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Optimization of working conditions and increase of productivity of aluminum hot extrusion press based on finite element analysis

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Abstract. The finite element simulation of extrusion allows a precise analysis of the metal flow, but also a detailed evaluation of the various parameters involved in the process: temperatures, pressures, velocities and stresses. The press productivity is directly related to the extrusion velocity. In turn, the maximum achievable extrusion velocity is limited by the exit temperature of the formed profile. Traditionally, most presses set a general billet temperature conservatively to ensure that extrusion does not exceed the pressure and stress limits for most dies. This study aims to provide an additional and non-exclusive methodology to increase productivity based on the correct choice of the billet temperature at the press with the help of a previous analysis by means of finite element simulation. A controlled reduction of the billet temperature makes it possible to increase the extrusion velocity while keeping the outlet temperature, stresses and pressure within the admissible range. The use of finite element simulation avoids iterative processes with several press trials and avoids the risks of excessive press pressure or tool stresses. Thus, it allows a quick determination of the optimum temperature and performs risk-free prediction. To demonstrate the use of the methodology, a billet temperature optimisation for an example die has been developed using the simulation software Qform UK. Together with the theoretical analysis, the results of the real die in the press in collaboration with Alumex PLC (Sri Lanka) are shown. This methodology is shown to be effective and may be of particular interest to companies already using extrusion simulation for other uses, such as die design.

Introduction

The cost-effectiveness and quality grade of extruded profiles are their main commercial factors. Both factors are directly related to the quality and performance of the extrusion die. In addition, there are other factors such as the characteristics of the extrusion press, the quality of the billet material, the capabilities of the auxiliary equipment and the downstream operations such as age hardening, painting, anodising or other possible. Due to its very fine tolerances, special material and high thermo-mechanical fatigue performance requirements, the die is probably the most critical extrusion element [1].

The use of finite element (FE) simulation for the optimization of hot extrusion dies design has become widespread among most die makers [2]. The simulation provides a very precise analysis of the behaviour of the metal during the deformation process. At the same time, it allows a detailed evaluation of the different parameters that are involved and determine the production process: temperatures, pressures, stresses...

The production level obtained by the press is directly related to the output speed of the extruded profile, called extrusion velocity. In addition, the maximum achievable extrusion velocity is limited by the temperature of the formed profile at the exit of the die. Therefore, the thermal gradients involved during the process affect its efficiency. For this reason, strict temperature control is required to optimise the extrusion process. In aluminium hot extrusion, the billet needs to be preheated to properly extrude the alloy and during the process the deformation energy and frictional forces between the billet and the tools cause a temperature increase in both the die and the profile. An excessive profile outlet temperature can cause various aesthetic defects or cracks on the profile surface, which can lead to scrapped products or reduced tool life. The exit profile temperature also increases considerably with extrusion speed, which creates a significant limitation in terms of maximum achievable productivity [3–6].

An effective and widespread solution to increase productivity through temperature control is the direct cooling with nitrogen channels immediately at the outlet of the formed profile. Nitrogen injection during the process has proven to be effective in achieving optimum temperature control and improved surface finish of the extruded profile. However, it requires investment in equipment and has an operational cost [7].

Usually, the choice of the billet temperature follows a criterion often linked to a traditional criterion that tried to define a single temperature valid for all dies. This includes those dies that require strict control of the maximum forces exerted by the press due to their resistance characteristics. The temperature set according to this criterion is usually in the range 460-480 ºC [7-8]. In most presses, the same temperature is used for all dies. It should be noted that for the initial billets the temperatures used are lower and sometimes conical heating is used. Changing the billet temperature without any risk is possible for the vast majority of dies, especially if the maximum force exerted during the process is controlled through simulation and the die components are designed to withstand the maximum press force.

The present study aims to provide an additional and non-exclusive methodology to increase productivity based on the optimal choice of billet temperature in the press with the help of a previous analysis by means of FE simulation. A lower billet temperature at the inlet of the press translates into a lower outlet temperature of the extruded profile [9]. As the outlet temperature is the limiting factor of the process speed, lowering the outlet temperature opens the possibility to increase the process velocity [10]. It is important to note that the reduction of the inlet temperature is associated with an increase of the maximum force in the press and, therefore, of the stresses supported by the tools [11]. These parameters need to be controlled through simulation in order not to exceed the limits.

This simulation-based methodology for increasing process speed offers the possibility of achieving higher productivity on the press without investment in equipment and without additional operational costs.

Materials and methods

The methodology used for this study focuses on the use of hot aluminium extrusion process simulation to show the possibility of increasing the process speed and productivity through a reduction of the billet temperature. It focuses on steady state of the process.

