EXTRUSION OF SHORT ALUMINIUM BILLETS - SIMULATION AND SEMI-PILOT TEST

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Abstract
A die setup for direct hot extrusion of extra-short aluminium alloys billets used in semi-pilot plant tests was simulated using DEFORM ™ 2D/3D software and results were compared with experiment. A die setup without welding chamber proved to shorten charge-weld to such extend that most of material could be recovered as usable samples. Having good agreement between simulated and experimental results of two tested die setups (with and without welding chamber) the effect of temperature on length of charge-weld was evaluated. A main drawback of die setup without welding chamber is too short and, consequently, too week charge-weld. Since many extruded profiles need to be stretched after cooling, die setup without welding chamber is not applicable for commercial production. Application of die setup without – or with shallow – welding chamber is limited to flat profiles with simple and symmetrical geometry like round or rectangular bars where mixing of extruded material is not crucial for the profiles properties.

Keywords: Extrusion, FEM simulation, Charge-weld

1 Introduction

A computer FEM (finite elements method) simulation of industrial processes, including simulation of direct hot extrusion of metals and alloys, becomes common practice in research and development over the last decades, e.g. [1-6] and citations thereof. Most of the simulations deal with continuous flow of material under various conditions or specific die designs [7-12]. In some cases the additional extrusion effects are analyzed using FEM software, e.g. buckling and waving [13]. Also discontinuous material flow was simulated using FEM during last decade. The analyses deal with both charge-welds as well as seam-welds [14-17].
Length of charge-weld is governed by several factors like billet temperature, geometry of profile, die design and volume of material in welding chamber, i.e. its thickness. While other technological parameters affect material flow significantly and must be kept within reasonable boundaries, thickness of welding chamber can be reduced with consequent decrease of charge-weld length. On the other hand, in commercial production length of charge-weld is limited by a sufficient strength of joined material for a subsequent stretching procedure.
In semi-pilot tests saving of costly experimental material is of particular interest. Stretching can be done after cutting of extruded profiles – charge-weld strength is not an important issue in these cases.

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2 FEM simulation of charge-welds

The interpretative engineering software DEFORM ™ 2D / 3D is suitable for the analysis of two-dimensional and three-dimensional forming processes of metal, thermoforming, cold forming, embossing and others. The software can be practically used as an effective tool for prediction of material flow in industrial (forming) operations without undue costs for the practical test. The software is working on the finite element method (FEM).

Deform uses five basic types of simulations: Lagrangian incremental, ALE rolling, steady-stade machining, ring rolling and steady-state extrusion. Lanrangian incremental method was used in our simulations. The Newton-Rhapson iteration method was used because it converges faster than other available methods.

Coulomb (sliding) friction is used when contact occurs between two elastically deforming objects or an elastic object and rigid objects, generally to model sheet forming process. The frictional force in the Columb law model is defined by:

$$f_s = \mu p \tag{1}$$

where f_s is the frictional stress, p is the interface pressure between two bodies and μ is the friction factor [16]. Container, die and stem with dummy block were regarded as the rigid bodies, billets were considered to be plastic material (aluminium alloy EN AW 6060).

The volumes of samples were meshed to 2000 elements with 29 elements across a width. Automatic re-meshing was applied in all simulations. Meshes with size ratio of 1:1 were used in all simulations.

The simulations of direct hot extrusion process were carried out with focus on shape and length of charge-weld. Billet arrangement (single or multi-billet extrusion), die setup (with or without welding chamber) and billet input temperature were varied in order to evaluate their influence on charge-weld.

The diameter of billets was – in accordance with planned semi-pilot tests – 6 inches (152 mm), billet thickness was 80 mm – it gives 1 meter of compact (round bar with diameter of 40 mm) providing that material is fully recovered as suitable sample. Friction coefficient used for all simulations was 0.3.

3 Experimental Conditions

The round bars with diameter of 40 mm were extruded on a 6-inch press. Extrusion ratio was 16:1, ram speed of 4 mm/s. Container temperature was kept at 375 °C, die temperature was the same as billet temperature, i.e. 400 °C. Material was air cooled after extrusion.

Extra-short billets with thickness of 80 mm were heated in oven to 400 °C and manually put into press. Two billet arrangements were tested. One arrangement was set consisting of three individual short billets (multiple billet) extruded in one stroke. Another one was one short billet extruded in one stroke with but-end cutting and extrusion of subsequent billet.

Material used for simulation as well as for experiment was alloy EN AW 6060 with composition given in **Table 1**.

