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Title: Improved weld seam quality using 3D FEM simulation in correlation with practice

Authors: B. Bourqui, A. Huber, C. Moulin, A. Brunetti, ALCAN

Y. Krähenbühl, MTD

Presented by: B. Bourqui

Abstract

The quality of the weld seams in profile is fully dependent on the die geometry and the extrusion parameters. Empirical models and practical rules are mainly used to define the criteria for healthy weld seams.

With the powerful growth of the 3 dimensional CAD and FEM modelling, it is actually possible to define more precisely the local internal pressures in a die, and better predict the criteria and parameters that influence directly the weld seams quality.

An innovative flow modelling approach coupled with experimental measurements is presented. It allows to predict the pressure in the welding die chamber to ensure healthy weld seams in the profile

1. Introduction

Healthy weld seams depend on both metallurgical phenomena and die geometry. Metallurgical factors are difficult to quantify; in contrast, geometrical factors such as weld chamber shape or bridges geometry, which play an important role for weld seam quality, can be optimised on a rational basis. The goal of this work is to validate an approach to estimate the weld seam quality *a priori*, based on the knowledge of metal flow behaviour predicted by numerical simulation correlated with experimental measurements.

Numerical modelling is being increasingly important for understanding the phenomena that occur during aluminium extrusion. The Alcan company has been employing numerical modelling for years, to help answering critical questions related to the press. The numerical techniques are applied for 2 different topics:

1. Mechanical resistance of the tools: the computational procedure which is being employed will not be discussed in this paper.

2. Metal flow: numerical modelling techniques are being developed to optimise aluminium flow through the die. It is well-known that flow modelling in extrusion is difficult because it involves solving a non linear set of differential equations coupling velocity field, pressure and temperature [7–9]. Furthermore, physical parameters of the equations are a priori unknown and have to be measured and / or calibrated on the basis of numerous trials. It is not yet possible to employ flow modelling as a standardised numerical tool, like for mechanical resistance. However, critical cases are being modelled, in view of getting better insight into the aluminium flow behaviour, thus improving the general conception rules. In particular, flow simulation helps to build up conception rules for better welding and improved productivity.

Here we first present energy criteria for longitudinal welding (section 2). It basically involves the normal stress $\boldsymbol{\sigma}$ at the contacting surfaces to be welded together and their contact time $\boldsymbol{t}$ after equalisation of the streams. The stress $\boldsymbol{\sigma}$ and the time $\boldsymbol{t}$ are to be determined by way of numerical simulation of metal flow, and to check and calibrate the parameters of the numerical model, it is important to measure the pressure of the aluminium which flows through the die. A new method to measure that pressure is introduced in section 3, and its practical application in section 4. Section 5 is concerned with description of the numerical model, and section 6 with the comparison between measurement results and numerical predictions. Finally, we show how to apply the welding criterion for different welding chambers, leading to different welding qualities (section 7).

2. Welding criteria

Weld quality depends essentially on the physical nature of the process occurring along the contact zone of the material surfaces being welded together [6]. There are 2 types of factors influencing the contact conditions:

1. Metallurgical / qualitative factors: structure and texture of the surface layers, properties of the oxide film, properties of the contaminants, and conditions facilitating the creation of interatomic bonds. The contact surface quality may be affected by air or lubrifiant contamination. These well known practical factors influence the quality of welding, but are not considered in our numerical optimisation of the process.

2. Mechanical factors: welding quality depends on flow behaviour (contact time) and pressure along the contact zone. Knowing these factors by way of numerical simulation allows a quantitative evaluation of the welding conditions based on appropriate welding criteria. Such an evaluation helps e.g. to design a better welding chamber.

An energy criterion for longitudinal welding has been proposed [3]. It requires the knowledge of a critical welding parameter C_{cr}, of the contact time t after equalisation of the contacting streams, and of the normal stress σ_n along the contacting surfaces:

$$C = \int_t \sigma_n \, dt > C_{cr} \qquad (1)$$

Contact time and normal stress are to be determined by way of numerical simulation for every die geometry. Comparison with practice in cases of both satisfactory and inadequate welding indicates the magnitude of the critical welding parameter. However, the quantitative application of the energy criterion (***Equation 1***) is still tedious in practice. Another criterion which is easier to employ in practice is that the pressure along converging flow lines in the weld chamber should be high enough.