It is important to note that it is vitally important to make use of simulation to analyse the most suitable temperature for the billet. Lowering the temperature of the billet increases the force required to deform the aluminium during extrusion. By using FE simulation, it is possible to properly control the maximum force required in order not to exceed the limits of the press. It is also possible to control the stresses in the die parts. Although most dies are designed to support the maximum press force, in some cases there is not so much allowance to ensure a long life of the die.

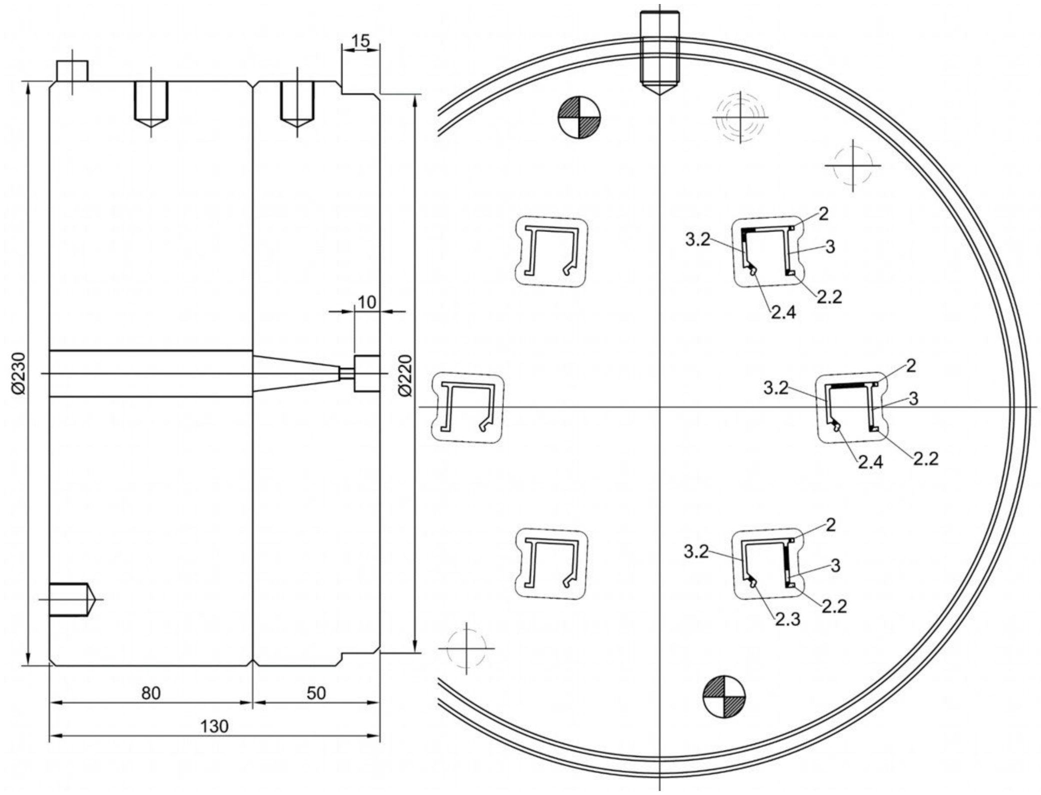

Fig. 1. Drawing of the die used for the experience.

An example die is used to illustrate the effects of the temperature variations proposed by the methodology. In addition, trial results are shown for the same die in the 23 MN and 178 mm container press of Alumex PLC (Sri Lanka). All simulations and trials have been carried out with the 6XXX group of aluminium alloys, in particular with the EN AW-6063-O alloy.

The die chosen for the application example is a 6-cavity solid die with a diameter of 230 mm and a total height of 130 mm. It consists of two parts: the die plate (50 mm) and the backer (80 mm). In the die plate there is only a single 10 mm deep feeder and the profile geometry with small bearing variations at the tips and due to the distance to the centre (Fig. 1). The die was produced by Compes, Spa.

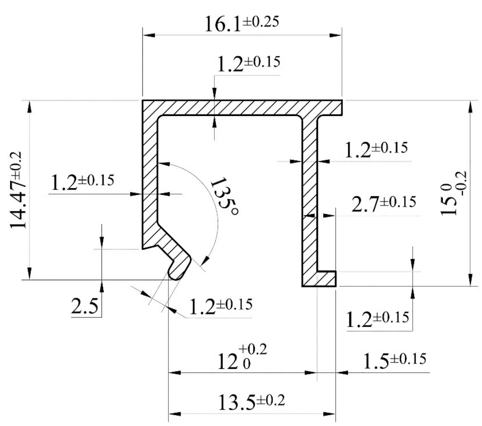

Fig. 2. Drawing of the profile used for the experience.

