International Students Olympiad in Extrusion Technologies

Reference report

Technical Support Team
QForm Group

2021

Outline

All attachments are presented at the end of this paper and saved in pdf-file located in the folder with the rest of the files.

1. Task

A profile extrusion company received an order to produce a 35 tons batch of hollow aluminium profile (Fig.1) from AA6061-T5 alloy. A press for direct extrusion was chosen to fulfill the order. There are 3 extrusion lines available at the facility with a container diameter of 145, 160, 166 mm and nominal press load of 16, 18, 20 MN respectively. Using simulation of profile extrusion process, develop a die set design required to complete the order and choose technological parameters of the process.

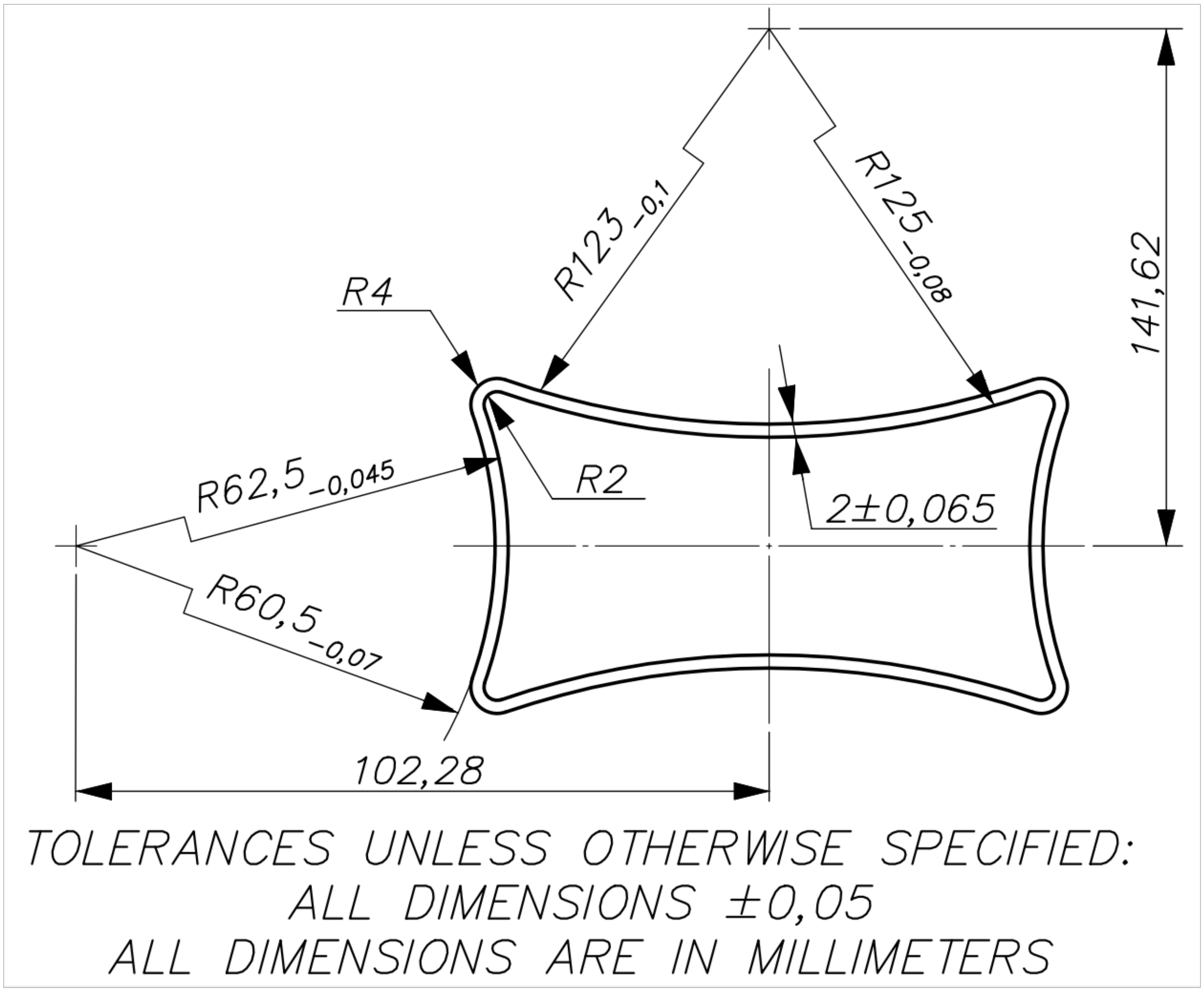


Fig. 1. Profile

Task notes

Create a report containing description of task execution, process simulation and steps of results analysis including calculations and technology verification. Use QForm

Extrusion as a tool for assessment and justification of the proposed technology. Quality, reliability and reasonability of approaches used to solve technological problems have an influence on the final mark, taking into account the following criteria:

- balance of material flow and lack of profile intersection with die set
- adjustment of extrusion temperature-velocity mode
- profile orientation on the die face
- adjustment of extrusion load mode (selection of billet length)
- analysis of die stress-strain condition
- productivity rate of the proposed technology (number of profiles extruded simultaneously and weight of profile per 1 press stroke)
- transversal seam length value and welding quality estimation of longitudinal seam
- universality of proposed components of support tools
- analysis of potential extrusion defects; prediction and elimination
- suggestion of appropriate heat treatment

6 hours provided to design the technology, to simulate it and to create a report using a text editor. At the end of the work create an archive (use special number provided by committee to name the archive) including the report and resulting simulation files of a single final version of technology. Report title and QForm-files have to contain your special number. Name of participant should not be specified.

Additional data

Overall dimension of die set (height) – 165 mm

Maximum diameter of die set – 250 mm

Total overall dimension of bolsters (height) – 220 mm

Material conditions – T5

Other requirements – according to local standards

2. Die design

The number of die orifices N is determined by the extrusion ratio λ, which should be in the interval between 30 and 80 units. It seems to be obvious to use the biggest container considering the productivity factor. λ can be calculated according to formula:

$$\lambda = \frac{F_{cont}}{F_{prof} N} \qquad (1)$$

If it is assumed that the higher value of λ from the described interval is preferable, it is needed to have a bigger container as well as smaller number of simultaneously extruded profiles. With only one profile extruded the extrusion ratio is very close to the smallest from the interval: $\lambda = \frac{F_{cont}}{F_{prof}N} \approx \frac{\pi * 166^2}{4 * 569{,}4 * 1} = 37{,}9$

That's why let's assume the number of profiles to be equal to 1.

Workpiece diameter should be sufficient enough in order to insert it in the container. Increase of workpiece diameter due to thermal expansion should be also taken into account as well as tolerances for workpiece diameter. Thus, the required dimeter:

$$d_{wp} = (0{,}97 - 0{,}98) * D_{cont} = 166 * 0{,}98 \approx 162\ mm \qquad (2)$$

The length of the billet (L) can be determined via the ratio $\frac{L}{d_{wp}}$, which should be in the interval between 2 and 4.5 units. Let's assume, at first, medium value of 3. L can be calculated according to formula:

$$L = (2 \ldots 4{,}5) * d_{wp} = 3 * 162 \approx 500\ mm \qquad (3)$$

The length of billet can be increased; however, it could result in very high extrusion load. So, the billet length can be specified via adjustment of temperature-velocity mode considering the maximum press load.

Die orifice

Temperature shrinkage should be taken into consideration. It can be done by multiplying the initial dimensions by coefficient K, which addresses thermal expansion of profile. Hence, profile dimensions on the die orifice is:

$$A = K * A_i \tag{4}$$

where A_i – initial dimensions, K = 1,012 – shrinkage coefficient. Resulting die orifice is presented in the figure 2.

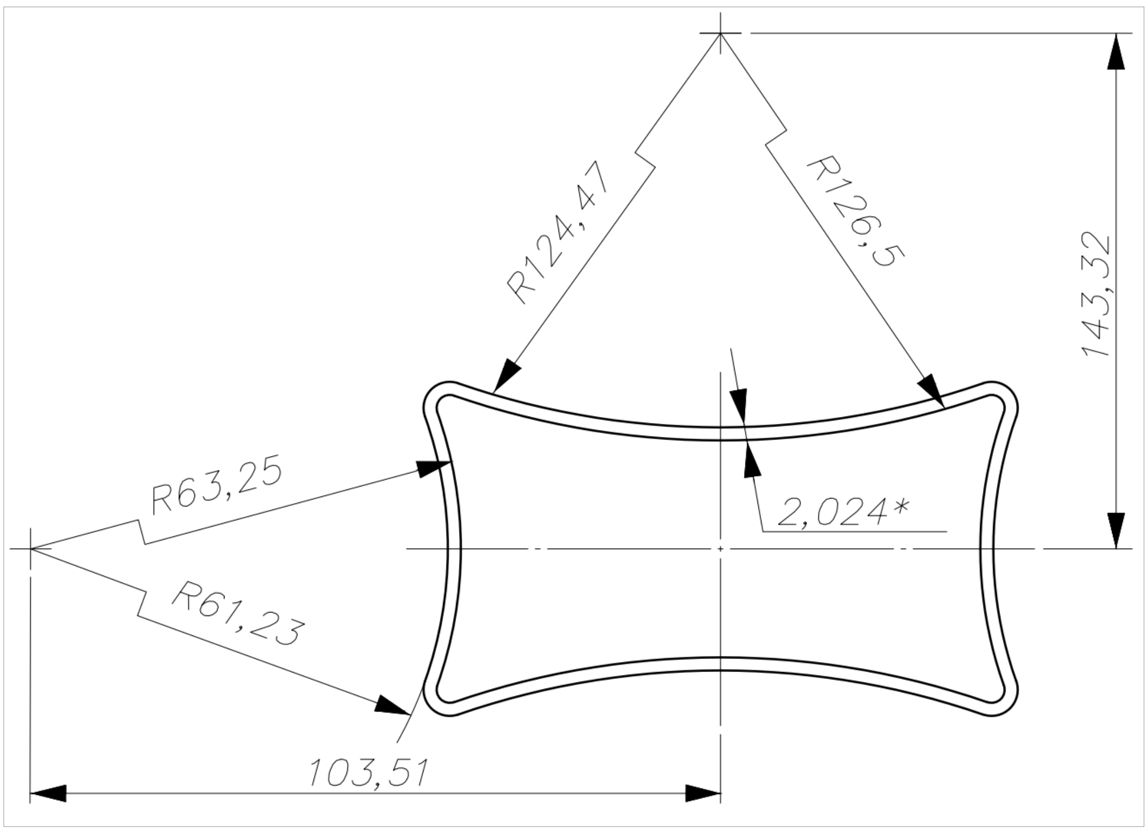


Fig. 2. Thermal expansion of the profile dimensions

Die dimensions are indicated in the figure 3. For the purpose of a time consumption minimization by simulation it is better to use symmetrical model. So, the quarter part was used for simulation. The red solid corresponds to the mandrel, the blue one corresponds to the die and the green one corresponds to the backer.