3. Pressure measurement concept

The weld criterion (***equation 1***) requires the numerical values of metal pressure within the die chamber. To calibrate and check the parameters of the numerical model (section 5), metal pressure was measured during the process.

Measuring metal pressure is difficult: employing stress gauges is delicate, because they tend to get easily damaged, do not generally resist to high temperature, and are not accurate enough in real process conditions. Therefore, a new technique based on deformation measurement has been developed : cylindrical, flat steel capsules are inserted onto the surfaces of the weld chamber and die entrance; their thickness and diameter have been optimised by way of numerical computations, so that their deformation occurs in the linear regime. This allows to perform measurements for various production cycles without having to replace the measurement system. A 6/10 mm deformation of the capsule corresponds to 260 MPa, and the measurement accuracy is of the order of ± 20 MPa. The capsule is connected through a hole to the deformation measurement system (see ***figure 1***).

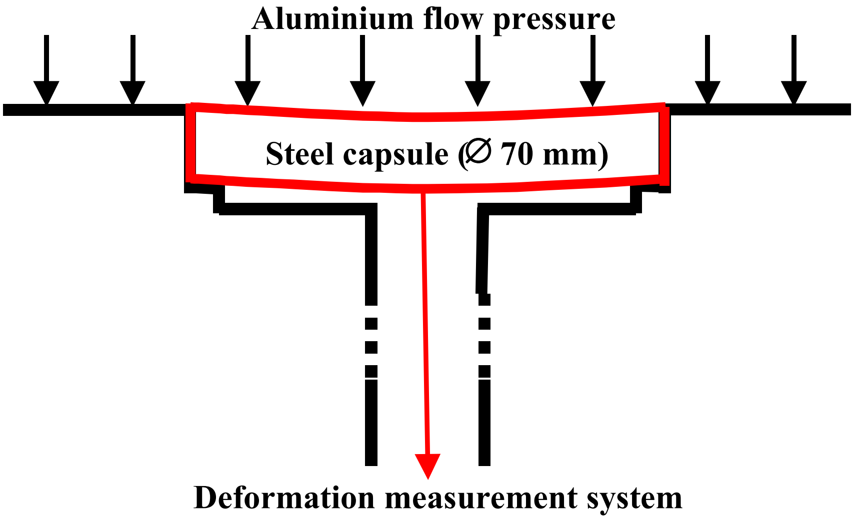

Figure 1: measurement principle. The capsule deformation is proportional to aluminium pressure.

4. Experiments at the press

The experiments have been performed on a 7'200 t press, with a Ø 500 mm recipient. The die system and profile geometry under study are shown on ***figure 2***:

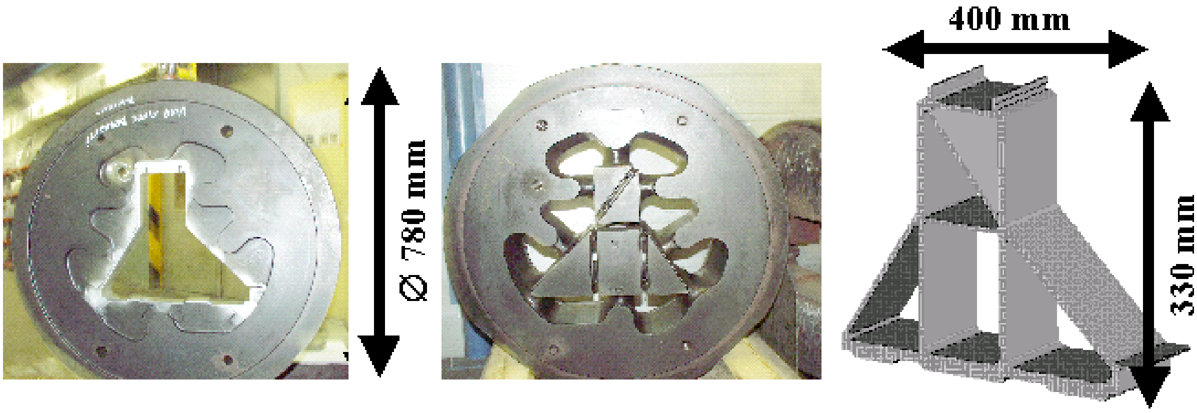

Figure 2 : Die system and profile

To measure pressure, two capsules have been inserted : capsule 1 at the die entrance, and capsule 2 within the weld chamber (see ***figures 3*** and ***4***).

