coeff.	A	m_1	m_2	m_3	m_4	m_5	m_7	m_8	m_9
Value	320	-0.00511	-0.12422	0.1	-0.01364	0.00024	0	0	0

Other physical and thermal properties were incorporated into the model using default parameters available in the software. The computational time required for the model was 7 hours on a 112-core Xeon processor utilizing parallel processing and 256 GB of RAM.

The accuracy of the numerical model was evaluated by comparing the predicted extrusion force to the force measured in physical experiments. The comparison, shown in Fig. 3, indicates that the numerical model accurately predicted the maximum extrusion force with an error of slightly less than 6%, and the disparity in minimum forces was slightly over 4%. These results are deemed accurate and acceptable within the context of this study.

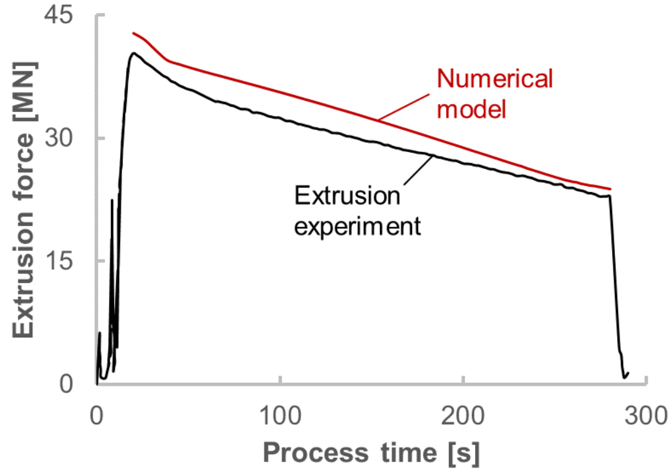


Fig. 3 Comparison of extrusion load between extrusion experiment and numerical model.

Results and Discussion

In hot extrusion of multi-chamber profiles, the material undergoes separation into multiple streams through die webs and subsequent rejoining within the welding chamber, thereby creating L-seam welds along the entire length of the profile. In the case profile in this research, the utilization of eight distinct portholes in the die design results in the formation of thirteen L-seam welds in total, distributing across the entire section of the profile, as illustrated in Fig. 4.

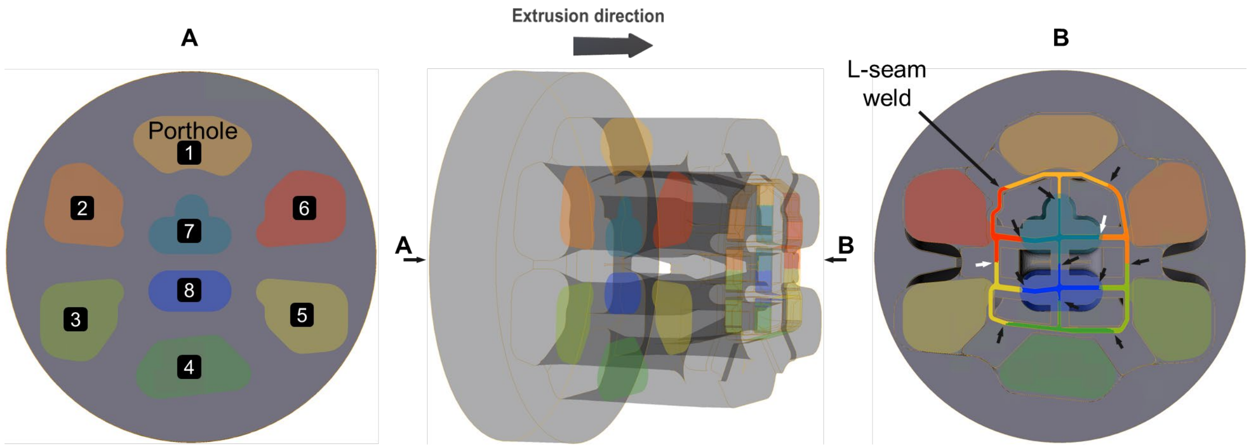
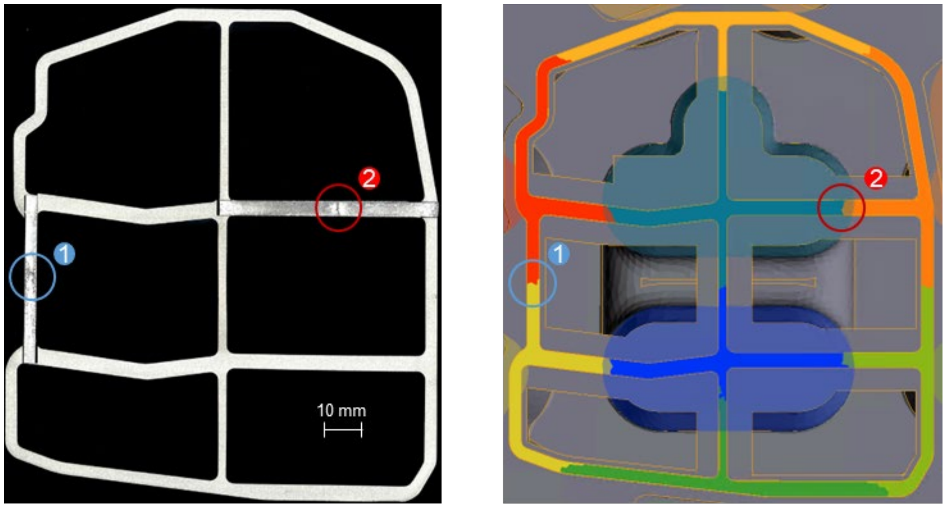