The extruded profile is a small profile (Fig. 2) with a weight of 0.151 kg/m. Therefore, the 6-cavity die has an extrusion ratio of around 75. This is a die that has already worked on several occasions prior to this research and Alumex PLC wishes to increase its productivity (Fig. 3).

Materials Research Proceedings 41 (2024) 781-790 https://doi.org/10.21741/9781644903131-86

In order to evaluate the benefits of controlled reduction of the billet temperature, several simulations will be carried out by changing the temperature and speed parameters. After analysing the best way to show the possibilities of the methodology, 3 sets of conditions of billet temperature, extrusion velocity and billet length have been defined. Table 1 shows the conditions chosen for the different trials.

Fig. 3. Image of the die used throughout the experiment.

The first trial uses the conditions under which this die used to extrude in Alumex PLC. There, usually all dies extrude with a billet temperature in the range 460-470°C.

The second trial uses a billet temperature 20°C lower and doubles the extrusion speed. These are the conditions that have been optimised with the help of FE simulation to significantly increase the speed while keeping the outlet temperature and maximum press force at admissible values. The condition set for determining the temperature was not to exceed 550°C at the exit of the profile and not to approach the maximum press force (23MN) during the process.

The conditions of the third trial are chosen to show that, in the event of a possible excess of force in the press due to the temperature reduction, it is possible to reduce the billet length to reduce the maximum force required.

Table 1. Conditions chosen for the different research trials.

Trial number	Billet temperature [°C]	Ram / extrusion velocity [mm/s]	Billet length [mm]
1	467	3	700
2	447	6	700
3	442	6	520

Numerical modelling results

Definition of the FE model. To verify the model predictions, they are compared with numerical simulation predictions employing the software Qform UK. It is a special-purpose software for the extrusion simulation based on the Lagrange–Euler approach. This software provides material flow analysis coupled with the mechanical problem in the tooling set, considering shape changes produced by the die deformation on the material flow through the die, which helps to ensure high accuracy of the numerical results [12].

All meshes are created with tetrahedral elements. A highly adaptive meshing is applied in order to optimise mesh quality and minimise the resources required to achieve accurate calculation results. The size of the elements in each zone is determined according to the extent of local deformation undergone during the process.

The billet material is EN AW-6063-O aluminium alloy and the die material is AISI H-13 steel. All the properties of these materials are temperature-dependent functions.

With regard to 6063 aluminium alloy, density, specific heat, thermal expansion, thermal conductivity, Young's modulus and Poisson's ratio are defined by employing a linear temperature-dependent function. The H-S model is used to represent the flow stress, and its dependence on strain is also considered. The H-S model function is derived by regressing the experimental data obtained from hot torsion tests [8]. The model employed by Qform UK is based on 6 coefficients (Eq. 1).

$$\sigma = A \cdot e^{m_1 T} \cdot \varepsilon^{m_2} \cdot e^{m_4/\varepsilon} \cdot (1+\varepsilon)^{m_5 T} \cdot \varepsilon^{m_3} \quad (1)$$

The AISI H-13 steel in the die is considered to be an elastic-plastic continuum subjected to small deformations. Steel density, yield stress and Young module are temperature dependent functions. Poisson's ratio for steel is 0.3 for this alloy and is independent of temperature. In the contact areas between aluminium and steel the heat exchange coefficient is 30000 W/(m^2·K).

Table 2. Temperatures of tooling.

	Temp [ºC]		Temp [ºC]
Container	440	Bolster	280
Ram	450	Die	450
Die ring	450	Backer	450

Qform UK models the friction between the aluminium and the die surface using the friction model proposed by Levanov [13], where σ_n is the normal contact pressure and m is the friction factor (Eq. 2):

$$f_\tau = m \cdot \bar{\sigma}/\sqrt{3}\,[1 - \exp(-1.25 \cdot \sigma_n/\bar{\sigma})] \quad (2)$$

In addition to the boundary conditions to be varied during the experiment, listed in Table 1, Table 2 shows the remaining main boundary conditions of the extrusion process used in the Qform UK FEM simulation.

Table 3. Numerical results for the different virtual trials.