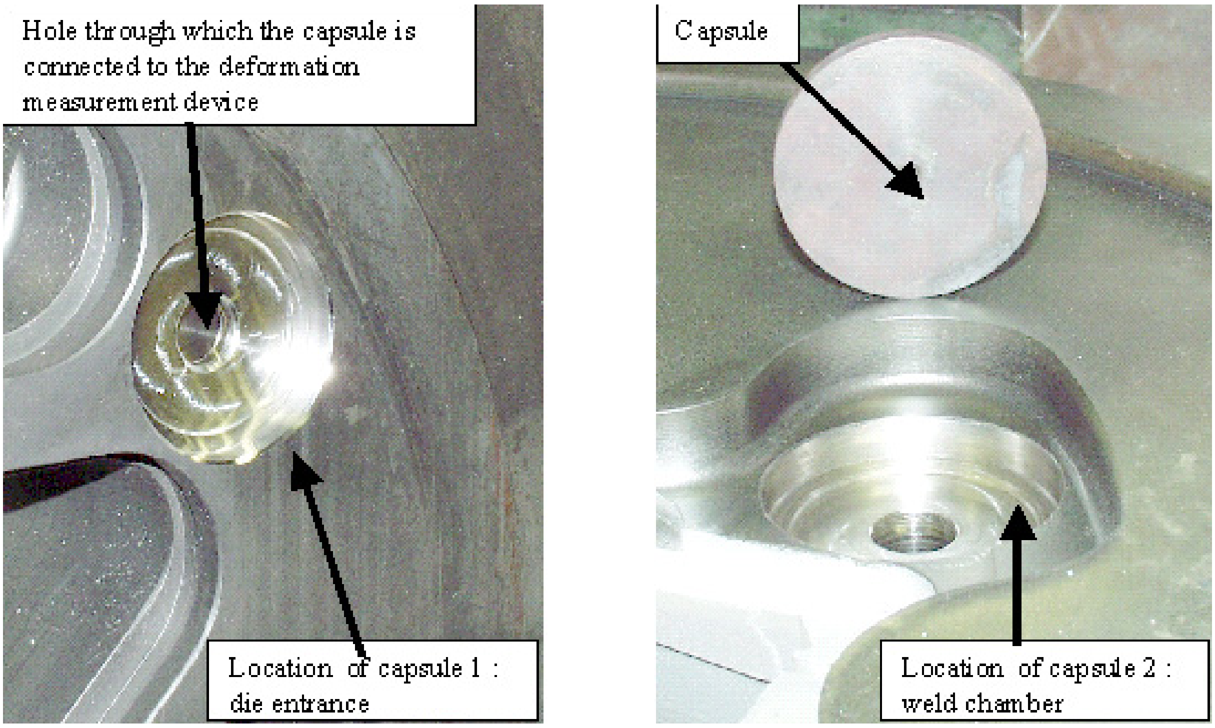

Figure 3: pressure measurement (1) at the die entrance, (2) within the weld chamber