It is better to have webs located in the corner of an extruded profile. But in some cases, considering the given limits on the toolset, it is needed to check whether or not it is enough to have webs only in the corner of the mandrel. If the stress-state of tool set is not safe, additional web in the center should be present in design. The weld chamber height was assigned for first case equal to 10 mm. Circumscribed diameter of feeders should not be bigger than 90% of the container diameter [1]. Thus, it was assigned equal to 146 mm. After first simulation the volume of metal that goes through particular port was analyzed and changed to achieve stable flow of the profile.

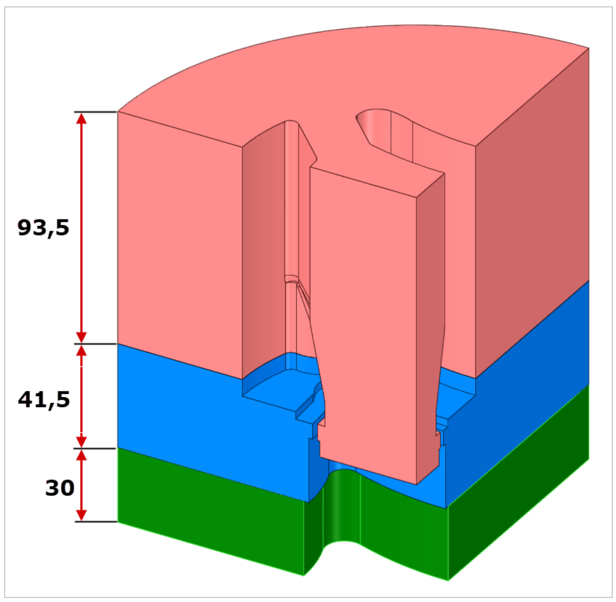


Fig. 3. Tool set dimensions

The web cross-section was applied based on suggestion that the metal after tapered part of the web should flow to the area of big port (Fig. 4).

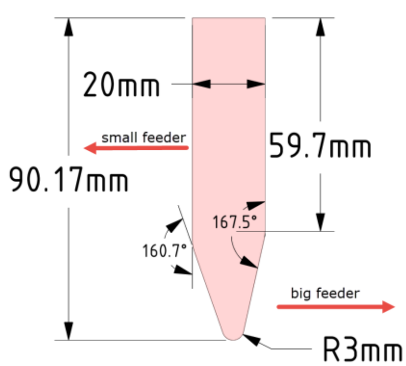


Fig. 4. Web cross-section

Initial bearing length was specified constant and equal to 6 mm. This parameter can be adjusted via simulation if needed. The height of bolster and sub-bolster was appointed equal to 110 mm. The inner hole of these arts was the same for both parts. Figure 5 shows dimensions for bolster geometry. Bolster and sub-bolster orifices meet the requirements of universality (simple curves like round or rectangular should be assigned).

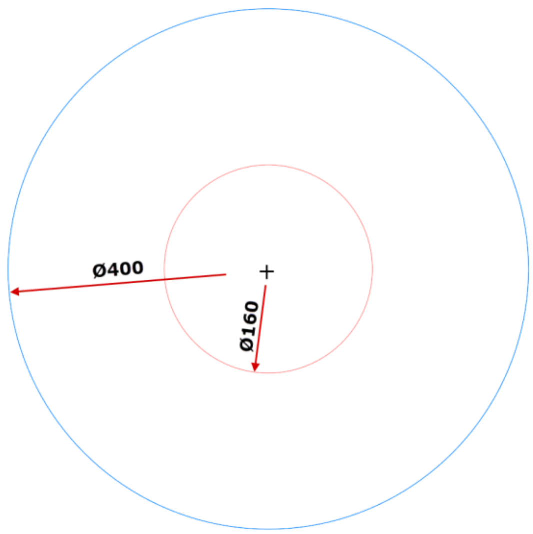


Fig. 5. Bolster geometry

Process parameters are specified in the tables 1, 2, 3.

Attribute / Object	Diameter, mm	Length, mm	Geometry type
Container	166	-	-
Billet	162	500	-
Die set	240	165	STEP
Die holder	400	-	-
Bolster	400	110	IGS
Sub-bolster	400	110	-
Pressure ring	200		

Table 1

Attribute / Object	Temperature, °C	Material
Billet	470	AA6061
Die set	460	H13
Bolster/Sub-bolster	300	
Ram	460	
Container	460	
Temperature taper	-	-

Table 2

Ram velocity	4 mm/s

Table 3

3. QForm Extrusion simulation

QShape provides a possibility to create a mesh for further simulation in QForm Extrusion. Mesh, including 3 elements within the profile thickness was obtained (Fig. 6).

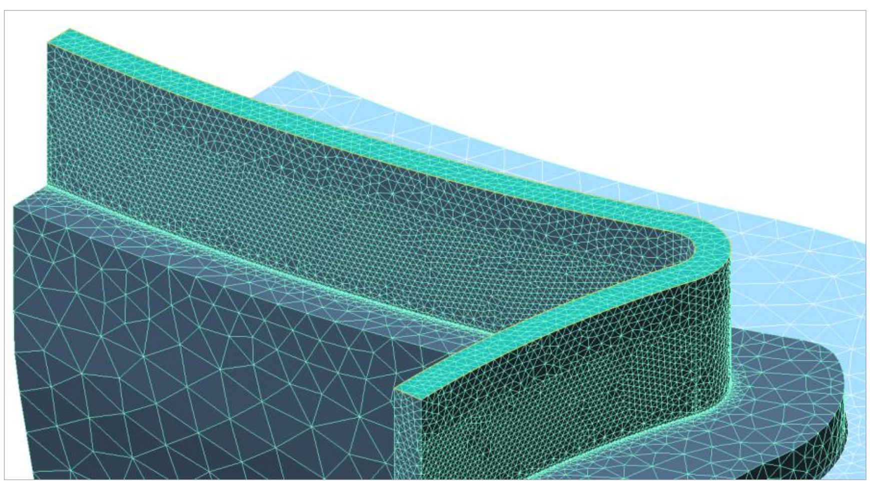


Fig. 6. FE Mesh

1st design

Flow instability was found. Figure 7 illustrates very high deviation in velocity of profile. Optimization should be found in redesign of feeders and finally in prechamber [2].

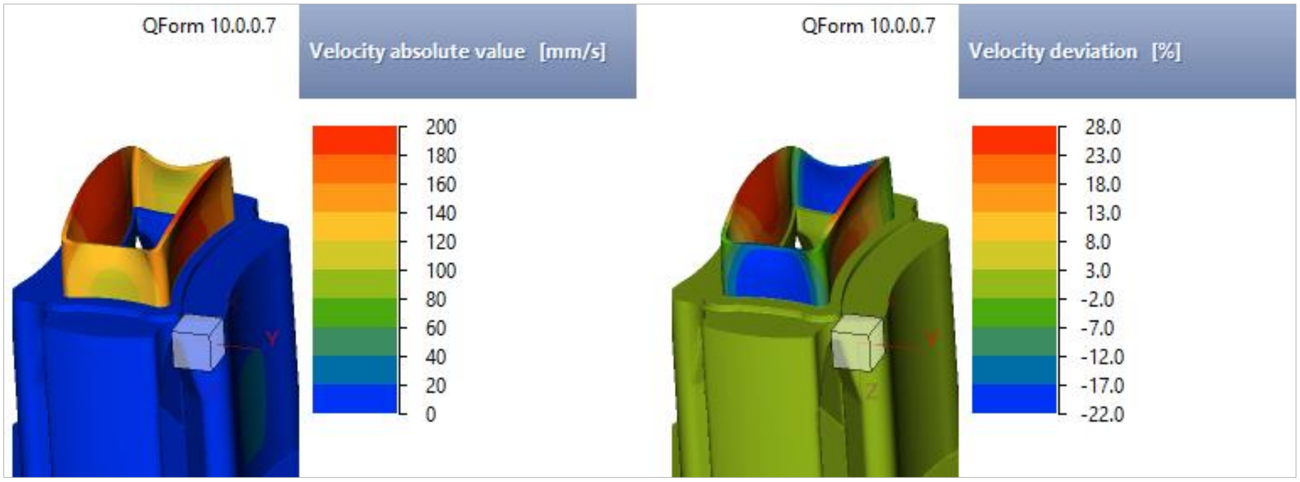


Fig. 7. Velocity deviation

The flow is unstable, it can be clearly identified from the value of steady-state criterion; due to such velocity deviation the profile has a contact with tool (Fig. 8). In some cases, a contact with tool can lead to a complete disaster during real extrusion process due to, for instance, sticking of profile to relief/backer/bolster parts.