Trial number	Billet temp. [°C]	Ram velocity [mm/s]	Billet length [mm]	Profile temp. [°C]	Max pressure [bar]	Max velocity deviation [%]
1	467	3	700	516	188.6	11.5
2	447	6	700	548	206.3	11
3	442	6	520	546	183.4	10.5

Model results. From all the results available in the simulation, those that are most representative for the research have been chosen:

- Temperature at process outlet (ºC). It allows to control the temperature of the extruded profile at the exit of the die.
- Absolute value of the velocity (mm/s). It allows to show the velocity reached by the process in steady state.
- Ram extrusion load (MN) and maximal pressure (bar). It allows to control the maximum force to be exerted by the ram of the press and the maximal pressure during the extrusion.

- Velocity deviation (%). It allows to control that the flow during the process is balanced comparing the velocity deviation between the fastest and slowest point in the extruded profile.

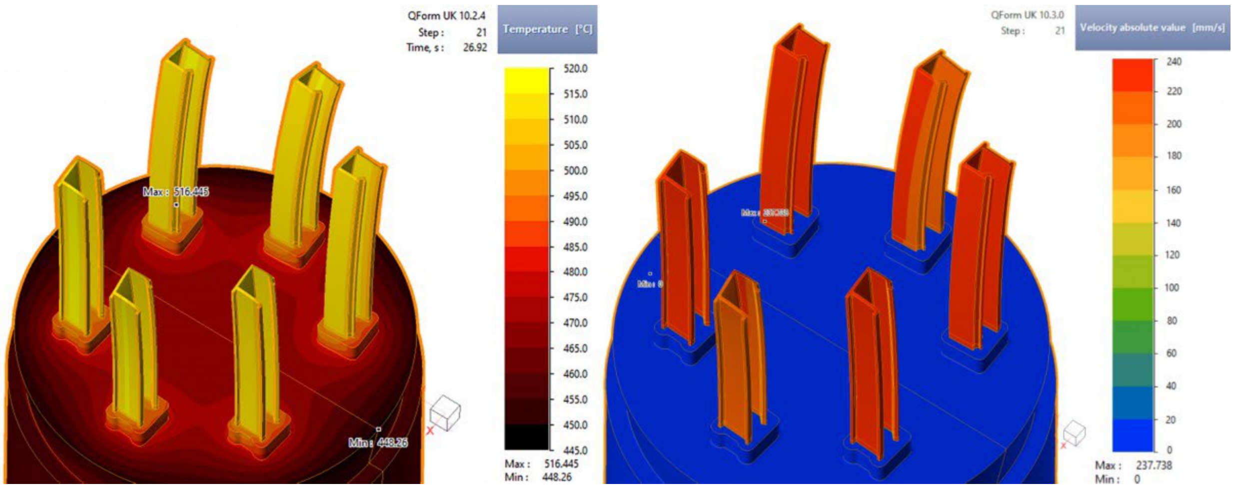

Fig. 4. Exit temperature and absolute velocity results for trial 1.

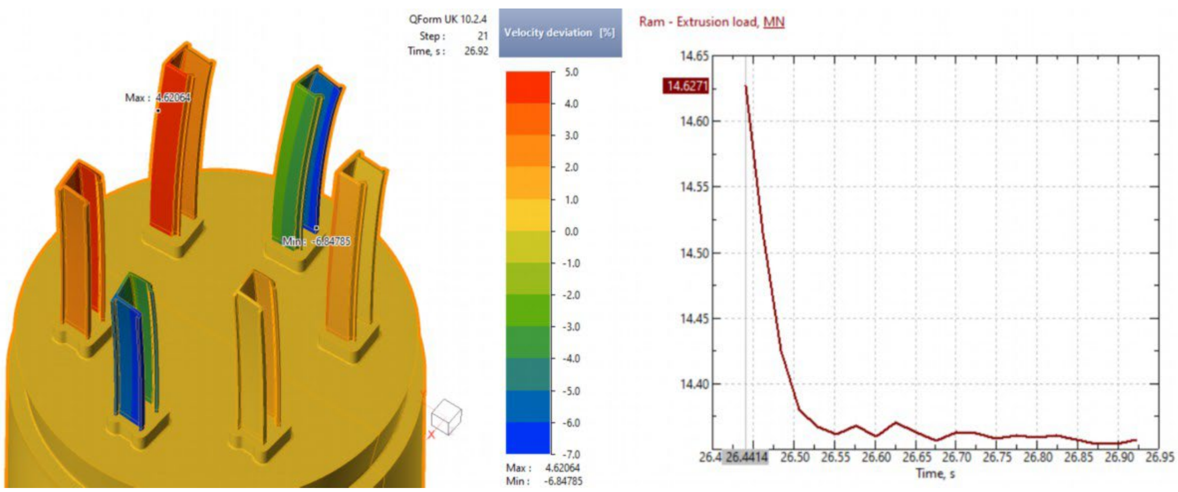

Fig. 5. Velocity deviation and ram load results for trial 1.