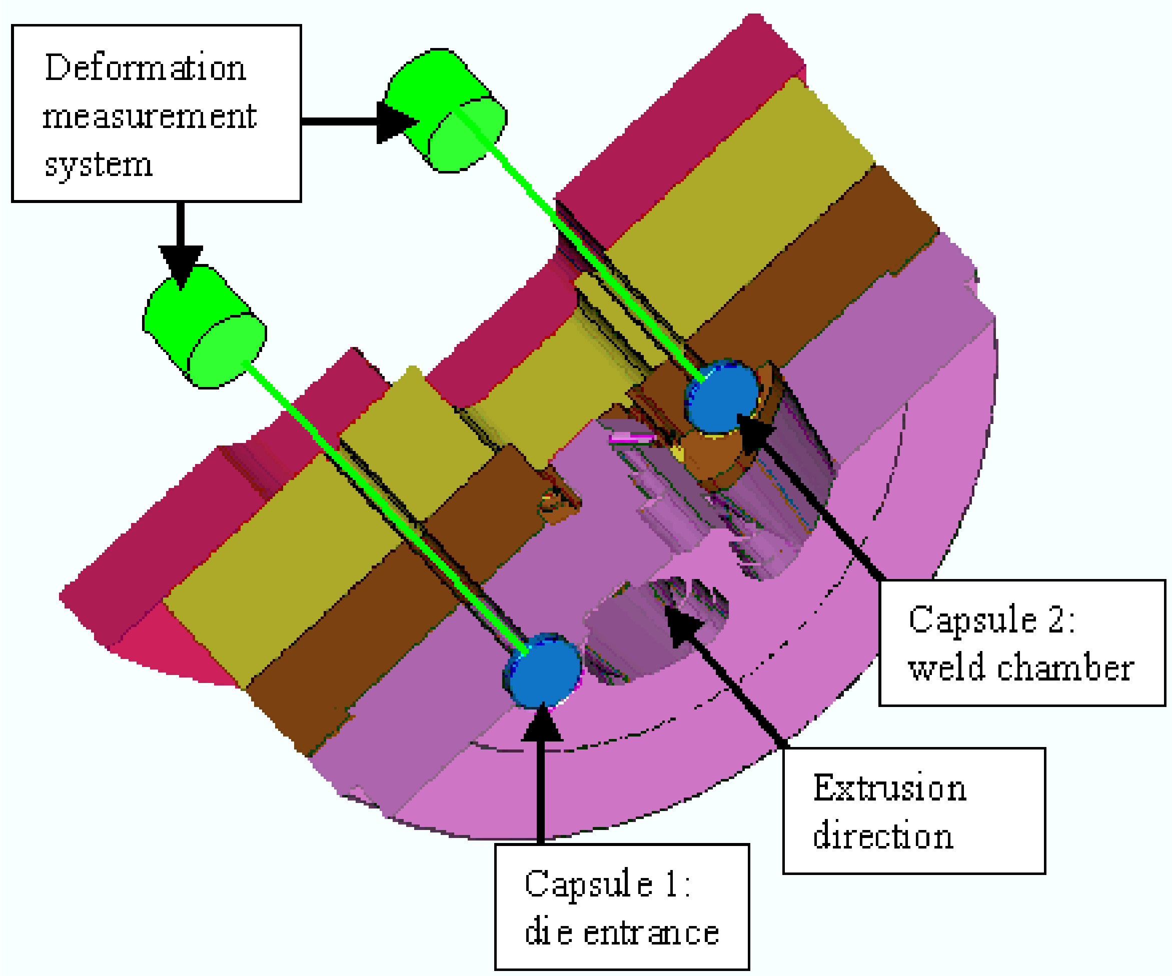

Figure 4: positions of the capsules. Their deformation is proportional to metal pressure.

Figure 5 shows an example of the deformations measured during the first few minutes of the process. The process begins after the pre-compression peak. The capsules deform under the combined effect of 2 phenomena : gradual compression of the tool and aluminium pressure. After a few minutes metal pressure is relaxed, but the tooling is maintained under pressure by the container. Therefore, at that instant, the sudden deformation release of the capsules reflects metal pressure only.

Measurements show the following results:

Capsule 1 (die entrance): 260 Mpa. This value agrees with the extrusion pressure corresponding to the measured piston force at the end of the process.

Capsule 2 (weld chamber): 190 Mpa. However, the pressure depends on the position within the weld chamber. This is confirmed by numerical simulation (***figures* 6** and *7*).