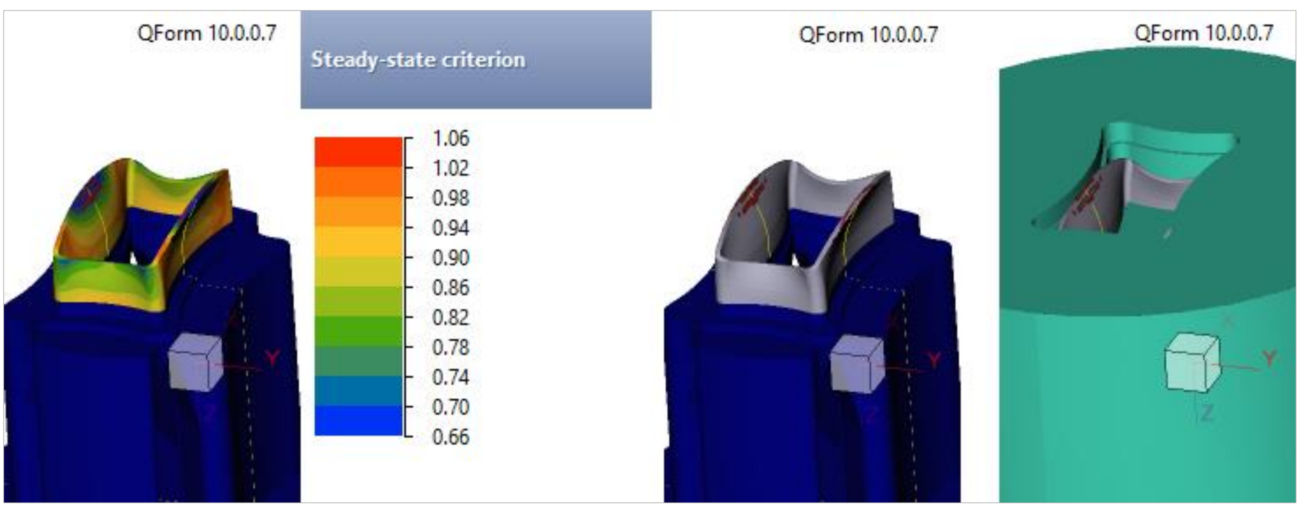


Fig. 8. Steady-state criterion and contact with tool

Die deflection in Z, X direction are within limits, while die deflection in Y direction is rather big (Fig. 9).

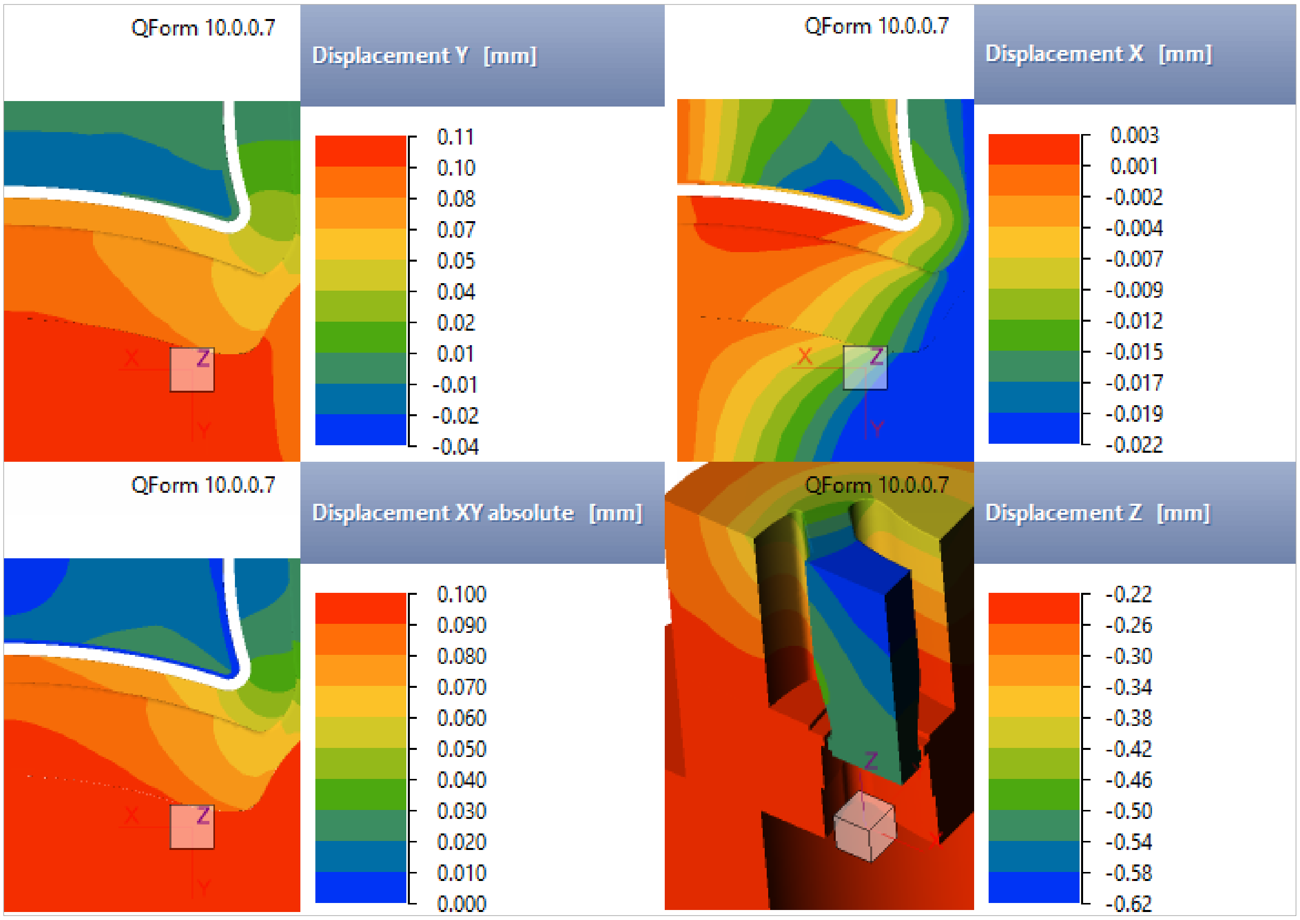


Fig. 9. Tool displacements

Displacement in Y direction is rather big considering the tolerances on the profile thickness – $2{,}024 \pm 0.065$ mm. So, this deviation of the die orifice should be taken into consideration in next die design. Stress-state of die is within limits (stresses and areas of plastic zone). It was analyzed in detail with final design.

Temperature of the profile is not above critical temperature for the alloy, which is approximately 550-560°C (Fig. 10). The temperature is rather low; thus, we can increase velocity of ram or initial temperatures of billet and tool set parts.

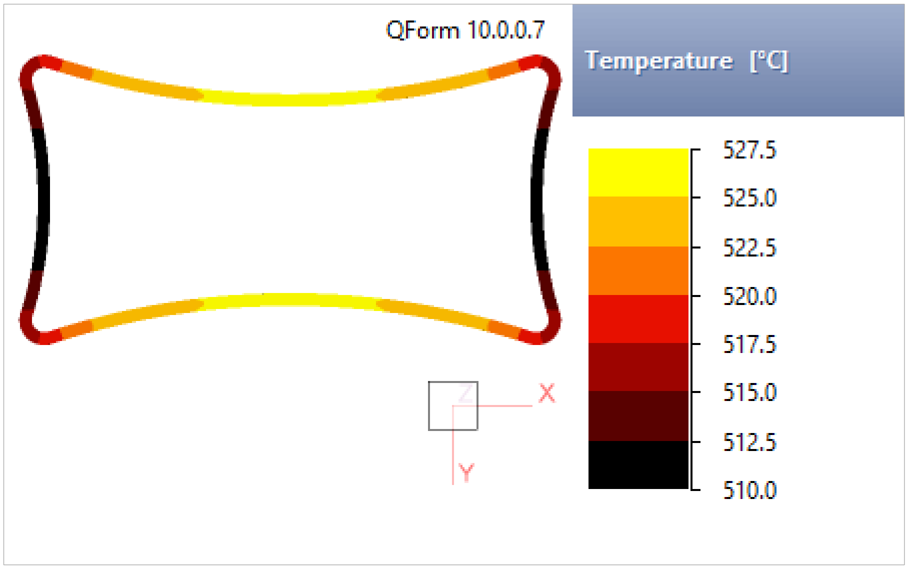


Fig. 10. Profile temperature

Information from simulation state shows maximum extrusion load, which is about 12 MN (Fig. 11). The real load graph is presented after final whole billet simulation, so, final estimation of this value was considered during temperature-velocity mode selection. Because the load is far less than the nominal press load, the length of the profile was be assigned equal to 700 mm (which is approximate limit from the equation 3).

Simulation state	
⊟ Process parameters	
Extrusion ratio	39.2322
Container diameter [mm]	166
Filling time [s]	12.9742
Extrusion load [MN]	11.765
Specific pressure [MPa]	543.399
Coupled task status	Calculated
Solution status	Completed
⊟ Calculation state	
Iteration	2
Velocity norm	0.00306321
Mean stress norm	0.000897367
Total simulation time	10 min 1 s

Fig. 11. Simulation state

Distance from stop-mark is approximately 2.5 m. Every extruder wants to have this value as small as it possible in order to have a smaller scratch. Weld quality is very low (Fig. 12). With further design using different form of weld chamber this value could be decreased. Based on experimental data, welding seams with quality value over 1 have structurally welded bondings and seams with value below 0.15 have visible welding lines, poor mechanical properties or even lack of welding [4]. The weld quality is very dependent on time of welding (ram speed), temperature, and stress state in the welding area. If we change the height of welding chamber it should results in better welding quality.