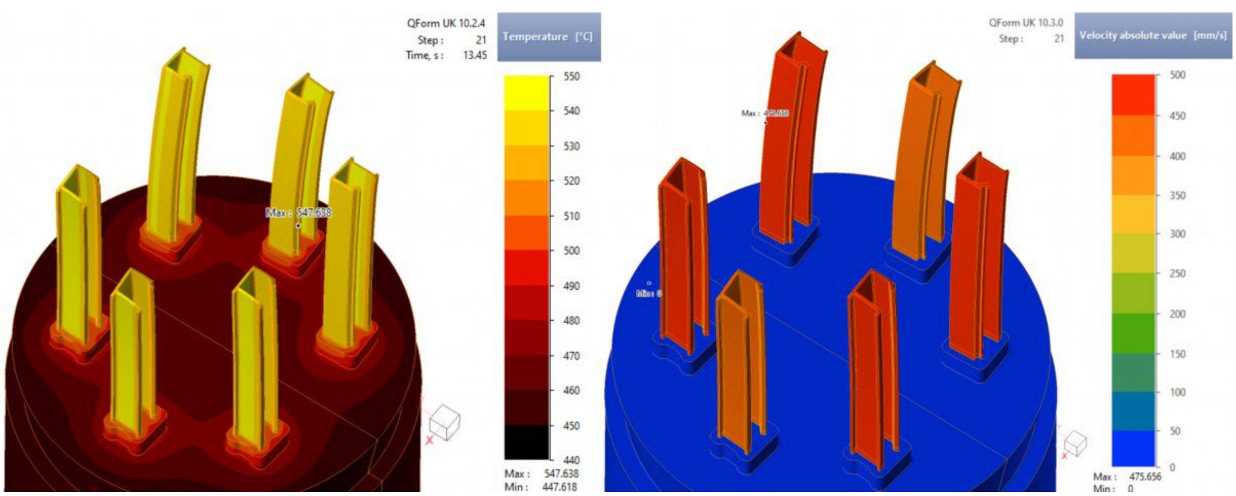

Fig. 6. Exit temperature and absolute velocity results for trial 2.

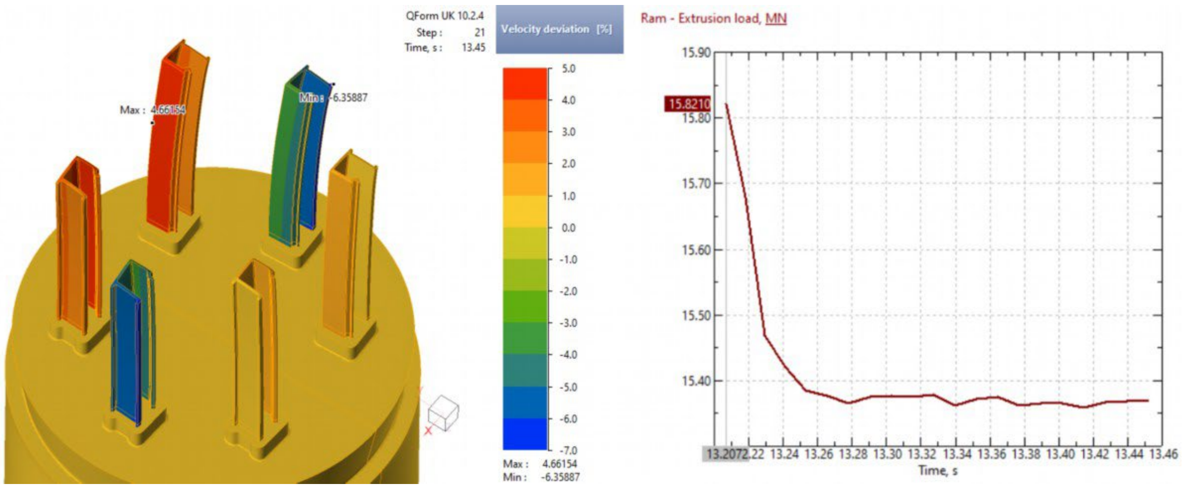

Fig. 7. Velocity deviation and ram load results for trial 2.