Table 1 Chemical composition of used EN AW 6060 alloy (in wt. %)

	Si	**Mg**	**Fe**	**Mn**	**Cu**	**Cr**	**Zn**	**Ti**	**Other total**
Min.	0.42	0.35	0.17	0.04					
Max.	0.47	0.40	0.21	0.06	0.02	0.02	0.02	0.02	0.1
Actual	**0.44**	**0.35**	**0.20**	**0.05**	**0.01**	**0.001**	**0.01**	**0.01**	

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Die setup with and without welding chamber are shown in the following drawings – **Fig. 1**.

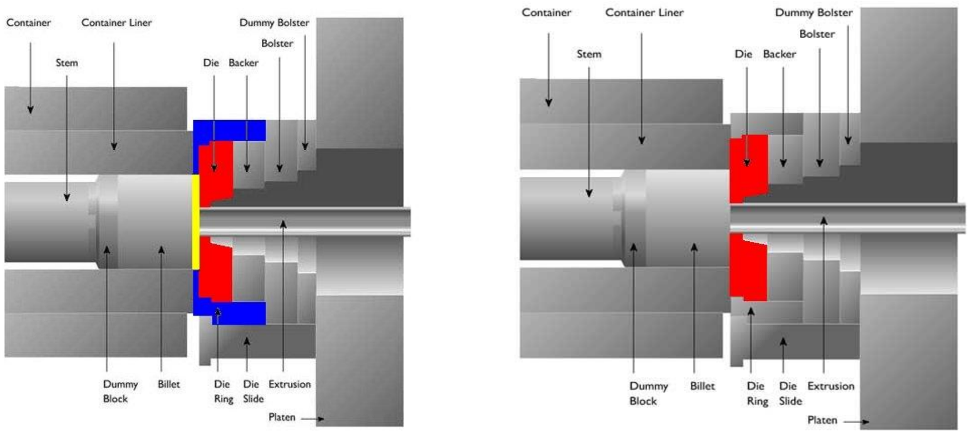

Fig. 1 Die setup with welding chamber – yellow color (left) and without welding chamber (right)

4 Results and discussion

4.1 Multiple billet extrusion with welding chamber

Setup of experiment for multiple billet extrusion together with effective stress evolved inside billet during extrusion and material flow - interface contours between two short billets is shown in **Fig. 2**.

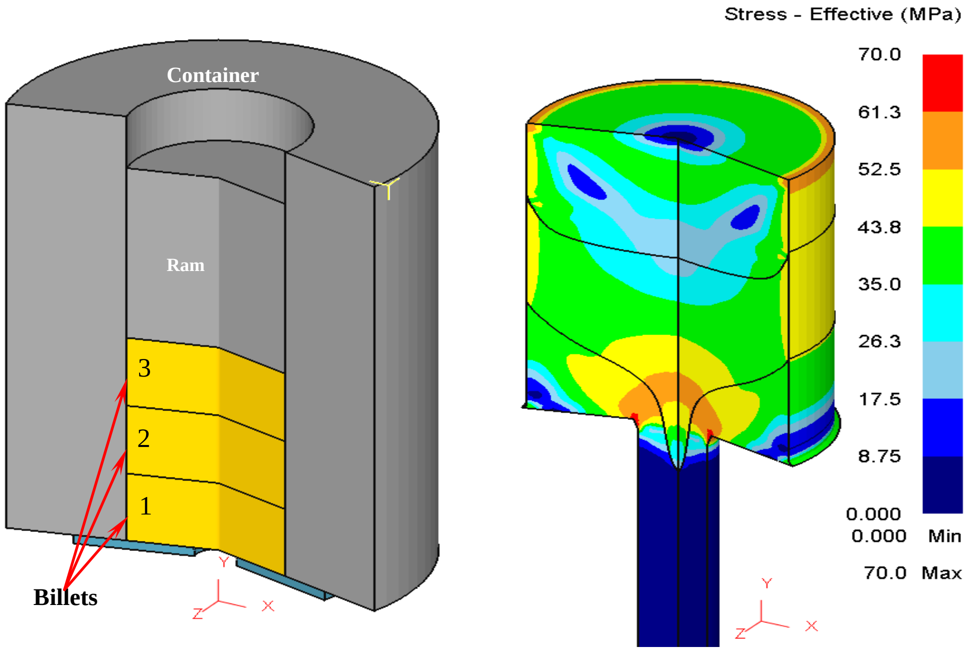

Fig. 2 Setup of multiple billet extrusion (left) and effective stress inside multiple billet with billet interface contours (right)

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As seen in **Fig. 2** (right), central part of billets is under higher effective stress comparing to corner of container. Part of material of first billet is still in a container while material of central part of second billet already flows into die forming charge-weld. FEM simulation predicts that under increasing effective stress material of first billet continues to flow into die forming double charge-weld, **Fig. 3** (left).