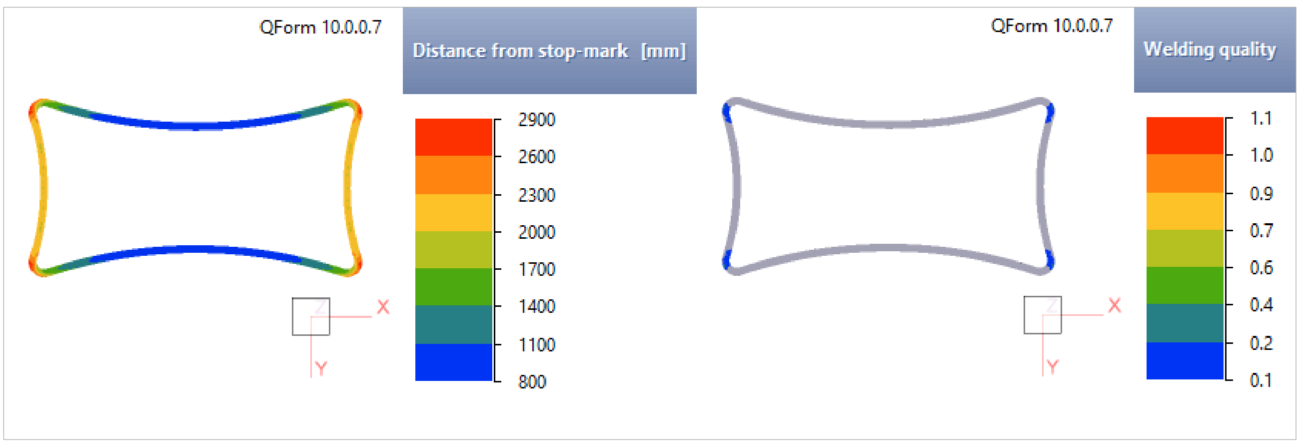


Fig. 12. Distance from stop-mark and weld quality

2nd design

In second simulation with second die new length of billet was assigned, equal to 700 mm. The velocity of ram was increased to 5 mm/s. 3 process with the same tool design were simulated until 1 active record of simulation results. After profile flow simulation, tool set temperatures and temperature taper were assigned. Review only of the final simulation of profile flow with adjusted parameters of temperature-velocity mode via whole billet simulation will be presented below. New model is presented below in the figure 13.

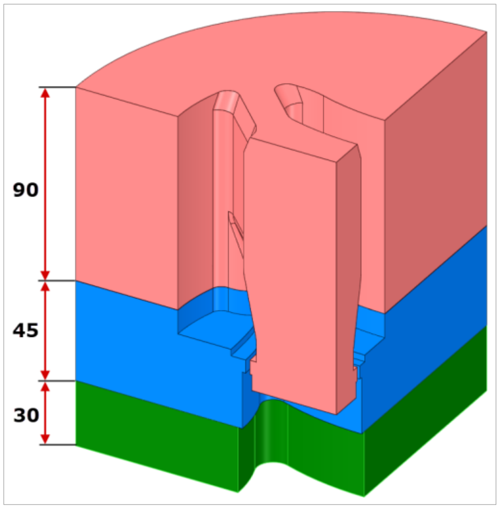


Fig. 13. New model

To achieve balanced and stable flow as well as a minimization of seam length (or distance from stop-mark value) new weld chamber was designed (Fig. 14).

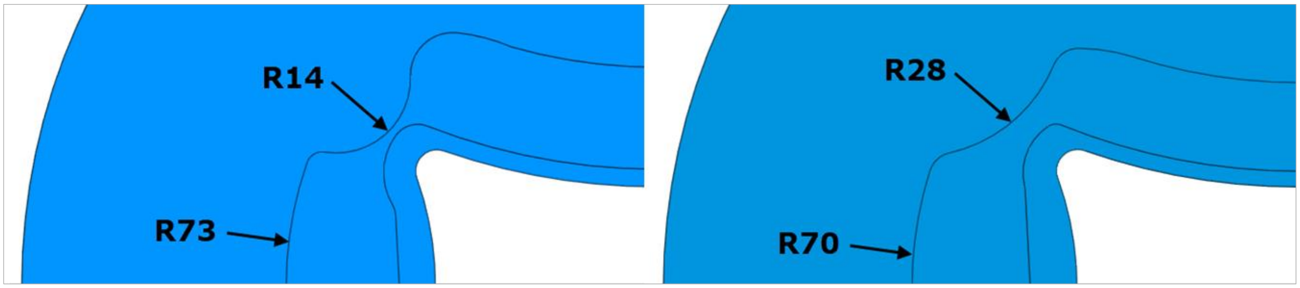


Fig. 14. New welding chamber (new model on the right)

New web cross-section was suggested (Fig. 15).

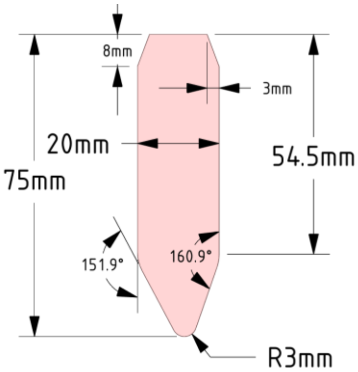


Fig. 15. New web cross-section

Welding chamber height was changed to achieve good welding quality of longitudinal seam (Fig. 16).

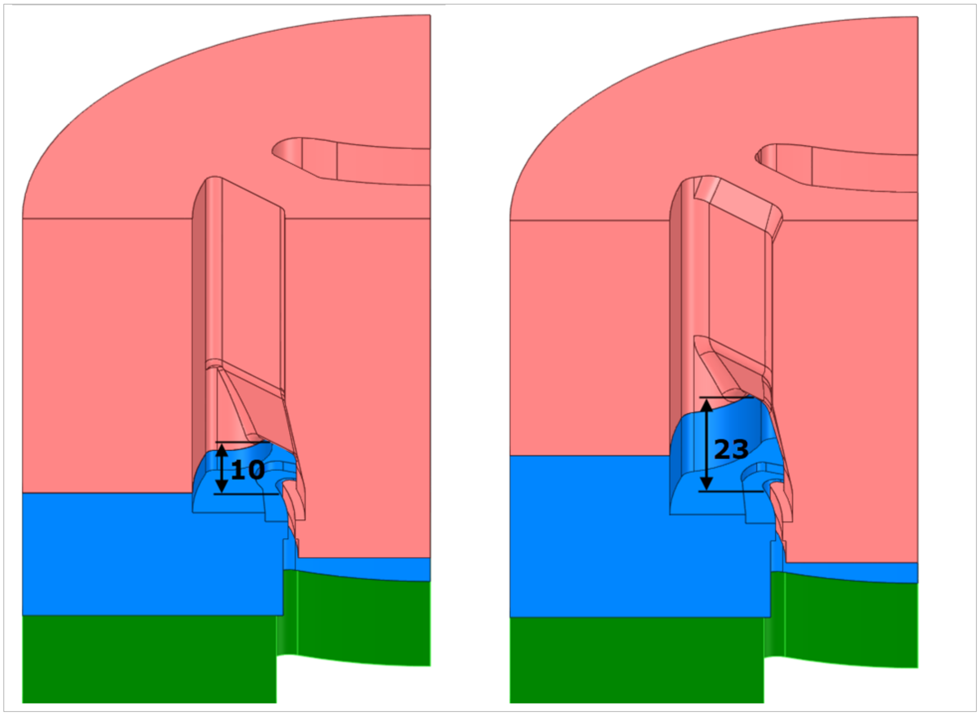


Fig. 16. Welding chamber height (new model on the right)

Using new design in simulation, stable flow of the profile was finally achieved. Figure 17 illustrates very low deviation in velocity of profile.

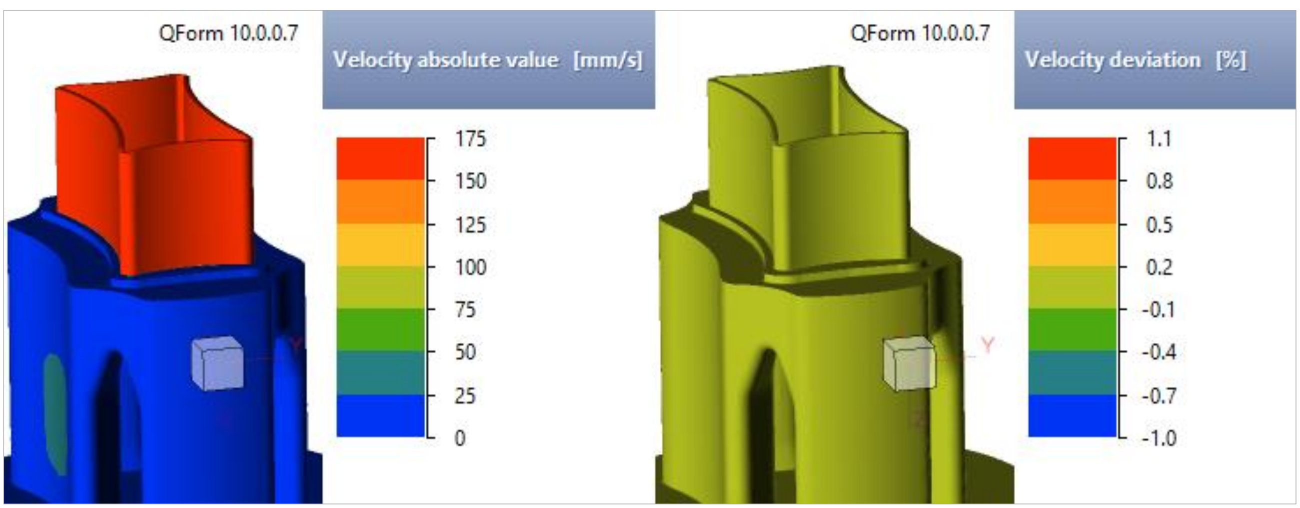


Fig. 17. Velocity deviation

The flow is stable, it can be clearly identified from the value of steady-state criterion which is close to 1; due to such velocity deviation the profile has no chance to have a contact with tool (Fig. 18). If during real extrusion trial, profile flow is a little bit different, die and mandrel bearings could be adapted to ensure a uniform flow.