Fig. 4 Material flows through portholes and their corresponding L-seam welds.

In this study, the quality of welding was analyzed, with a specific focus on L-seam welds formed through material flows originating from portholes 2-3 and 6-7 (refer to the white arrow in the right figure of Fig. 4). By employing the velocity vectors derived from the extrusion simulation, the flow path of the material was identified, thereby determining the positions of the L-seam welds. The comparison of L-seam weld locations between experimental characterization and numerical simulation is depicted in Fig. 5. It can be observed that the numerical model can effectively capture the positions of L-seam welds in the cross-section of the profile.



a) Experiment b) Numerical model

Fig. 5 Comparison of L-seam welds positions on the profile's cross section.

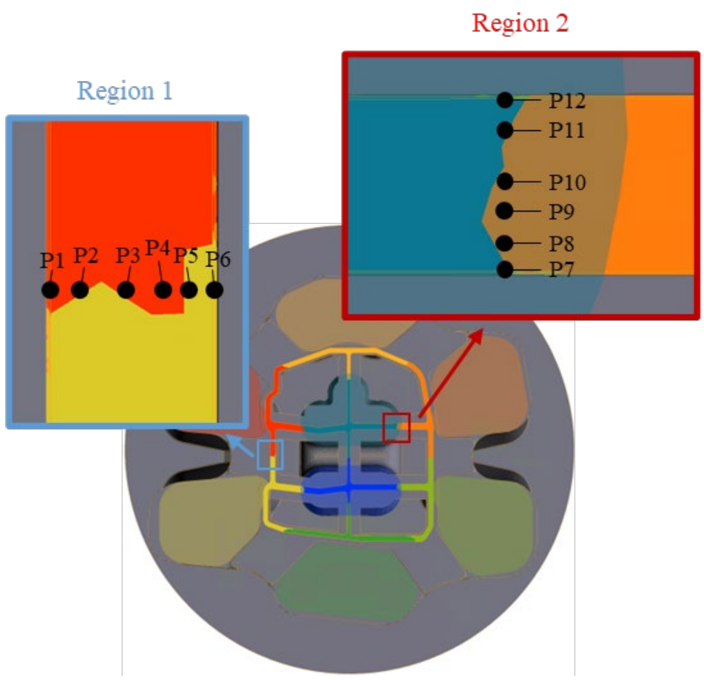


Fig. 6 Position of tracing points.

To explore the solid-state bonding process in the selected areas during extrusion, an examination was undertaken by using tracing points positioned along each L-seam weld. Six tracing points were placed on each L-seam weld, and their positions are illustrated in Fig. 6. The examination of the welding path, traced through the backtracking of each point, reveals key thermo-mechanical variables in the solid-state welding process, such as mean stress, effective strain (rate), and temperature. In Fig. 7, the evolutions of thermo-mechanical variables within the welding chamber during extrusion are shown by P1-P6 located in Region 1. Variations in the welding time were noted for tracing points P1 to P6, with durations of 16.7 s, 5.4 s, 3.4 s, 3.2 s, 2.6 s, and 5 s, respectively. These durations represent the time that each tracing point was subjected to the solid-state welding process within the welding chamber, with the reference point (0 s) being the initiation of the welding process. Throughout the solid-state bonding process, the hydrostatic pressure exhibits overall downward trends with increasing welding time. Simultaneously, the effective stresses and effective strain rates initially increase and then decrease, and the temperatures rise to 548°C. Furthermore, a comparison between the metal flows in the welding chambers of P1 and P6 reveals distinct characteristics from those of P2-P5. The latter experiences higher mean stress, effective stress, and effective strain rate. Consequently, the quality of solid-state welding at the centre of the L-seam in the extruded profile is compromised, whereas the quality near the inner and outer surfaces remains relatively better. Additionally, these findings are in accordance with the study by Yu et al. [7].