In a semi-pilot test round bar with diameter of 40 mm was extruded as described above. The bar was cut into 100 mm long pieces and each piece was etched in hot sodium hydroxide for 1 minute to evolve charge-weld marks. Sequence of charge-welds is shown in **Fig. 3**. Double charge-weld is seen in **Fig. 3** (right) as predicted by FEM simulation.

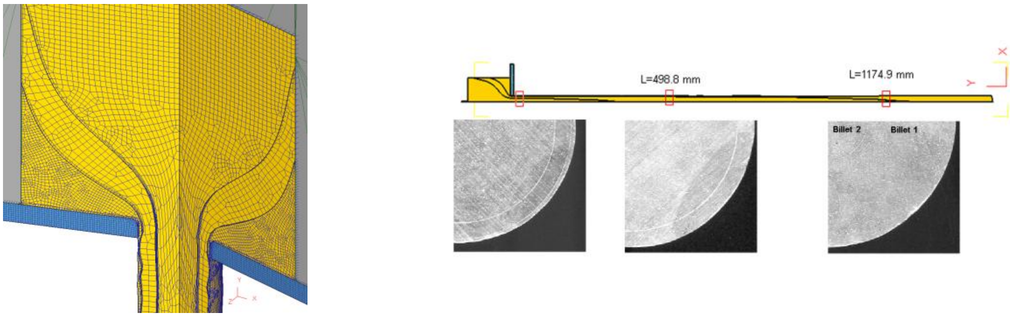

Fig. 3 Development of charge-weld along round bar, double charge-weld is seen in right picture, detail of double charge-weld evolution (left)

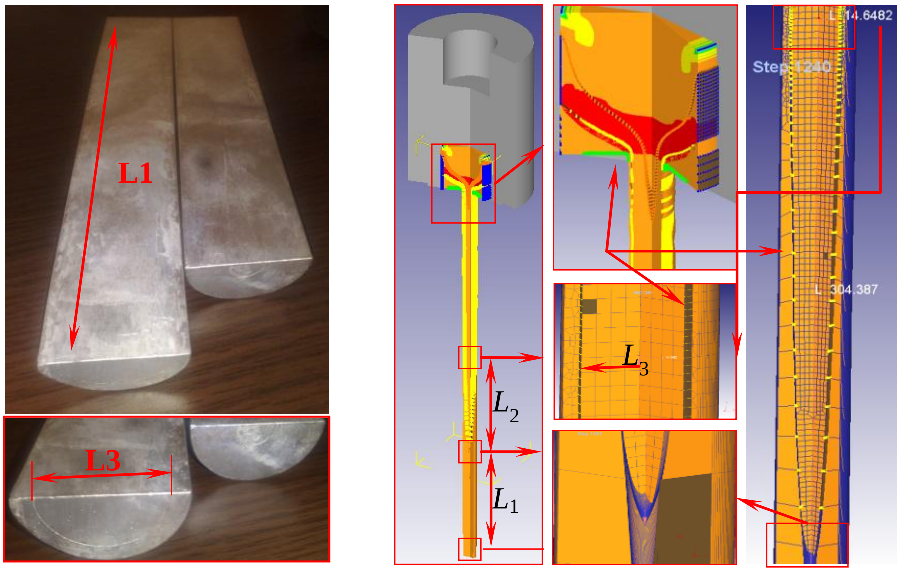

Fig. 4 Evaluation of charge-weld parameters – comparison of the experimental results with simulation

In order to evaluate agreement between experimental results and simulations the close inspection of charge-weld evolution was carried out. Three parameters were evaluated as shown in **Fig. 4**,

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namely distance from front of round bar to tip of charge-weld (L1), distance from tip of charge-weld to point where diameter of charge-weld is 75% that of diameter of round bar (L2) and average diameter of charge-weld (calculated from two measurements perpendicular to each other – L3) at distance L2 from tip of charge-weld.
The parameters L1, L2 and L3 are shown in **Table 2** for different billet temperature compared with experimental results. It is seen that agreement between simulated and experimental results is nearly perfect for temperature of experiment of 400 °C. This confirms that material properties used in simulation are chosen correctly.
In addition to comparison of simulated and experimental results also effect of temperature on charge-weld length is shown in **Table 2**. Temperature increase causes charge-weld length decrease – this is due to a better material plasticity at higher temperatures that decreases effective stress in central part of billet and – consequently – easier material flow into die.