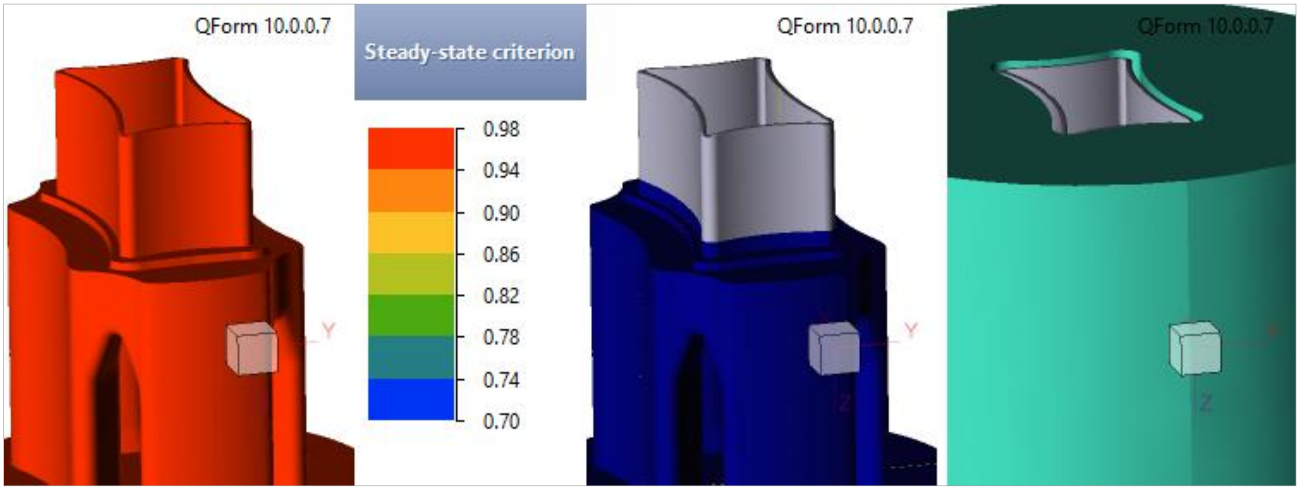


Fig. 18. Steady-state criterion and contact with tool

Die deflection in Z, X direction are within limits (Fig. 19).

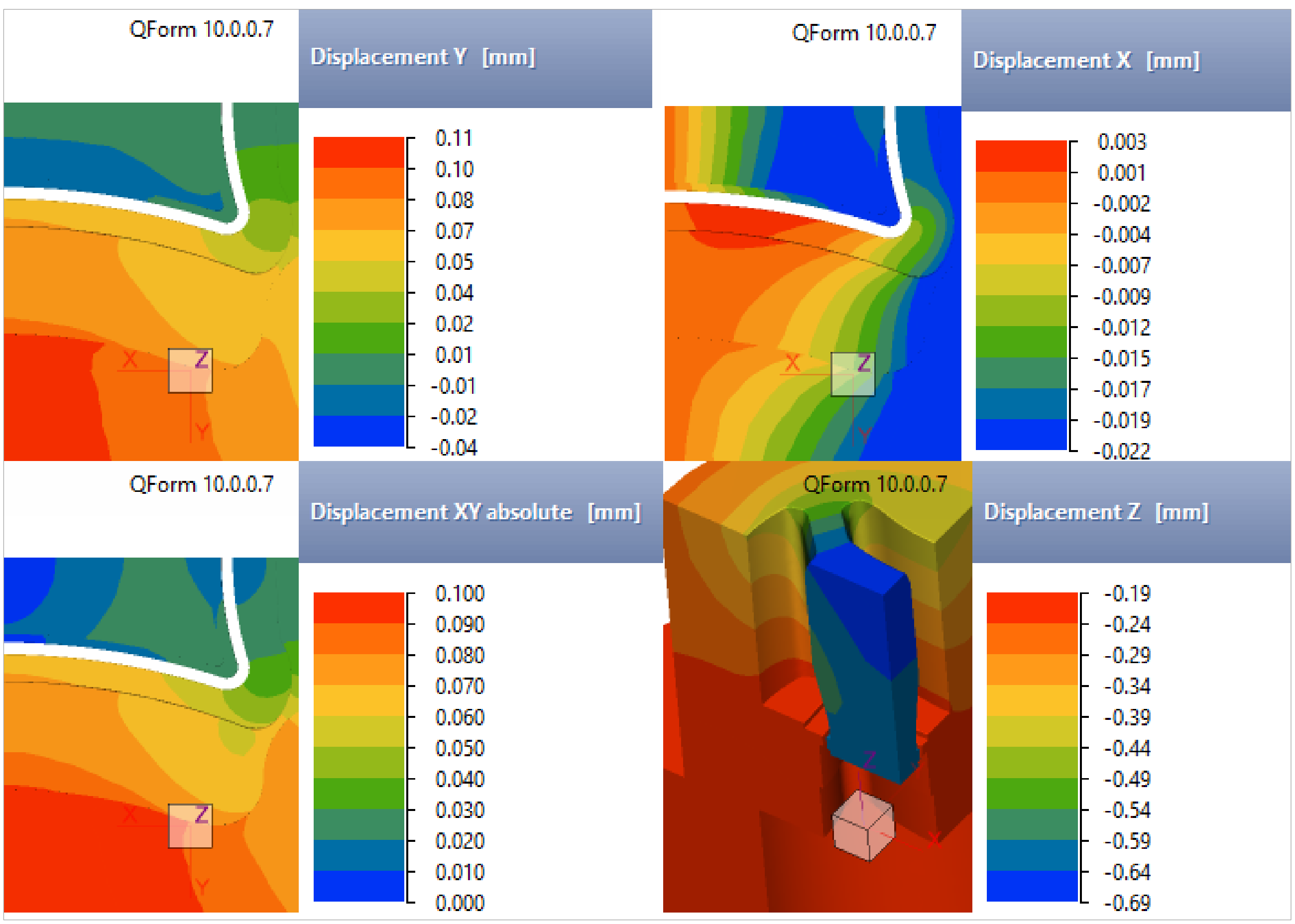


Fig. 19. Tool displacements

Displacement in Y direction that for the first design was earlier considered to be rather big, was compensated by shifting the outer radius of the top side of the profile by 0,025 mm (from the value of 124,47 mm to 124,495 mm). Compensating such a value, the required 2 ± 0.065 mm thickness can be achieved.

Stress-state of die should be analyzed to ensure a rigidity of the tool set. Triaxiality value is a special parameter which is determined by the effective stress and mean stress. Areas, where tension stresses are dominant are the most dangerous. Such places are typical ones where the crack could appear. Plastic areas in the mandrel are typically located under the webs. Such places should be analyzed considering probability of crack appearance.

Triaxiality value is in the safe limit, which is lower than 0,55 (Fig. 20, 21). Based on industrial experience and simulation analysis it is supposed that if the triaxiality value is less (or not too much bigger) than 0,55, nominal die life is guaranteed. Plastic areas under the webs don’t create «closed loops» areas.

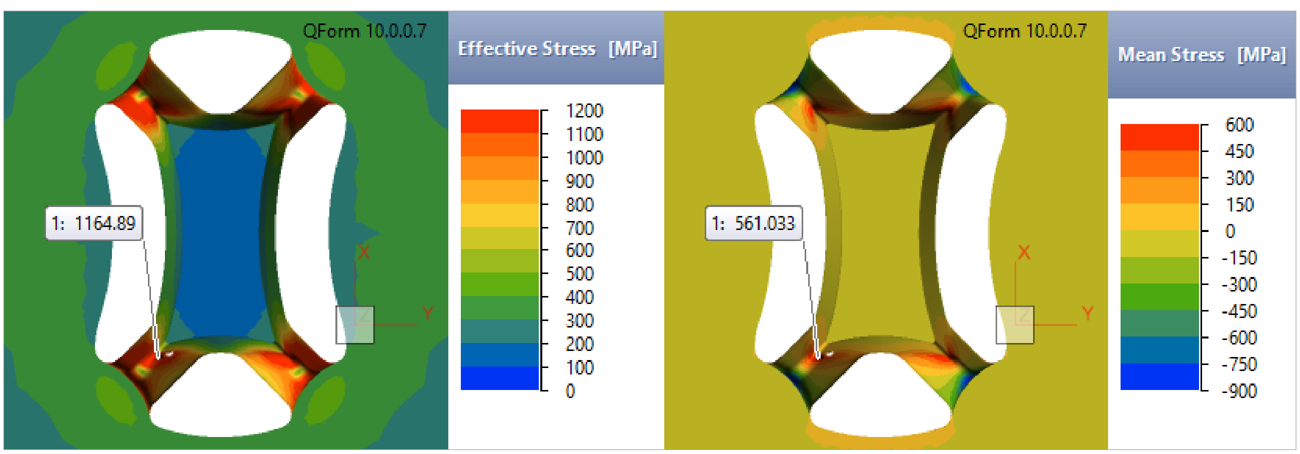


Fig. 20. Tool stresses

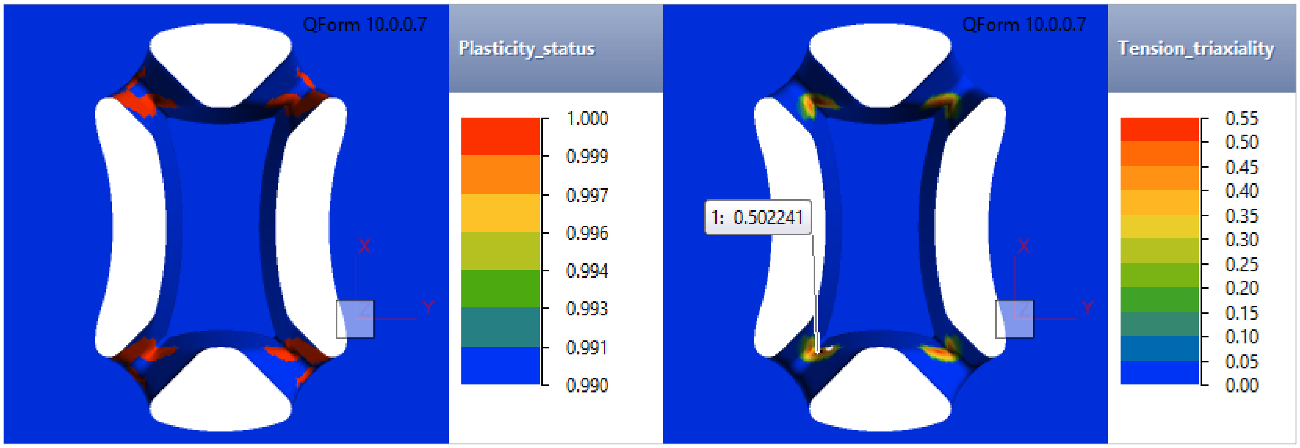


Fig. 21. Plastic area and triaxiality value

Whole billet simulation task was calculated. Second record of simulation results of such a task shows better correspondence with the reality (considering temperature distribution) than 1 record of profile flow simulation. 2 processes of whole billet simulation were calculated. Temperature-velocity mode parameters were assigned to ensure stable temperature and flow of the profile as well as stress-state of the die. For example, if temperature is grown very fast at some stage of extrusion process, flow trend could be changed, which, in turn, could result in «waving» (very unstable flow with appearance of «waves» form) of the profile.