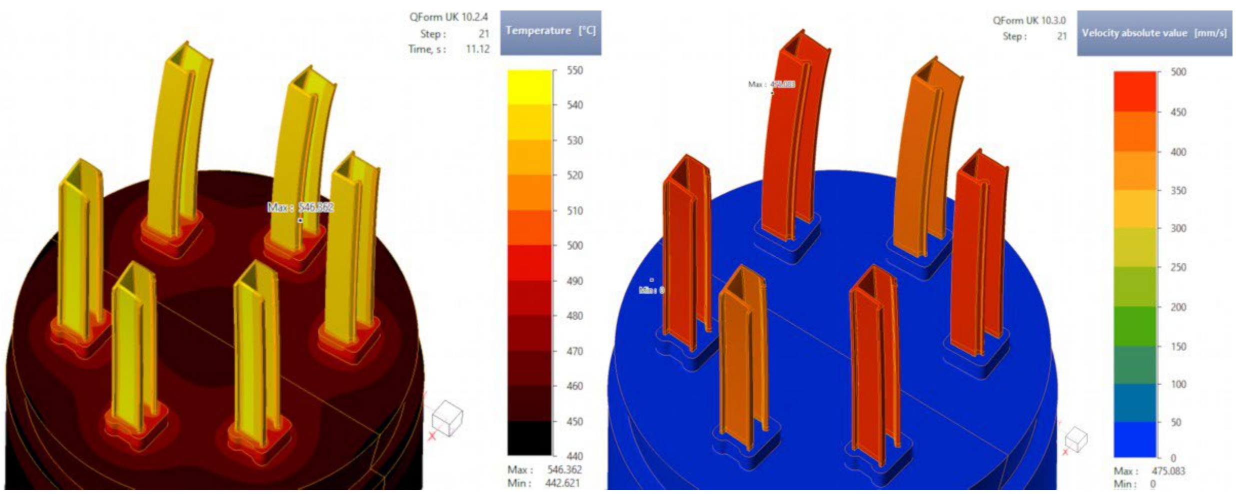

Fig. 8. Exit temperature and velocity deviation results for trial 3.

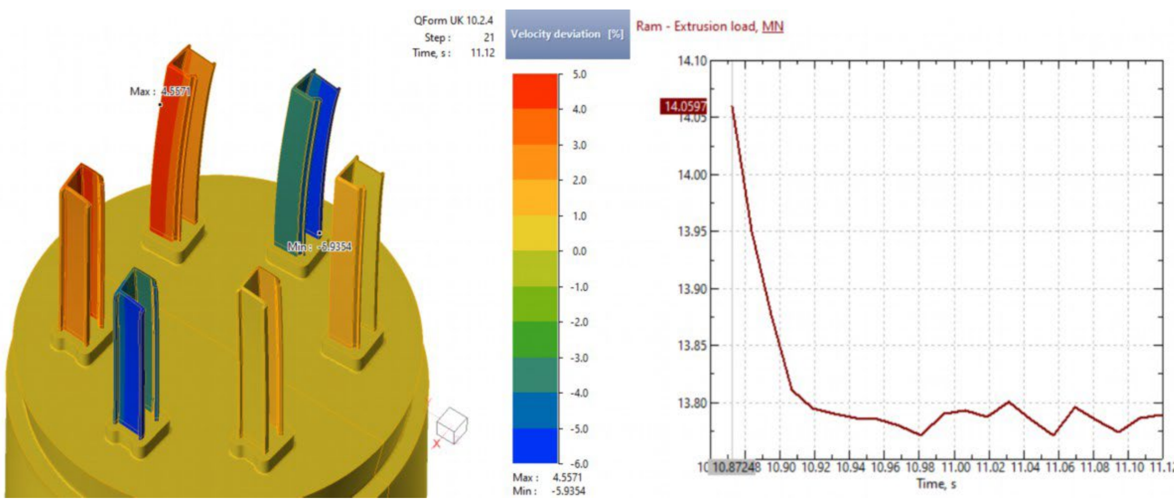

Fig. 9. Velocity deviation and ram load results for trial 3.

For each of the trials performed, the results obtained in the FE analyses are shown in Table 3. Fig. 4 to Fig. 9 show the exit temperature, absolute profile velocity, velocity deviation and ram load results for each of the trials. The rest of the graphs of the results can be consulted in the dataset associated with the research [14].

Trials results

The three trials have been carried out under exactly the same conditions as those defined in the simulations described above. It should be noted that in all trials the extrusion result was correct:

- The flow of the aluminium was sufficiently balanced.
- The surface finishing of the profiles is correct.
- The profiles conform to all dimensional tolerances.

Fig. 10 shows the images of the test specimens resulting from trials 1 and 2. The remaining images of the trials and the videos of the process can be consulted in the dataset corresponding to this paper [14]. Table 4 shows the actual results obtained in each of the trials in the press.

Table 4. Actual results for the different research trials.