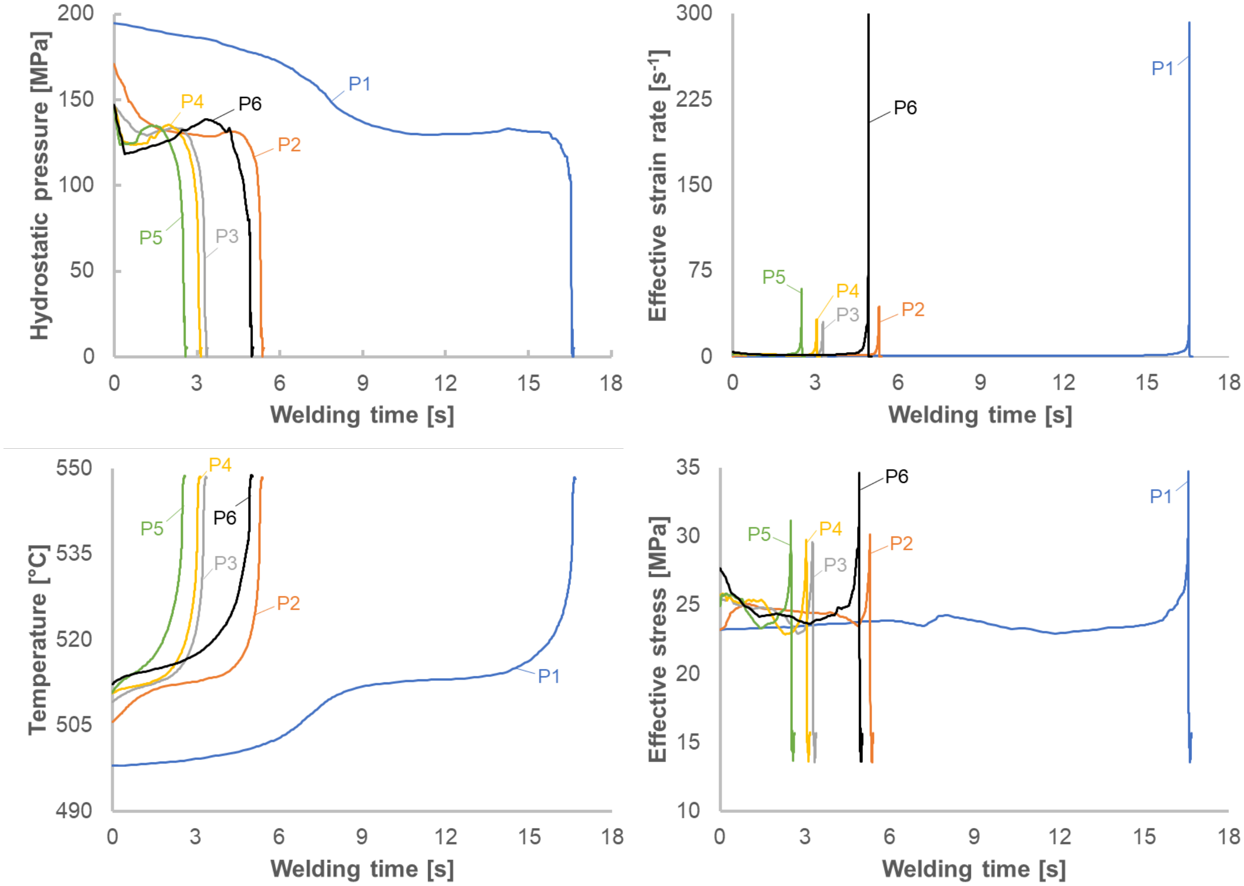
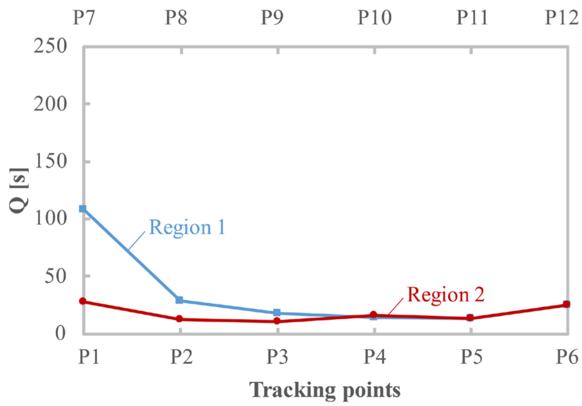
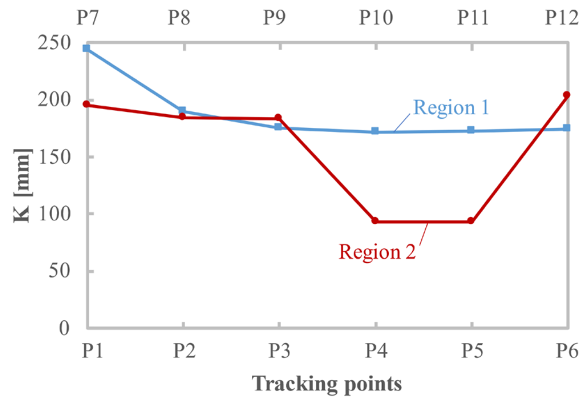