First whole billet simulation was set up with the same process parameters from tables 1-3, with some changes indicated on the page 13. Second process, with taken into account compensated die orifice, was calculated with temperature taper of the billet (Fig. 22) as well as with new temperatures of the tool set. All process parameters of final process are presented in tables 6-8.

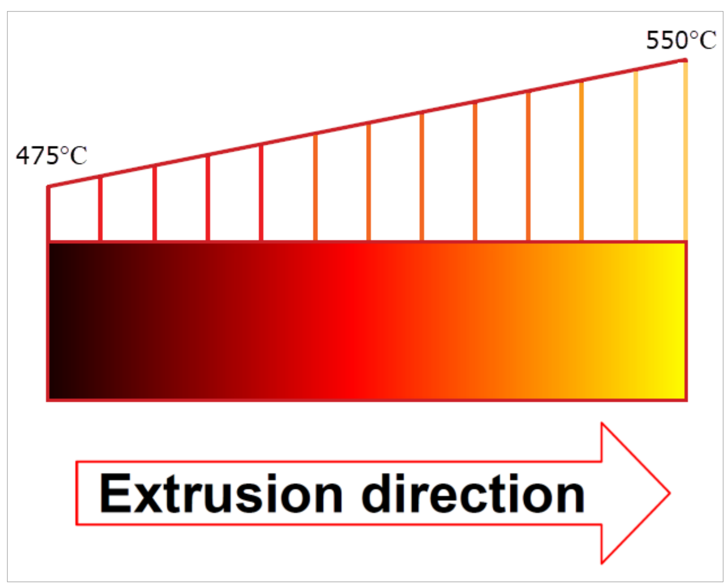


Fig. 22. Temperature taper of the billet

Comparison between the first whole billet simulation and the second one is shown in the figure 23, 25 respectively. In the figures 3 stages of the process is presented – 1) initial stage, 2) intermediate and 3) ending stages. It can be clearly seen that the first process has problem with overheating. In the contrary, it is not inherent to the second one. Change of the mean value of temperature during the first extrusion process is approximately 16°C. For the second – less than 10°C. Velocity deviation is changed insignificantly during the process (Fig. 24, 26), but the flow trend is stable.

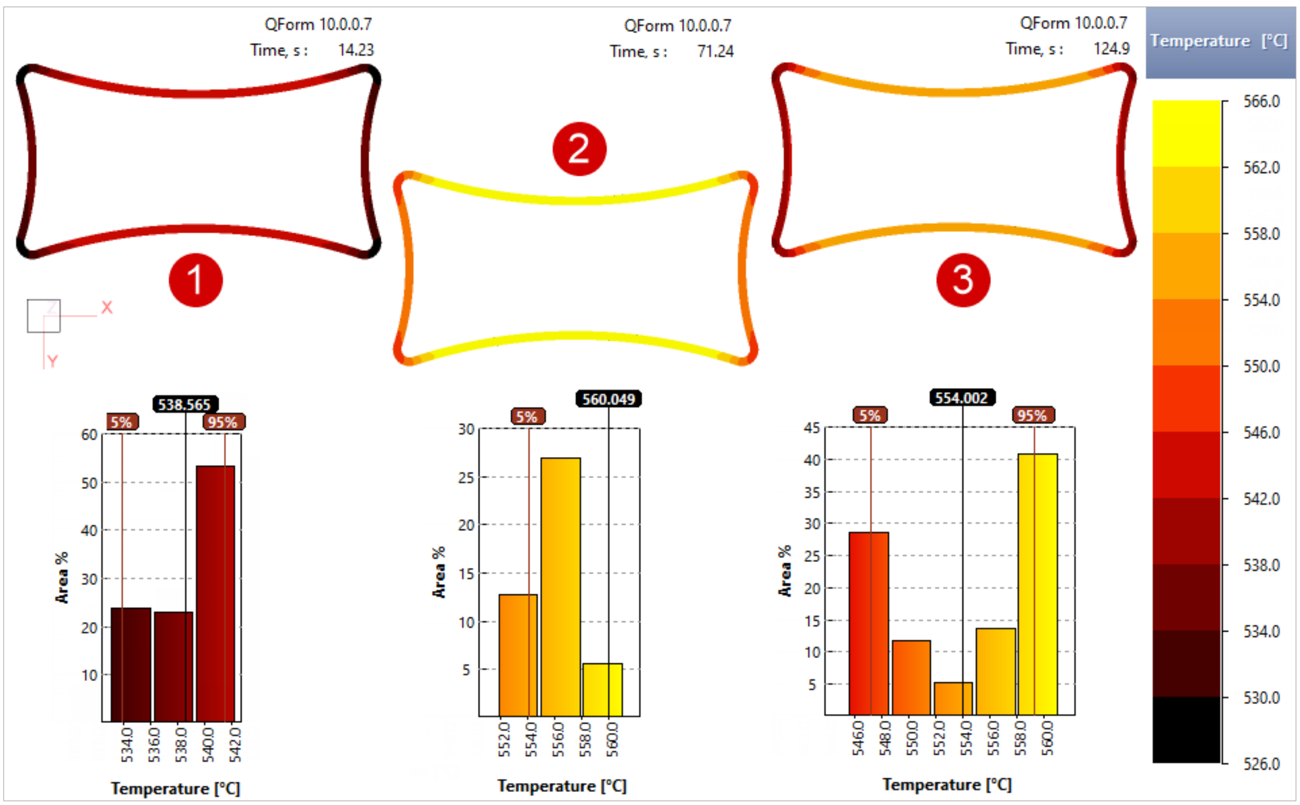


Fig. 23. Whole billet simulation. First process

Fig. 24. Whole billet simulation. Velocity deviation-1

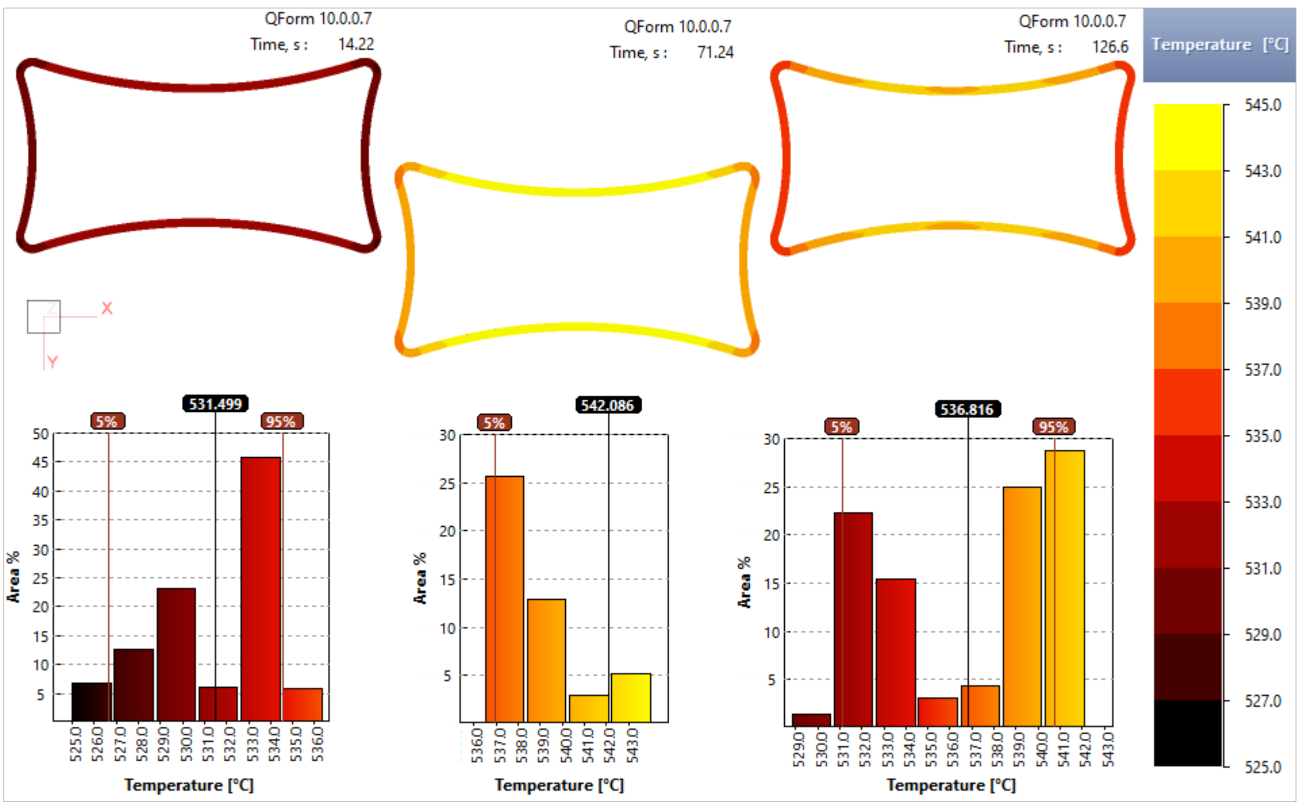


Fig. 25. Whole billet simulation. Final process

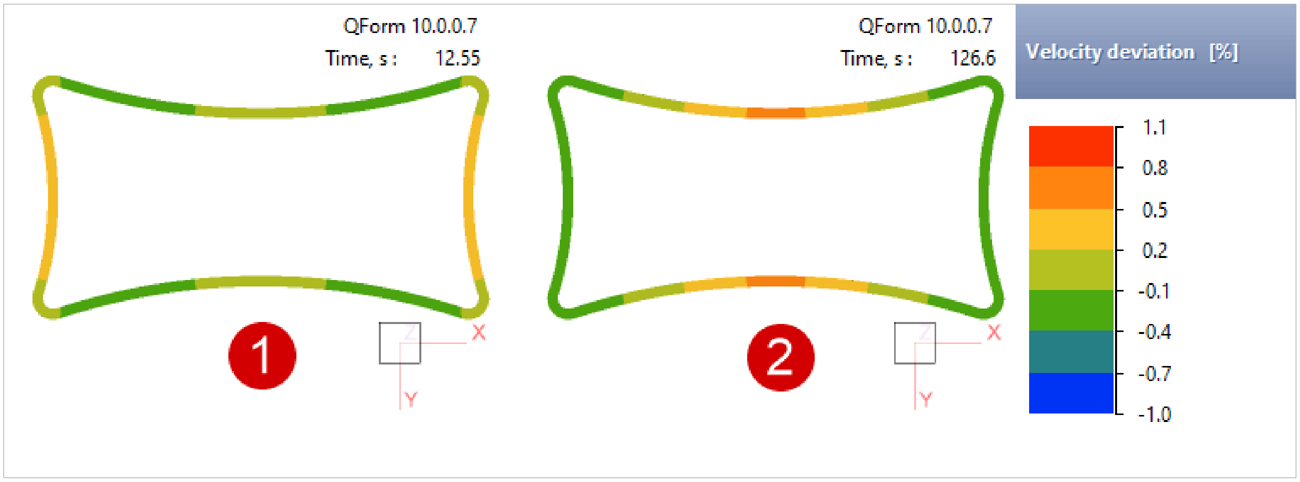


Fig. 26. Whole billet simulation. Velocity deviation-2

The length of transversal welding seam was decreased, since the shape of welding chamber was changed (Fig. 27).