Trial number	Billet temp. [°C]	Ram velocity [mm/s]	Billet length [mm]	Profile temp. [°C]	Max pressure [bar]
1	467	3	700	523	200.5
2	447	6	700	565	208.8
3	442	6	520	564	195.3

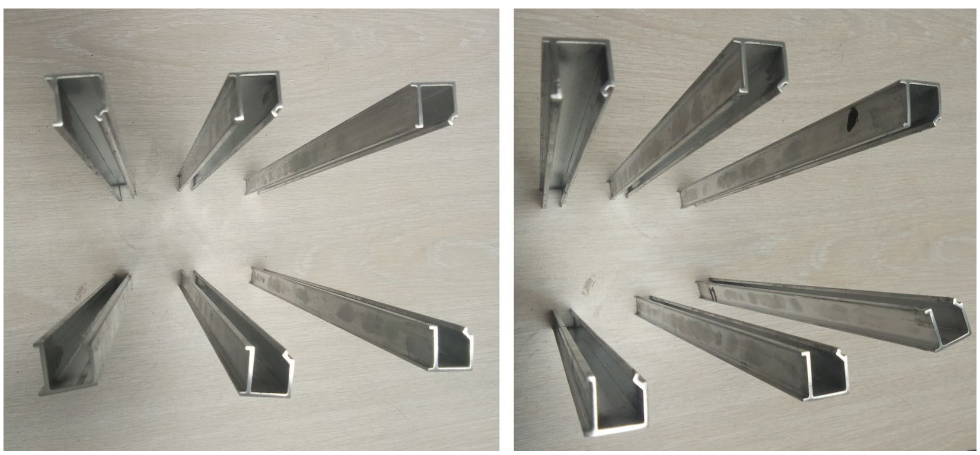

Fig. 10. Test specimens resulting from trial 1 (left) and trial 2 (right).

Discussion

Table 5 shows the comparison of the experimental results versus the FE simulation results. An analysis of the values confronted in this table shows that, in general terms, they are very similar. The profile temperature values are very slightly higher in the real trials (2-3%). The pressure values show a somewhat larger difference (up to 6.5% in the case of trials 1 and 3), being always higher in the real trials.

Table 5. Comparison of the experimental results versus the FE simulation results.

Trial	Billet temp.[°C]	Ram vel. [mm/s]	Billet [mm]	Profile temp. FE Simul. [°C]	Profile temp. Press [°C]	Max pressure FE Simul.[bar]	Max pressure Press [bar]
1	467	3	700	516	523	188.6	200.5
2	447	6	700	548	565	206.3	208.8
3	442	6	520	546	564	183.4	195.3

Therefore, it is possible to state that the predictions of the FE simulation are very close to reality and are reliable for making decisions to reduce the billet temperature in order to increase the velocity of the process. This is the most important point as the proposed methodology is based on the use of FE simulation prediction to directly choose the most appropriate conditions to maximise press productivity without risk or the need for iterative testing at different temperatures.

On the other hand, comparing the results of the first two trials, it should be noted that, as expected, with a reduction of 20ºC in the billet temperature it has been possible to double the process speed with an increase in profile temperature of only 42ºC (maintained at 565ºC, within an admissible range, as shown by the good surface finish of the specimens).

Comparing the results of trials 2 and 3, it can also be seen, as expected, that by reducing the billet length it is possible to reduce the maximum pressure/force exerted by the press.

From the FE simulation results it can be seen that the maximum predicted speed deviations are around 10.5-11.5%. The validity of this maximum deviation is highly dependent on the geometry and tolerances of the profile. As it has been verified later on the press, they are totally admissible and do not pose any problem in obtaining the extruded profile. It is observed that the velocity deviations are distributed exactly the same for the different process conditions analysed, which indicates that the creep behaviour of the extruded profile in the press is very similar for all cases.

Conclusions and future research

The main conclusion drawn is that the proposed methodology to optimise the extrusion parameters by means of FE simulation is very valuable from the point of view that it allows deciding the optimum extrusion conditions to maximise the productivity of the press without any risk for the tools and without the need to carry out iterative trials on the press, with the cost that this involves.

Furthermore, the numerical and experimental analysis conducted in this study shows that the strategy of reducing the billet temperature is a good solution for increasing the productivity of some dies. Moreover, it is a strategy that does not require investment in press equipment, compared to other strategies such as nitrogen cooling.

It shows that it is important to discard the widespread strategy of using standardised and equal conditions for the extrusion of most dies because potential process productivity is being wasted by doing so.