Table 2 Comparison of simulated and experimental results of multi billet extrusion

No	Billet temperature [°C]	L_1 [mm]	L_2 [mm]	L_3 [mm]
1	350	310,96	323,01	14,66
2	375	311,13	315,13	14,65
3	**400**	**311,38**	**304,39**	**14,65**
4	450	313,33	267,93	14,64
Experiment	**400**	**311,22**	**304,00**	**14,72**

4.2 Single billet extrusion without welding chamber

As stated above, high recovery of material from semi-pilot plant tests is crucial for saving cost of experiments. Based on the previous results – both simulated and experimental – die setup without welding-chamber was opted. Results of simulation were optimistic for this die setup. It was proved in experiments that agreement between experiment and simulation is very good – **Fig. 5**.
A recovery of material with die setup without welding chamber was over 75 %. Most of a technological scrap is butt-end (15%) and charge-weld, 8%.
However, it must be said that such shallow charge-weld is weak. Extruded compacts need to be stretched piece-by-piece that is acceptable for semi-pilot plant tests but not for regular production unless compact is as long as run-table itself.

5 Conclusion

Two ways of extrusion of extra-short billets in semi-pilot scale tests were experimentally verified and compared to the results of FEM simulations:

1. Extrusion of multi billets set of short (80 mm thick) billets with welding chamber proved to evolve long - and in some parts of compact double – charge-weld. No usable material could be recovered with this die setup.
2. In contrary to previous case, over 75% of usable material can be recovered with die setup without welding chamber and single extra-short billet extrusion. Most of material scrap is technological one, namely butt-end cutting (ca 15%) and charge-weld (ca 8%).
3. Die setup without welding chamber is suitable for semi-pilot tests but not for regular extrusion. Very shallow charge weld is too week as to withstand compact stretching after cooling.

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4. Die setup without welding chamber is suitable for simple shaped flat profiles.

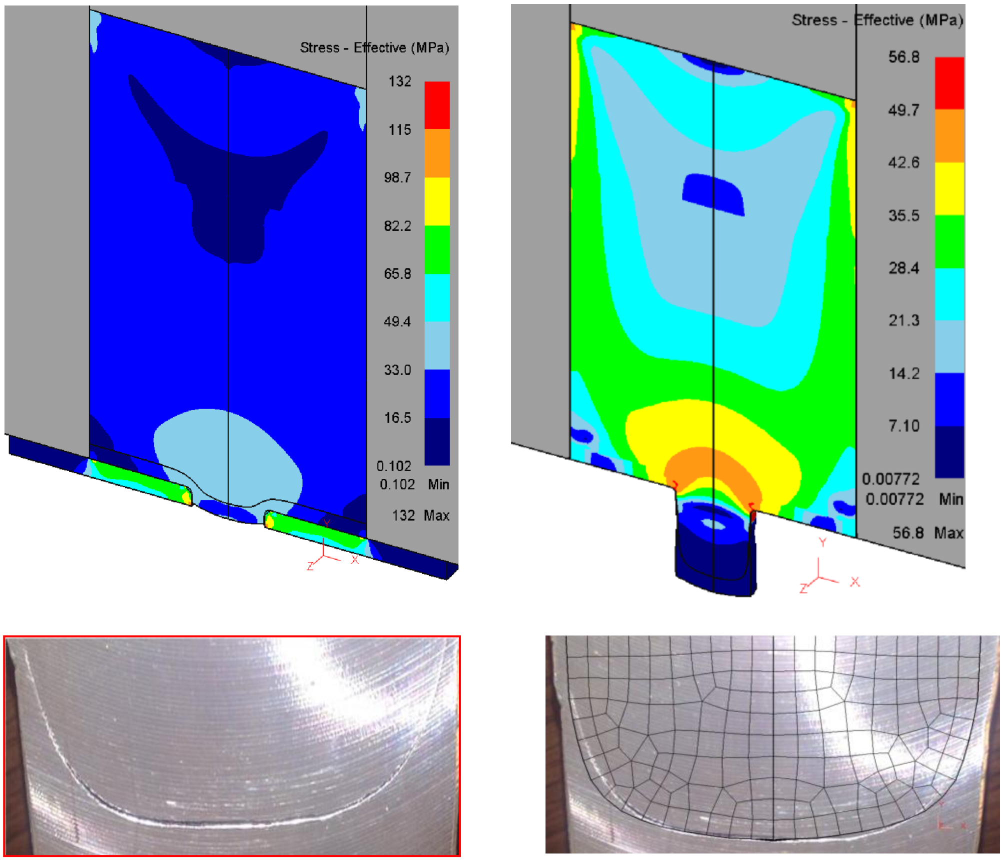

Fig. 5 Effective stress at a beginning of extrusion (top left), during extrusion (top right), charge-weld, experiment (bottom left) and comparison of experiment and simulation (bottom right)

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