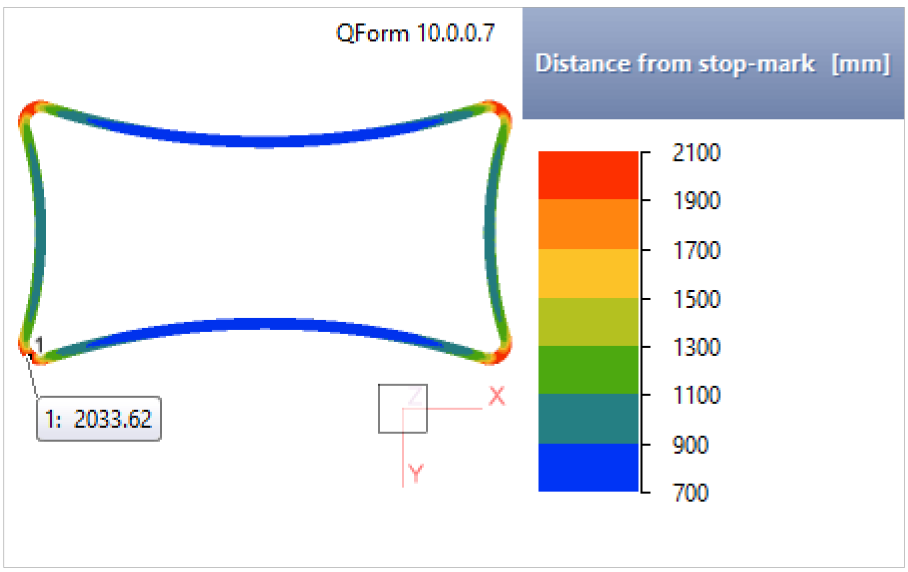


Fig. 27. Distance from stop-mark value of final process

The weld quality was also improved due to increased weld chamber height (Fig. 28). Based on experimental data, welding seams with quality value over 1 have structurally welded bondings. Moreover, based on the analysis of welding quality distribution, there will be no visible welding lines along the profile.

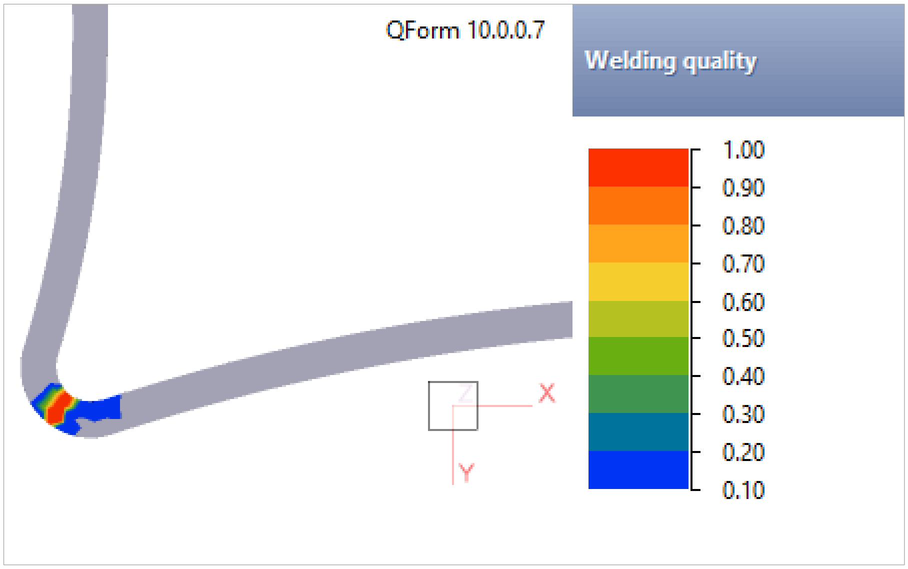


Fig. 28. Weld quality

Extrusion load is still less than nominal press load, die set load is approximately 8,5 MN (Fig. 29).

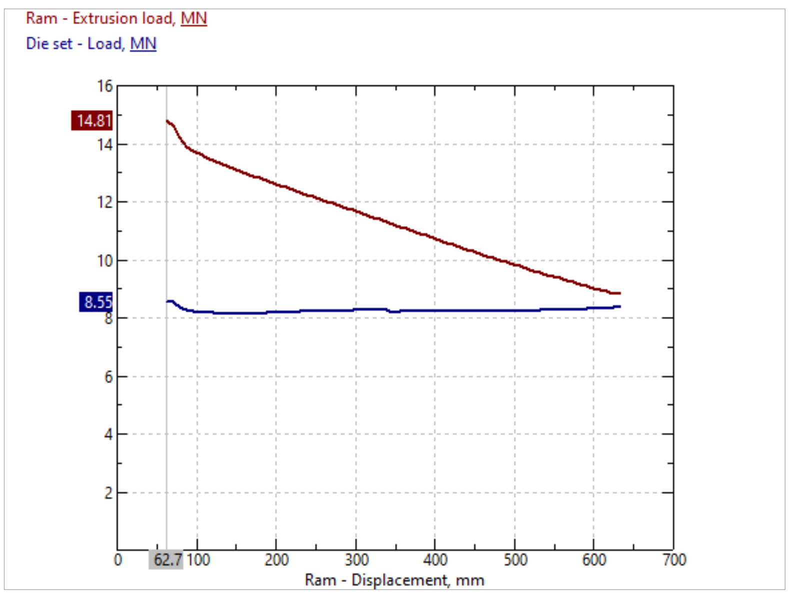


Fig. 29. Load check

During temperature-velocity mode selection, compensation of die orifice displacement was also provided. Using CAD, it is possible to measure overall dimensions of deformed die orifice as well as die deflection (Fig. 30). As it was pointed out earlier, in order to achieve required product accuracy,

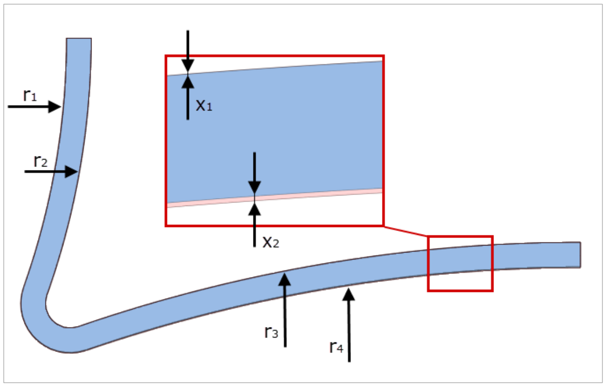


Fig. 30. Tolerances

By means of CAD initial die orifice contours were shifted in the direction of its displacement. As it was presented on the figure 19, only one dimension should be optimized. This dimension is r_4 which can be seen in the figure 30. By shifting the outer radius of the top side of the profile by 0,025 mm (from the value of 124,47 mm to 124,495 mm). If we consider bigger value of compensation, it leads, in turn, to higher value of thermal effect of deformation, leading to higher gradient of temperature distribution in the profile cross-section. Compensating such a value, the required $2{,}024 \pm 0.065$ mm thickness was achieved. The results are presented in the table 4.

Initial dimensions, mm	Real dimensions (maximum deviations during the whole process), mm
$2{,}024 \pm 0{,}065$	$\approx 2{,}015$
$61{,}23_{-0{,}07}$	64,25
$63{,}25_{-0{,}045}$	63,27
$124{,}47_{-0{,}1}$ (without +0,025 mm taken into account)	124,415
$126{,}5_{-0{,}08}$	126,43

Table 4. Profile dimensions

It should be strictly pointed out that the final dimensions are not only dependent on die deflection, but also dependent on cooling/quenching parameters. Let's consider that cooling is perfect. If so, the final product dimensions are in tolerances.

Defect of underfilling was not found (Fig. 31).

