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FEM Codes Benchmark for Aluminum Extrusion Process Analysis

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The paper presents an overview on the two previous editions of the benchmark conferences (2007 and 2009) and compares the accuracy of the different FEM codes in predicting critical process outputs. In the 2007 edition four L-shaped profiles were produced under different profile thickness and pockets shape thus realizing different final profiles length. In the 2009 edition a multihole dies producing two overlapped U-shape profile was used: the two die openings were differently designed in order to realize different die deflection (fully supported and partially supported tongues). Profile lengths, die and profile temperatures, and process load were used as benchmarking parameters for FEM comparison moreover in the 2009 the particular design of the die allowed also the monitoring of tongues deflections during the extrusion stroke. The paper starts with a brief description of the experimental conditions, repetitions and main results, then a summary of the different FEM codes computational times and of the main outputs and their comparison with experimental results are presented. A detailed discussion for all output parameters is realized in order to understand potentials and limits of each code. Finally a discussion on future perspective for FE code application and designing guides is reported.

Keywords: *Extrusion, AA6082, FEM codes, benchmark, die deflection.*

1. Introduction

In the aluminum extrusion sector in the last years FEM codes are becoming the most important tools for process and product optimization. Nowadays, the simulation of the extrusion process by means of FE codes has been applied in a great number of papers available in literature but its application in everyday production was limited due to several factors like computational times, user's skills as well as prediction accuracy. Indeed, the inner complexity of the process, characterized by extremely high deformations, strain rates and heat exchange phenomena, has lead only in the last few year commercial FE codes to gain sufficient accurate solving capabilities. In order to clearly evidence the several code' accuracy, reliability and computational times a conference series has been organized with the specific aim to benchmark the most diffused FEM codes by mean of a systematic comparison of the outputs with experimental trials performed under strict monitored conditions. The paper summarizes the main outcomes emerged from the comparison of experimental results with FEM predictions as emerged during the 2007 and 2009 conference editions.

2. The experiments

Every extrusion benchmark has a particular focus: in the 2007 edition held in Bologna [1] the die was designed with the aim to compare the influence of pocket shape with respect to profile thickness (figure 1), while in the 2009 edition organized in Dortmund [2] the die was designed in order to allow the monitoring of the die deflection during the process (figure 2).