Finally, the question arises as to whether it is cost-effective to use simulation to try to increase the productivity of the extrusion press. From the authors' point of view, for companies that manufacture their own dies and/or purchase dies that have been designed using simulation, the cost of this type of study for each die is very low and the potential benefit is large. In these cases, moreover, it is a change that can be introduced in the very short term. And since these are process changes that do not require any investment in press equipment, any improvement in productivity is always positive.

For companies that are totally unfamiliar with FE simulation, this strategy is more difficult to take on board in the short term. It requires a medium-term strategy to introduce FE simulation into the corporate culture.

This billet temperature reduction methodology must always be accompanied by simulation to control the final profile temperature and maximum press pressures. In any case, it would be possible to avoid its use for dies very similar to others already studied.

For future research, it is intended to further develop this methodology by analysing cases of more complex solid dies and hollow dies. Alumex PLC is a perfect candidate to use the methodology and further develop it because it has fully integrated FE simulation in the development and design of its dies.

References

[1] A. F. M. Arif, A. K. Sheikh, & S. Z. Qamar, A study of die failure mechanisms in aluminum extrusion. *Journal of Materials Processing Technology*, 134 (2003) 318–328. https://doi.org/10.1016/S0924-0136(02)01116-0

[2] E. Giarmas & D. Tzetzis, Optimization of die design for extrusion of 6xxx series aluminum alloys through finite element analysis: a critical review. *International Journal of Advanced Manufacturing Technology*, 119 (2022) 5529–5551. https://doi.org/10.1007/s00170-022-08694-3

[3] S. S. Akhtar & A. F. M. Arif, Fatigue failure of extrusion dies: Effect of process parameters and design features on die life. *Journal of Failure Analysis and Prevention*, 10 (2010). https://doi.org/10.1007/s11668-009-9304-4

[4] S. Z. Qamar, A. K. Sheikh, A. F. M. Arif, M. Younas, & T. Pervez, Monte Carlo simulation of extrusion die life. *Journal of Materials Processing Technology*, (2008). https://doi.org/10.1016/j.jmatprotec.2007.08.062

[5] S. Z. Qamar, A. F. M. Arif, & A. K. Sheikh, Analysis of product defects in a typical aluminum extrusion facility. *Materials and Manufacturing Processes*, 19 (2004). https://doi.org/10.1081/AMP-120038650

[6] P. K. Saha, Thermodynamics and tribology in aluminum extrusion. *Wear*, 218 (1998). https://doi.org/10.1016/S0043-1648(98)00210-5

[7] R. Pelaccia, B. Reggiani, M. Negozio, & L. Donati, Liquid nitrogen in the industrial practice of hot aluminium extrusion: experimental and numerical investigation. *International Journal of Advanced Manufacturing Technology*, 119 (2022). https://doi.org/10.1007/s00170-021-08422-3

[8] A. Gamberoni, L. Donati, B. Reggiani, M. Haase, L. Tomesani, & A. E. Tekkaya, Industrial Benchmark 2015: Process Monitoring and Analysis of Hollow EN AW-6063 Extruded Profile. *Materials Today: Proceedings*, 2 (2015) 4714–4725. https://doi.org/10.1016/j.matpr.2015.10.004

[9] H. H. Jo, S. K. Lee, C. S. Jung, & B. M. Kim, A non-steady state FE analysis of Al tubes hot extrusion by a porthole die. *Journal of Materials Processing Technology*, 173 (2006). https://doi.org/10.1016/j.jmatprotec.2005.03.039

[10] A. Medvedev, A. Bevacqua, A. Molotnikov, R. Axe, & R. Lapovok, Innovative aluminium extrusion: Increased productivity through simulation. *Procedia Manuf.* (2020). https://doi.org/10.1016/j.promfg.2020.08.085

[11] M. M. Marín, A. M. Camacho, & J. A. Pérez, Influence of the temperature on AA6061 aluminum alloy in a hot extrusion process. *Procedia Manufacturing*, 13 (2017) 327–334. https://doi.org/10.1016/j.promfg.2017.09.084

[12] N. Biba, S. Stebunov, & A. Lishny, The model for coupled simulation of thin profile extrusion. *Key Engineering Materials*, 504–506 (2012) 505–510. https://doi.org/10.4028/www.scientific.net/KEM.504-506.505

[13] A. N. Levanov, Improvement of metal forming processes by means of useful effects of plastic friction. *Journal of Materials Processing Technology*, 72 (1997) 314–316. https://doi.org/10.1016/S0924-0136(97)00191-X

[14] J. Llorca-Schenk, L. Gayashan, & P. Hewage, Dataset for increasing of productivity of aluminum hot extrusion press. *Mendeley Data*, (2024). https://doi.org/10.17632/chr2mnfh3j.1