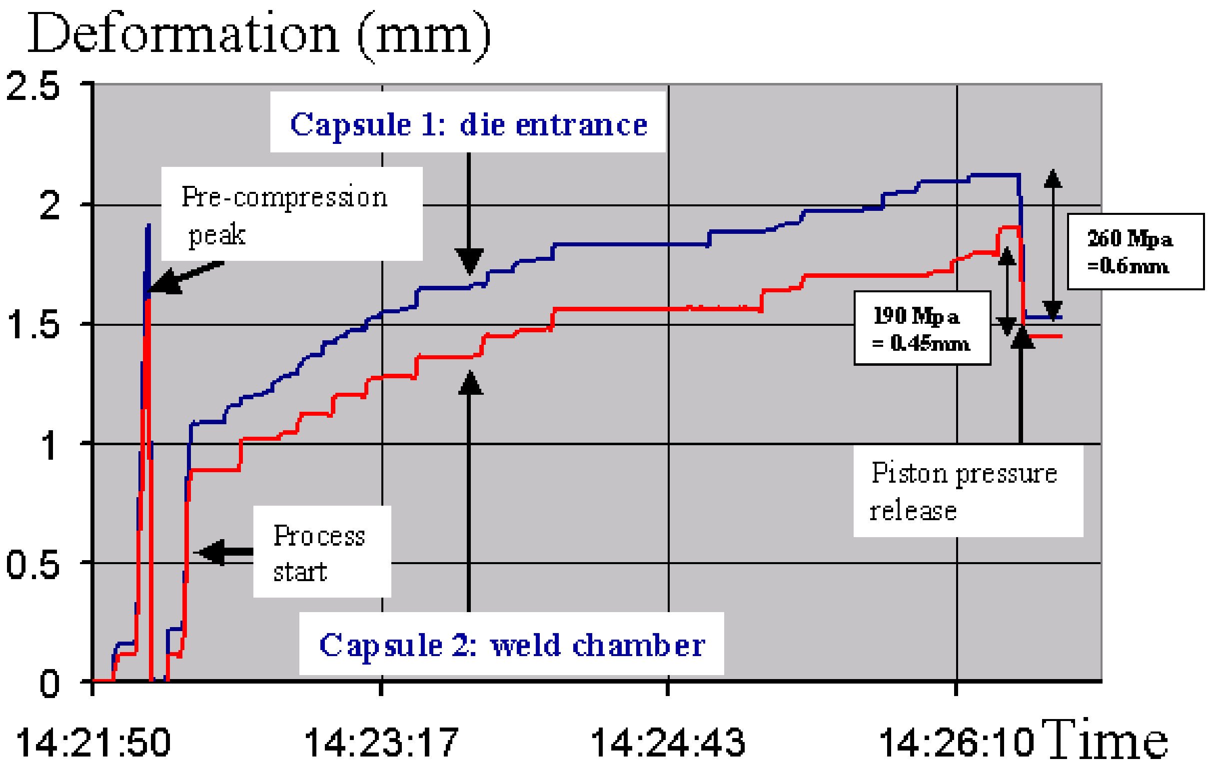

Figure 5: deformation of the pressure capsules at the die entrance and within the weld chamber. After 5 minutes the process was stopped, to allow calibration of the zero pressure.

5. Numerical simulation

Aluminium flow through the press is described by a set of partial differential equations involving the variables velocity (3 components), temperature and pressure [7-9]. These equations are coupled: the fluid viscosity or flow stress σ depends on temperature, and heat production depends on fluid velocity and pressure.

To perform a computation, knowledge of the physical parameters and boundary conditions are required. The most critical are:

- Flow stress σ: it depends on deformation rate, alloy and temperature. These properties have been measured by several authors, e.g. in the case of torsion experiments [2]. The experimental values have to be adapted to the conditions of extrusion practice. In the present numerical model, the values are fitted to a non newtonian power law model for the alloy 6xxx [1,7-9] ;

- Friction: viscous flow with full sticking is assumed [7-9];

- Radial heat losses through the die : there are important in the case of large presses. The heat transfer coefficients are known from numerical experiments and comparison with practice.