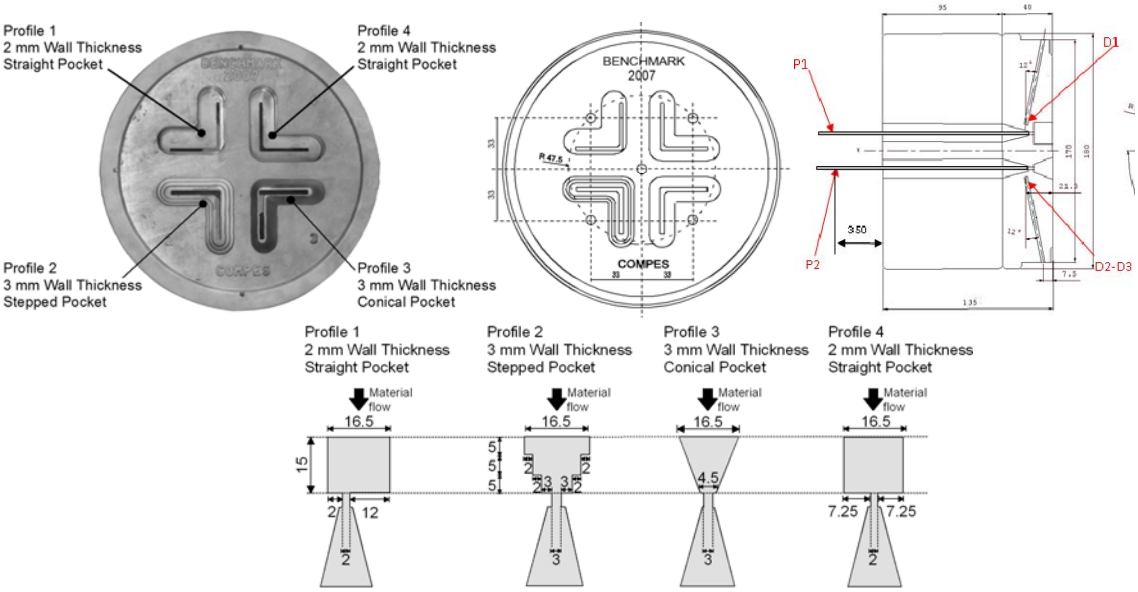

Fig. 1: 2007 benchmark die design

The 2007 die produced four L-shape profile of 2 and 3mm thickness respectively (figure 1) under different pocket shape configurations (straight off-centered, stepped, conical and straight centered); figure 1 reports also the location of the thermal sensors in the die (D1, D2 and D3 points) and on the profile (P1 and P2). A multiple hole die was chosen in order to preserve the same conditions on the different holes within the same experiment, while two different profile thicknesses were adopted in order to provide direct information on how much the pocket is active on material flow influencing. The very controversial issue on step – versus – conical pocket was analyzed in the lower (thicker) couple of profiles. On the two thin profiles it was decided to check the drag effect of placing the die exit as close as possible to the pocket wall. The general layout of the four profiles was determined by the maximum diameter available at the die exit on the experimental press facility. AA6082-O aluminum billets of 140 mm diameter and 302 mm length were used for the experiments. The experiments were carried out on a 10 MN extrusion press at the laboratory of the Institute of Forming Technology and Lightweight Construction (IUL) at the TU Dortmund University. The die, designed and built by Compes, Italy, was made by AISI H-13 tool steel. The extrusion experiments were performed at ram speed of 0.5 mm/sec with a maximum ram stroke of 250 mm. Before the experimental trials some extrusions were performed in order to stabilize the temperature in the whole system. In order to obtain consistent results, the experiments were repeated three times with equal initial temperatures, thus resulting in stable and comparable results. Figure 3 (left) reports in red the load stroke diagram of the 2007 benchmark with the error bars extracted from trial repetitions: a typical direct extrusion diagram was found with a maximum load of 7.13 MN. Figure 4 (left) shows in the last row the final length of the four different profile as experimentally measured: the longest is the profile 2 (3mm thickness, stepped pocket) then profile 3 (3mm thickness, stepped pocket), 4 (2mm thickness, straight centered pocket) and finally profile 1 (2mm thickness, straight off-centered pocket). If greater lengths of thicker profiles were expectable, the big difference between stepped vs. conical and centered vs. off-centered pockets was surprising, especially in comparison to the changes in profile thickness. It's worth noting that all the three repetitions showed the same difference in profiles lengths. In figure 5 and 6 (left) the temperature evolution in the die and on the profiles are shown: initial and stationary die temperatures are evidenced (with an increase from 405° C to 470° C) although with a constant difference of around 20°C between D1 and D2 locations; profile measurements could be taken only when the profiles had come out of the die package, which happened after 20 and 50 mm ram stroke for profiles 1 and 2, respectively. The profile exit temperatures showed a steady state value and the lower values for profile P1 proved a lower exit temperature and/or a faster cooling on the thinner profile. Details on experimental conditions, input settings for the simulations and results are fully reported in [3].