Fig. 7 Examination of welding paths in terms of thermo-mechanical conditions within the welding chamber.

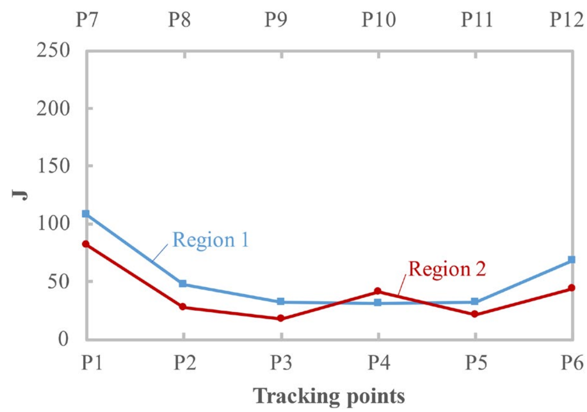
Furthermore, the welding quality indices were calculated by applying three typical welding criteria reported in the literature (Q, K and J criteria), considering the thermo-mechanical history of the tracing points along the welding path. For the calculation of J-criterion, the value of k_0 was set to 1, following the investigation conducted by Yu et al. [7], where Q was set at 142 kJ/mol and R at 8.314 J/(K·mol).



a) Q-criterion



b) K-criterion



c) J-criterion

Fig. 8 Computation of L-seam weld quality indices calculated using Q, K and J criteria.

In Fig. 8, the welding quality indices for both Region 1 (P1-P6) and Region 2 (P7-P9) are presented. In Fig. 8a, the quality indices based on the Q-criterion reveal that the Q values of P1-P3 are generally higher than those of P4-P6, while the Q values of P7-P12 exhibit consistency. Conversely, when comparing Regions 1 and 2, the Q values of P1-P3 appear greater than those of P7-P9, potentially suggesting an overall superior welding quality in Region 1 compared to Region 2. Examining quality index calculations based on the K-criterion in Fig. 8b, the K-criterion mirrors the behaviour observed with the Q-criterion in Region 1. However, in Region 2, P4 and P5 exhibit smaller K values compared to the other points. Regarding the J-criterion (Fig. 8c), points near the inner and outer surfaces display greater J values than those in the centre. These findings align with the observations from Fig. 7. It can be asserted that the primary reason behind these observations is that the J-criterion takes into account several critical factors, such as mean stress, effective stress, effective strain (rate), and temperature. In contrast, the Q and K criteria only consider the effects of mean stress, effective stress, and material flow speed on the welding quality.

Conclusions and Outlook

This paper examines the L-seam weld quality and mechanism within multi-chamber aluminium profiles to investigate how the thermo-mechanical history during extrusion influences the weld quality, employing both experimental, analytical and numerical approaches. The analysis of the thermo-mechanical history of the material within the welding chamber reveals a compromise in the quality of solid-state welding at the centre of the L-seam in the extruded profile. However, the quality near the inner and outer surfaces remains comparatively higher. Moreover, upon a comparative analysis of Q, K, and J criteria, it is observed that the J-criterion more accurately captures the thermo-mechanical observations, particularly with greater values near the surfaces than at the centre. However, further experimental validation is necessary to confirm these findings and further assess the prediction capabilities of the quality indices.

The findings of this research gained insights into the understanding of the impact of 'local' thermo-mechanical conditions on L-seam weld quality. Future studies will concentrate on a more quantitative characterization and modelling of microstructural and mechanical properties in L-seam welds within multi-chamber profiles, facilitating to validation of the prediction capabilities of quality indices as well as enhancing the process control in aluminium extrusion with a particular focus on L-seam weld quality.

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