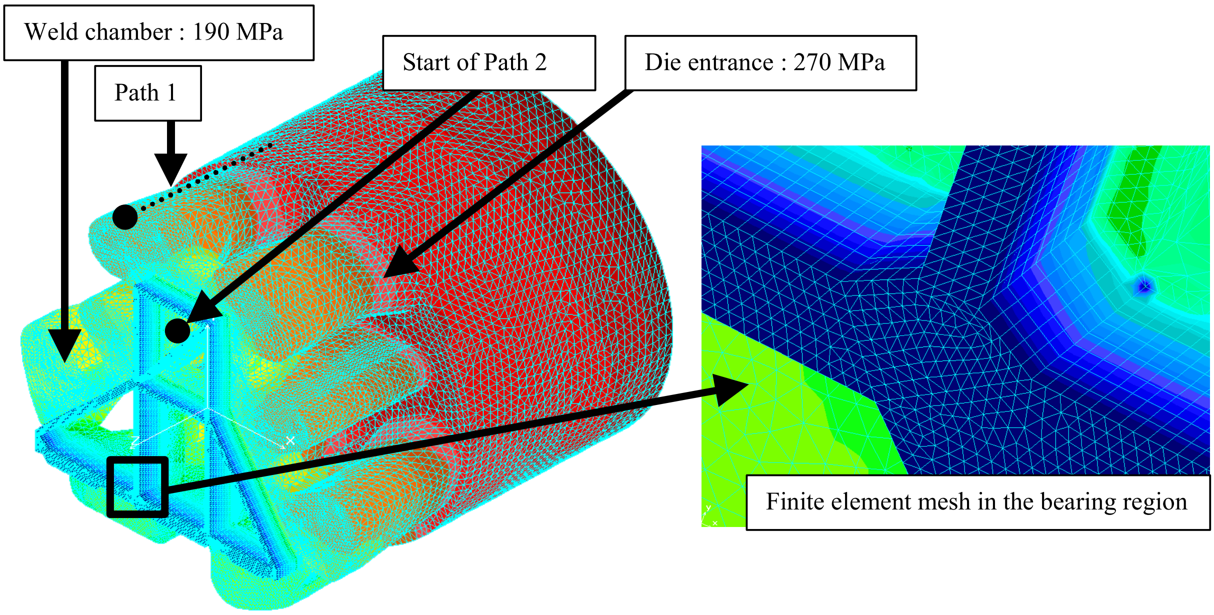

Figure 6: finite element mesh (aluminium part) and pressure field

The CAD geometry requires specific treatment and adequate simplification to enable tractable flow computation. Some geometrical details are unimportant for flow description, and others cannot be discarded. The finite element mesh has to be adequately refined (see ***figure 6***). In particular, an inadequate mesh quality in the bearing region may lead to erroneous results [8]. Furthermore, both die and aluminium have to be meshed, because aluminium flow is affected by heat transfer through the die.

Figure 7 shows the pressure field in 4 different sections perpendicular to the extrusion direction. As expected, the pressure depends on the position within the weld chamber, and more pressure is required to extrude thinner parts.

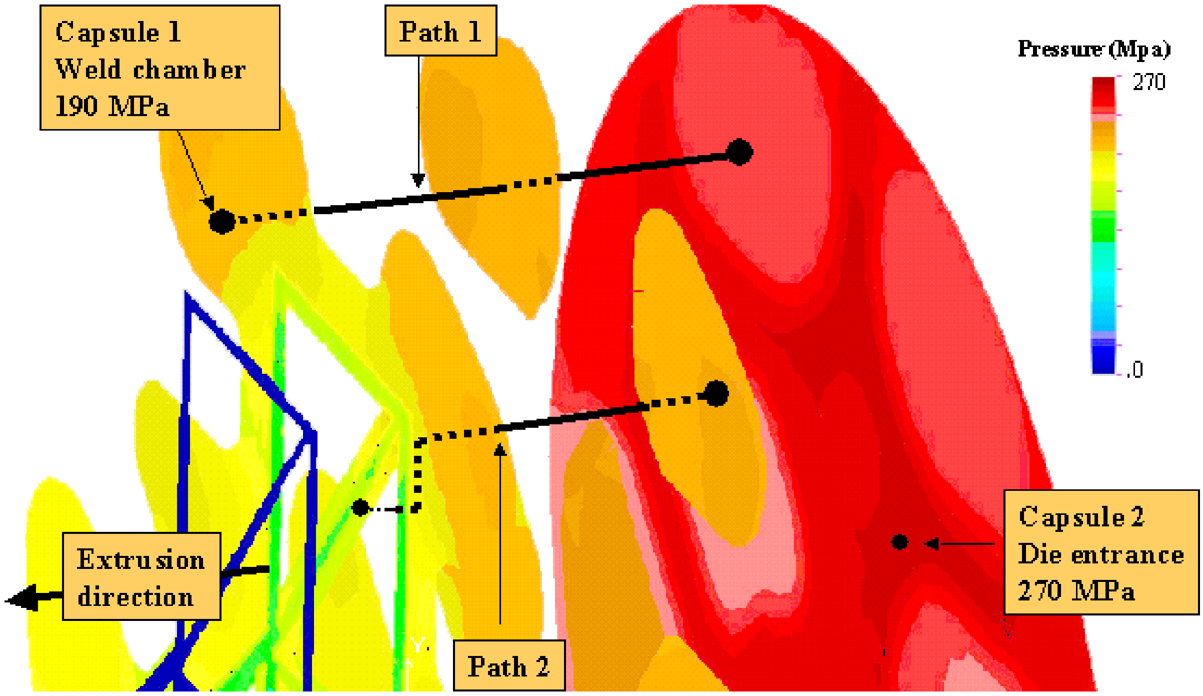

Figure 7: pressure field in 4 sections perpendicular to the extrusion direction

Pressure as a function of position along 2 different paths is shown on ***figure 8***. Path 1 runs from the die entrance (260 Mpa) to the weld chamber at the position of capsule 1 (190 Mpa), whereas path 2 runs down to a position in the central chamber (120 Mpa) where profile weld seams turn out to be critical (see section 7).