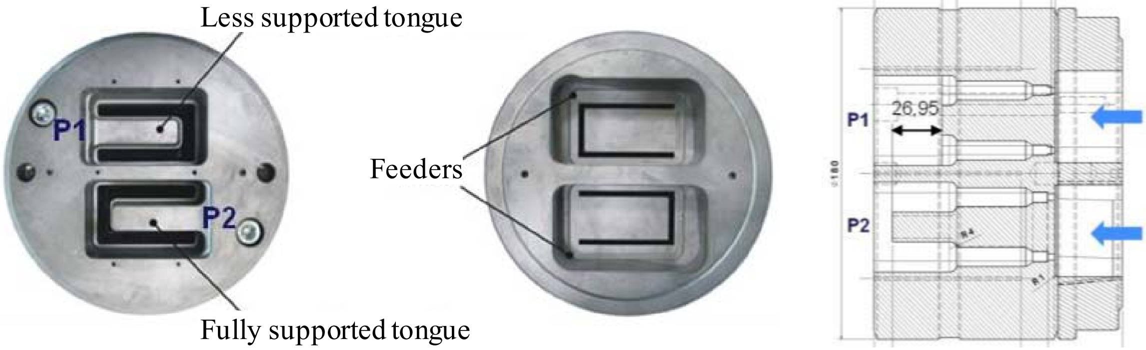

Fig. 2: 2009 benchmark die design

In the 2009 benchmark, a multiple hole die for the simultaneous extrusion of two U shape profiles was designed (Figure 2) in order to produce an effective comparison for different tongue design strategies. Both profiles have the same dimension and feeder in order to balance material flow entrance. The two profiles were arranged one upon the other: the bottom one is characterized by a standard supporting tongue while the upper one was deeply shortened (26,95mm reduction) in order to achieve a measurable die deflection during the process. With this configuration, a higher deflection of the upper part of the die with the less supported tongue is expected, thus producing a loss of contact in the bearing zones and an alteration of the thermal field at the two exits; as a consequence a difference also in material flow and profile distortions are expected for the two profiles. At the same time, the U-shape of the profiles allows the accessibility for the laser measuring devices to detect the deflection of the tongues along the extrusion direction, while the length of the U shape (59,3mm) allows an adequate magnification of the die deflection, as better described in [4]. The die was made of AISI H-13 hot-working tool steel tempered to 45 HRC hardness and built by WEFA, Germany. AA6082-O billets were used also for the 2009 trials, but, as consequence of different billet suppliers, the material flow stress was characterized again by means of hot torsion tests. As in the 2007 edition, the experiments were carried out at the laboratory of IUL at the TU Dortmund University but with a higher ram speed (10 mm/sec) and with a maximum ram stroke of 290 mm. The load stroke diagram of the experimental trial with the confidence interval of the three repetitions is reported in figure 3(right): the typical direct extrusion load-stroke diagram was found with a maximum load of 8,00MN while 8,04 and 8,51 MN were obtained within trial repetitions. Due to the die deflection during the stroke, different friction conditions acted in the bearing zones thus altering the material flow and consequently the final profiles length. The three repetitions showed exactly the same tendency in profiles speed: upper profile (partially supported) always ran slower than bottom one (fully supported) thus producing shorter profiles. Figures 5 and 6 report the die and profiles temperature evolution during the process: again experimental data with the confidence interval based on the three repetitions are reported in red. The die temperature remained constant during the whole stroke as consequence of the process settings, of the starting die temperature (393°C) and especially of the type of die heating system (the die is heated directly in the press by a closed loop control and the heating system remained active also during the process stroke). Concerning profile temperatures, the upper profile (P1) temperature reached a steady state condition, after an initial raising up to 100 mm stroke, at a value of 488°C. During the initial phases of the extrusion process, the aluminum pressure acted almost equally on the two die tongues, but as consequence of the different support of the two profiles the upper tongue (partially supported) significantly deflected under the aluminum pressure. The tongues displacements were recorded trough laser system and the difference in the deflection of the upper tongue respect to the lower one is reported in figure 7: after material filled the die the difference of tongues displacements remained almost constant during the whole process stroke and equal to

0.5mm. A more detailed description of experimental conditions, input settings for the simulations and results is available in [4].

3. FEM code results

Six FEM codes joined the 2009 benchmark session: four were already present at the 2007 edition (Deform, HyperXtrude, Dieka, QForm,) but two new entries were very welcomed to the 2009 edition (Simufact and MTD). The codes differ one from the other for different simulation approaches (lagrangian, eulerian or mixed) and consequently type of analysis (transient, steady state, mixed) thus generating different computational time or setting times. All the benchmark players were asked to fill in a standard Results Data Form until the same deadline in order to allow a simple and equal comparison of software capabilities. Some comparison between software results and experimental ones are summarized below, while the full Results Data Forms are available on conference proceedings.

	Code 1	Code 2	Code 3	Code 4	Code 5	Code 6	Code 7
Model set-up	70 minutes	360 minutes	120 minutes	30 minutes	10 minutes	5-6 minutes	55 minutes
Calculation time	61 hours	80 hours	150 hours	9.2 hours	3 hours	12-37 hours	157 hours

Table 1: FEM codes set up times and computational time 2009 edition

	Code 1-07	Code 3-07	Code 4-07	Code 6-07	Code 7-07
Model set-up	200 minutes	240 minutes	30 minutes	6 minutes	200 minutes
Calculation time	629 hours	720 hours	10 hours	224 hours (23.3 mm stroke)	1224 hours (37 mm stroke)

Table 2: FEM codes set up times and computational time 2007 edition

Table 1 summarizes the set-up and computational times for the different codes (as declared by the participants): seven codes are there reported because one presented also different data depending on the adopted approach type (UL or ALE). By comparing table 1 with table 2 referred to 2007 data, it’s very important to note that computational times extraordinarily decrease in just 2 years: in 2007 the computational times were in the range of 10-1200 hrs while now they are in the range of 3-150 hrs. For some codes the reduction of computational time is greater than 500% thus demonstrating the great effort that FEM codes developers invested in this direction. Stating such results it’s possible to say that today FEM codes are tools ready for application in everyday production and that probably another important reduction in computational times has to be expected in the next years.

Figure 3 shows the load stroke comparison between experiments and simulation: in the left graph the comparison is referred to 2007 benchmark where is possible to note that almost all codes (except code 6 and 3) overestimate the maximum load, even if a correct slope in the decreasing curve is generally found while in the right depending on the different simulation strategies some code are able to predict the load also in the die filling –i.e. before the peak load (codes 2,4,6 and 7)- while the others start the computation immediately after the peak load. A generally good prediction in term of diagram shape (with a nearly overlap for code 5) and quantitative values is now found for all the codes except for the code 2 that deeply overestimated the prediction. Moreover it’s worth noting that almost all codes are now able to simulate the whole process stroke.

Figure 4 reports the computed profile speeds: if in 2007 the right sequence was computed by only one code, and generally the values were not very accurate, in 2009 almost all code were able to predict the correct profiles speed. Nevertheless only code 6 properly estimated that the fully supported profile will produce a longer profile: such minor discrepancy is related to the complexity of this benchmark for FEM codes; in fact, such difference can be obtained by the codes only if the elastic behavior of the die is considered.

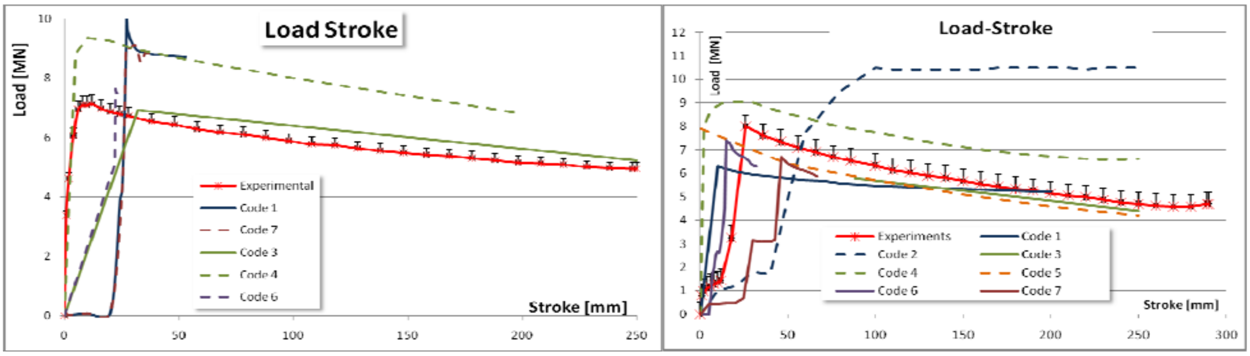

Fig. 3: Load stroke comparison benchmark 2007 (left) and 2009 (right)