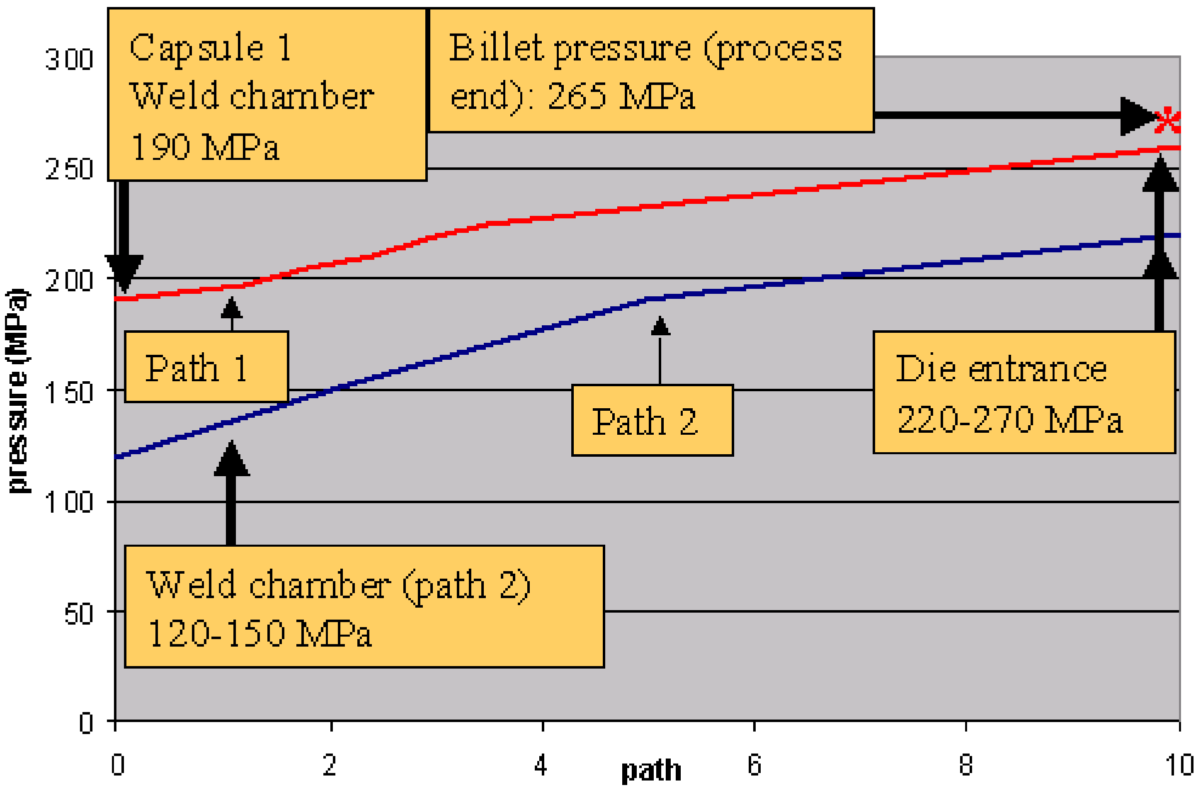

Figure 8: FEM computed pressure along both paths defined on ***figure*** *7*. The values measured in the weld chamber and die entrance are in good agreement with the numerical predictions.

6. Comparison between measurement results and numerical predictions

At the positions of both capsules, the measured and computed values of pressure agree (see ***figure 8***): 190 Mpa within the weld chamber (capsule 2) and 260 Mpa at the die entrance (capsule 1). This last value also agrees with the extrusion pressure corresponding to the measured piston force at the end of the process. This good agreement validates the values of the pressure which are obtained by numerical simulation, in particular in regions where measurements cannot be performed in practice.

The numerical results show how pressure depends on position within the weld chamber. The accurate knowledge of the pressure field in regions where welding may be critical is important to predict weld seams quality on the basis of the criteria presented in section 2 (***equation 1***).

7. Welding quality

In practice, the weld seam quality of the profile central leg was not satisfactory. This is due to the fact that pressure was too low in the die chamber : along path 2 (*figure 7*) numerical computation shows that it drops down to 120 MPa. In comparison, at the end of path 1 in the die chamber, pressure (computed and measured) is 190 MPa. ***Figure 9*** shows a welding defect due to insufficient pressure within the die chamber along path 2.