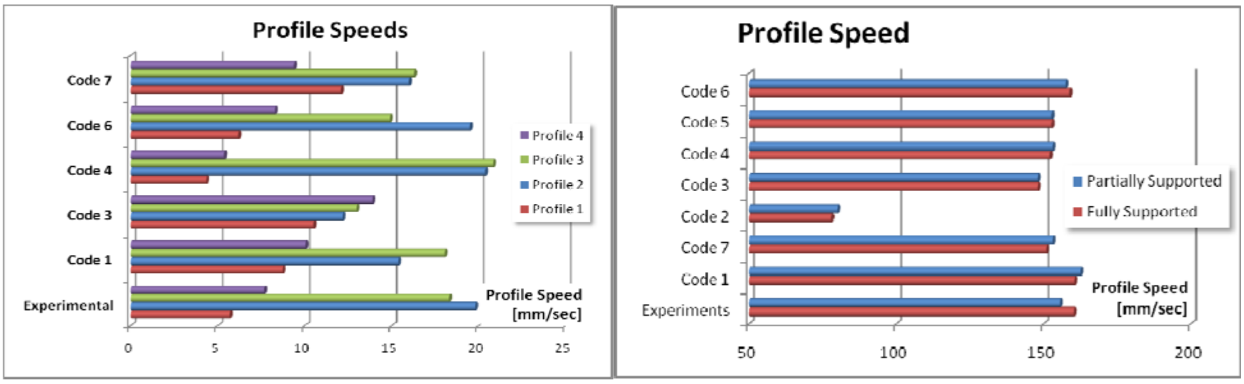

Fig. 4: Monitored and Predicted exit speeds, 2007 (left) and 2009 (right)

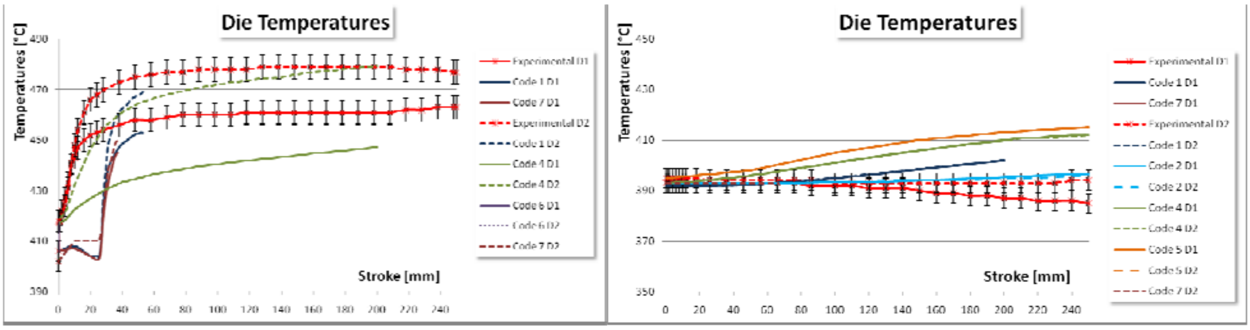

Fig. 5: Monitored and Predicted die temperatures, 2007 (left) and 2009 (right)

In order to clearly evidence the step ahead in process simulations accuracy, figures 5 and 6 reports the estimated die and profiles temperatures on the same y-axis range: it’s clearly visible the improvements of the codes in predicting the die temperature (maximum error of 20°C for two codes in 2009) and also the estimation of profile temperature deeply increases for all the codes. In 2009 all the codes properly predict the temperature increase related to stroke increment and also the absolute values; just code 4 seems slightly overestimating such measured temperatures. In figure 5 two codes are missing: code 3 performed only isothermal simulations, while code 6 used a rigid model for the die without thermal computation.

Finally, the benchmark 2009 allowed measuring and then computing also the die deflection: as previously described, figure 7 shows the difference in deflection (delta displacement=disp.$_{\text{partially supported}}$ – disp.$_{\text{fully supported}}$) between fully and partially supported tongues. Almost all the codes underestimated the deformation and they surprisingly predicted the same delta deflection: the discrepancy could arise also on the definition of AISI H-13 temperature dependent young modulus that was taken from literature and not tested on the specific tool steel used for die manufacturing.