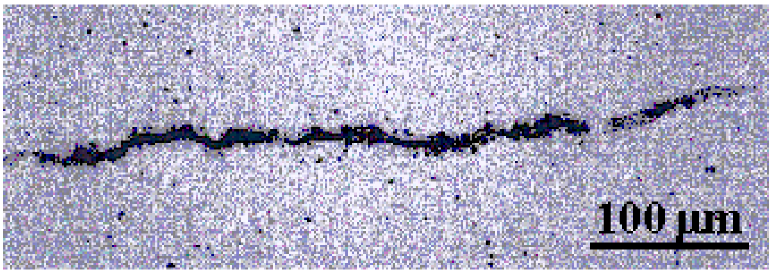

Figure 9 : weld seam defect due to insufficient pressure in the weld chamber

A way to overcome this problem is to increase the length of the weld chamber by e.g. 15mm. Figure 10 shows the difference between both chambers.

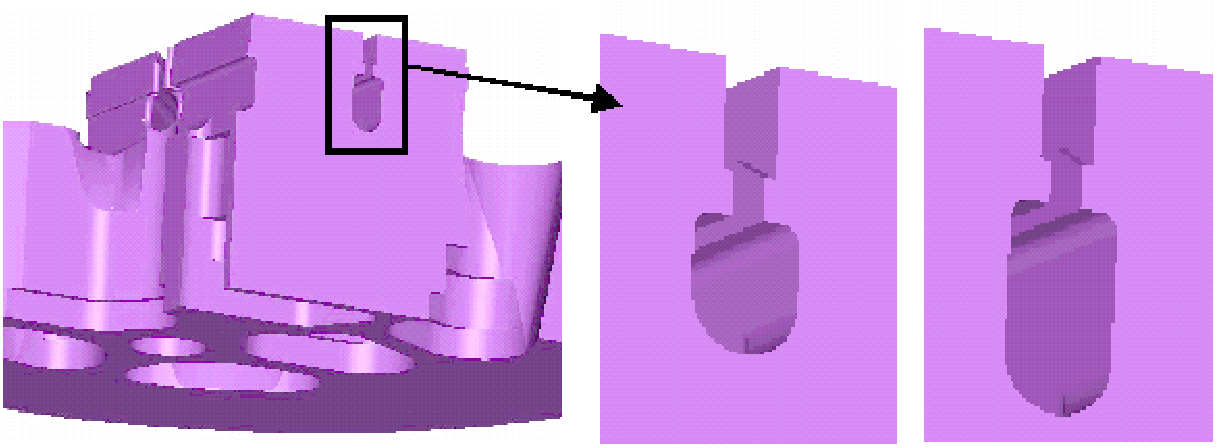

Figure 10: the two different weld chambers. (a) shorter chamber (b) longer chamber

With the longer chamber, the type of defect shown on ***figure 9*** disappears. The quality improvement with the 15mm longer weld chamber is confirmed by mechanical tests.

In the case of a longer chamber, not only the normal stresses σ_n along the converging flow lines are higher but, due to the 15mm longer flow path, also the contact time is longer. The information which is necessary to take these effects into account and apply the energy criterion (***equation 1***) is implicitely contained in the results of the FEM flow computations, and the critical value of C has to be estimated as follows:

$C(\text{shorter chamber}) < C_{cr} < C(\text{longer chamber})$

However, the quantitative application of the energy criterion (***equation 1***) is still tedious. Another criterion which is easier to employ in practice is that the pressure along converging flow lines in the weld chamber should be high enough. For example, in this case, modifying the weld chamber geometry (***figure 10b***) increases pressure.

To obtain healthy weld seams the pressure in the weld chamber should exceed a critical value, which is here half the die entrance pressure: $P_{weld} > 0.5 \times P_{Die\ Entrance}$.

8. Conclusions

The weld seams quality essentially depends on aluminium pressure in the weld chamber. The values of pressure are obtained by numerical flow simulation. To check and calibrate the results of the numerical model, a new technique to measure aluminium pressure during the process has been developed.

To obtain healthy weld seams the pressure in the weld chamber should exceed a critical value, which is here half the billet pressure : $P_{weld} > 0.5 \times P_{Die\ Entrance}$.

The practical application of welding criteria will have to be validated and refined in other cases, taking into account further factors such as temperature and alloy. The goal of these developments is to reveal quantitative criteria to be employed in future as guides for the conception of dies.

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