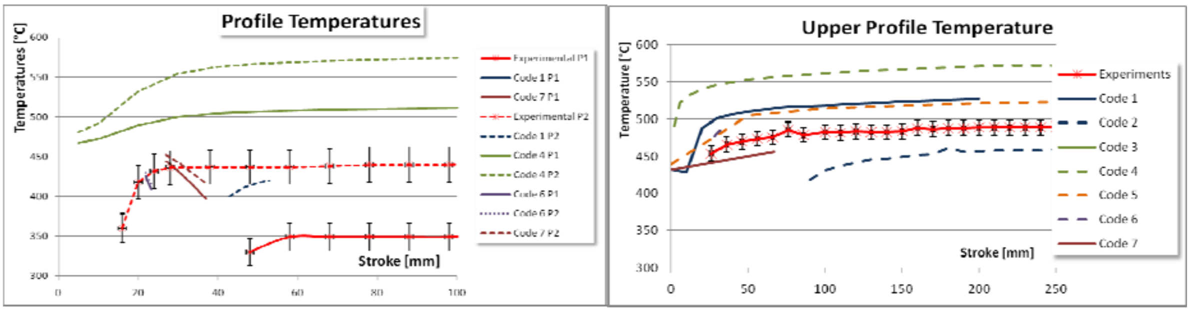

Fig. 6: Monitored and Predicted profile temperatures, 2007 (left) and 2009 (right)

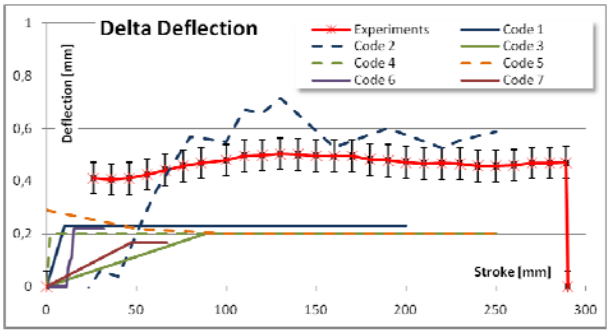

Fig. 7: Monitored and Predicted difference in tongue deflection in benchmark 2009

4. Conclusions

The current state of the numerical simulation applied to the extrusion process was exploited by the extrusion benchmark. A generally high increase of codes accuracy was found in the prediction of process load, material flow and temperature evolution; in particular the prediction of the evolution of the thermal field can be now be considered as acquired knowledge. In the 2009 edition, the codes were tested for the first time also on die deflection estimation: a general agreement with maximum deformation values was found but some more efforts have to be carried for gaining higher accuracy. Of extraordinary interest is the deep reduction in computational time respect to the 2007 edition, reduction that raise up to 500% for same codes, and that seems promising for a further important reduction in the next years. A special remark is finally addressed to the role of the benchmark session: as stated by some developers, the benchmark conference series acts as 'fitness' task and they were able to improve their accuracy and computational time thanks to the participation to the conference, where they were subjected to a strict comparison with experimental data as well as competitors results.

References

[1] http://diemtech.ing.unibo.it/extrusion07
[2] www.iul.eu/extrusion09
[3] L. Donati, L. Tomesani, M. Schikorra, A. E. Tekkaya "Extrusion Benchmark 2007 – Benchmark Experiments: Study on Material Flow Extrusion of a Flat Die", Proceedings of the Extrusion Workshop and Benchmark, Key Engineering Materials Vol. 367 (2008) pp. 1-8
[4] D. Pietzka, N. Ben Khalifa, L. Donati, L. Tomesani and A. E. Tekkaya "Extrusion Benchmark 2009-Experimental analysis of deflection in extrusion dies", Proceedings of the Extrusion Workshop and Benchmark, Key Engineering Materials Vol. 424 (2009) pp. 19-26.