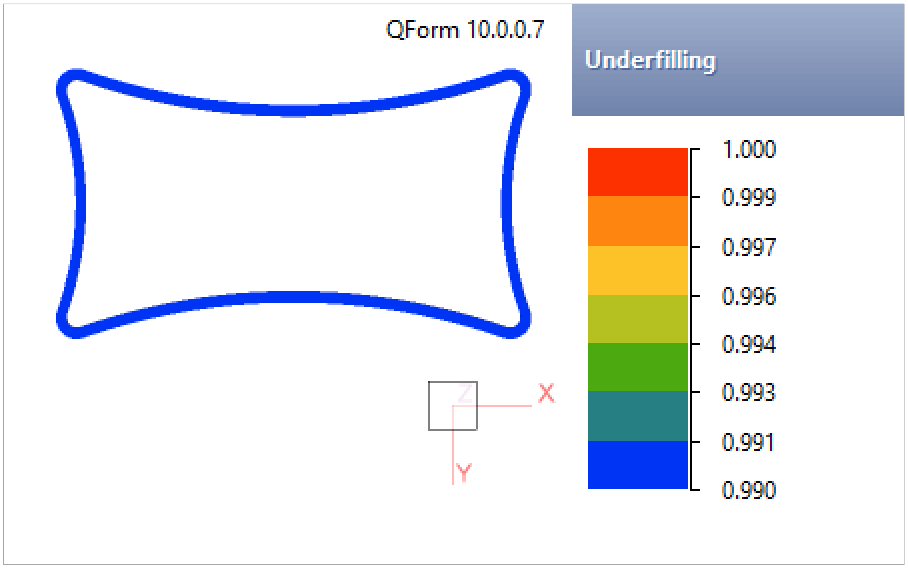


Fig. 31. Underfilling

Analyzing streaking lines distribution, the probability of streaks appearance can be predicted. The probability of visibility of streaking lines is indicated by the red color. Streaking lines are presented in the figure 32.

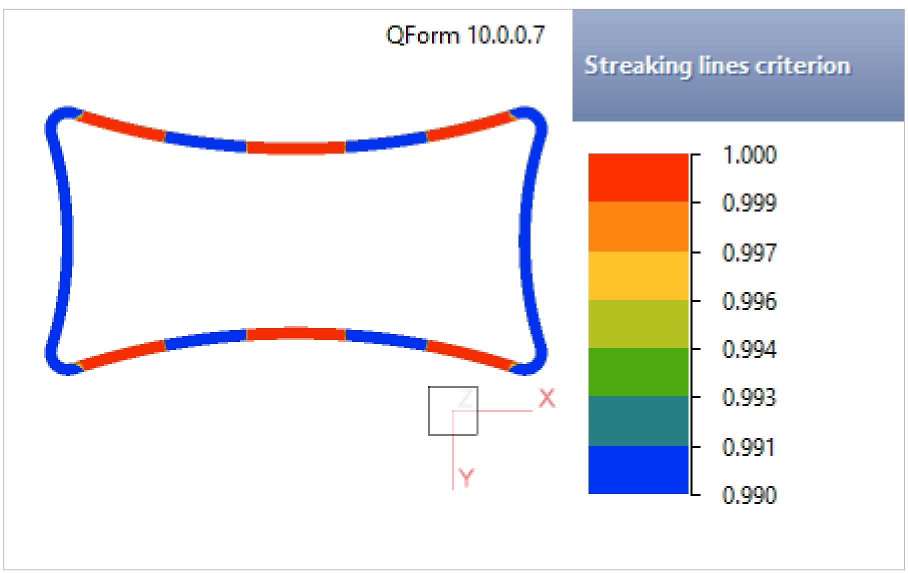


Fig. 32. Streaking lines

There are no special requirements for streaking lines visibility in the initial task, so the results in this matter can be considered as acceptable.

4. Industrial efficiency

Distance from stop-mark is a good value for analyzing the industrial efficiency. Visualization of stop-mark and transversal seam is presented in the figure 33.

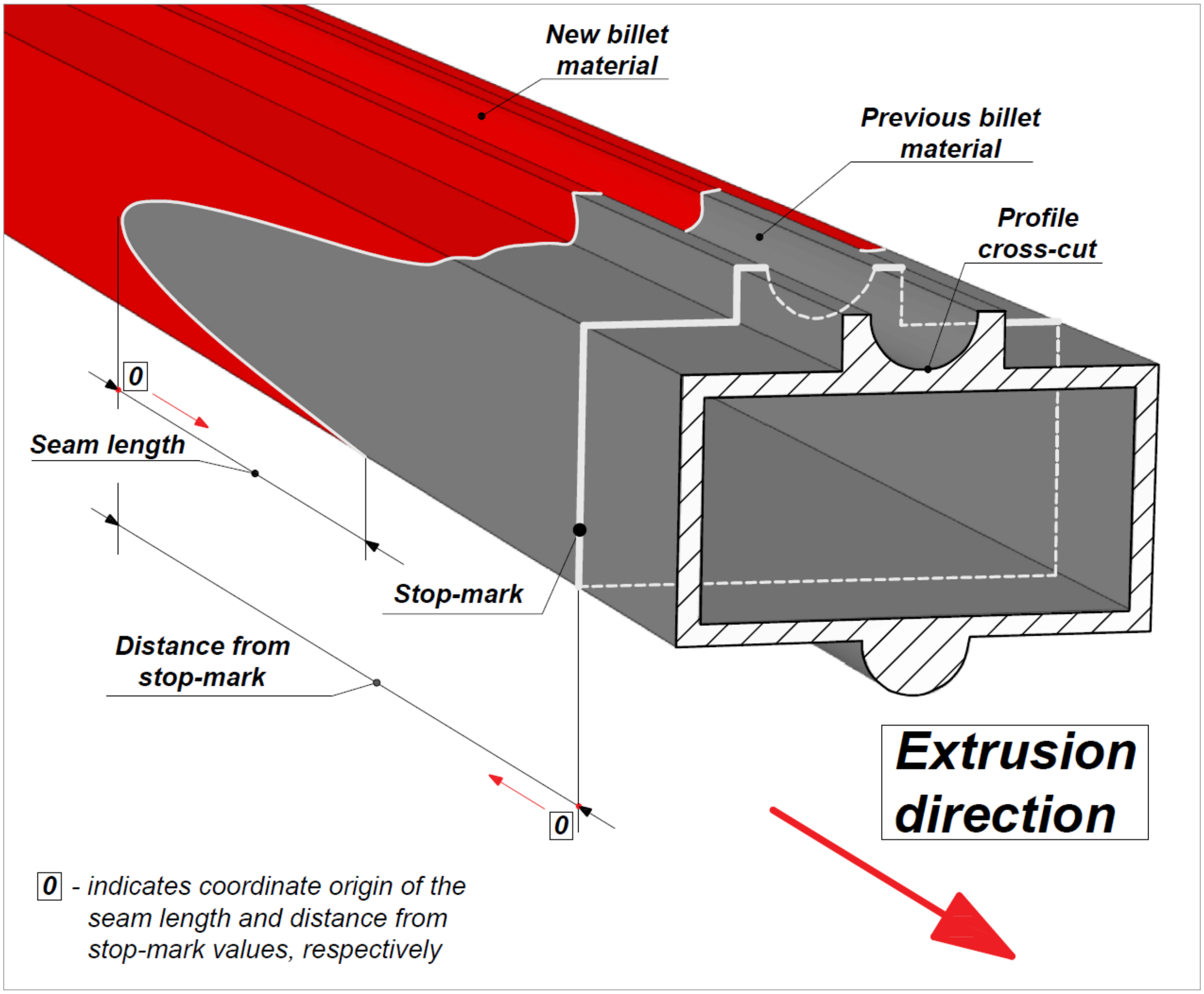


Fig. 33. Distance from stop-mark graph

Mix of two billet materials, in case of billet-to-billet extrusion, is present in the product in the interval of 700-2000 mm from the stop-mark (Fig. 34).

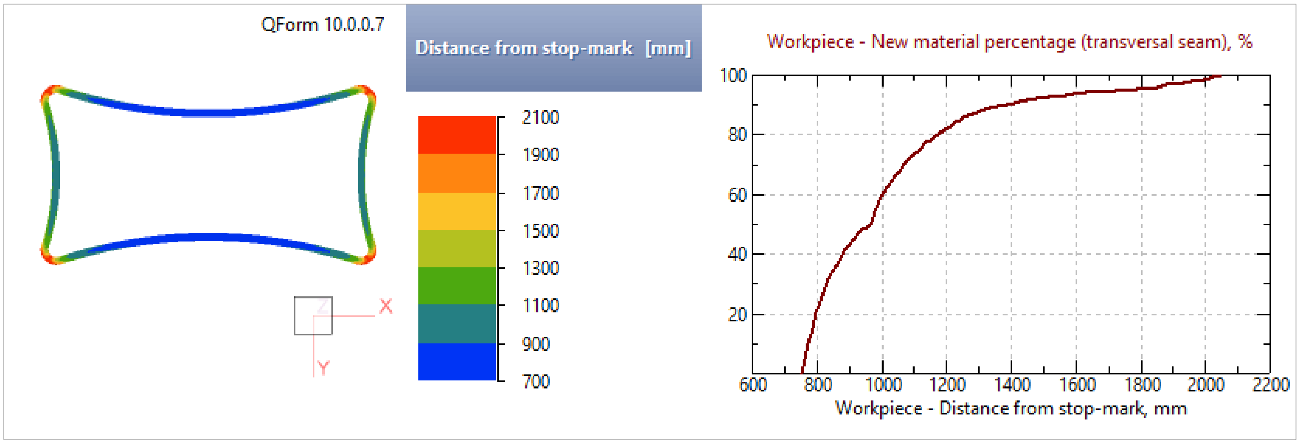


Fig. 34. Distance from stop-mark graph

Let’s calculate the number of billets that are necessary to complete the order. The industrial practice involves the scrap of 1000 mm before the stop-mark for skin contamination and, for the charge weld, 1000 to 3000 mm after the stop mark in relation to the profile extrusion ratio R: for R<30 1000 mm, for 30<R<40 2000 mm, for R>40 3000 mm. Therefore, in this case, a total length of 2000 mm should be discarded for each profile according to recommendations. The simulation shows a charge weld with a similar value of 2040 mm. Thus, to minimize the scrap and keeping the "safe gap", the value of 2150 mm can be taken as an accepted result. In order to limit the skin contamination within the profile, butt-end (B_{b-e}) was chosen equal to 1/6 of container diameter. Let's consider skin contamination by additional 200 mm of discarded profile length (B_s). After initial billet upsetting, the billet length becomes 635 mm (B_L), and so neglecting the butt-end, a total length of 607 mm is extruded. At this point, the percentage of billet length loss (billet scrap) for contaminations is evaluated dividing the profile scrap by the extrusion ratio:

$$B_{scrap} = \frac{Pr_{scrap} + B_s}{\lambda} + B_{b-e} = \frac{2150mm + 200mm}{37{,}9} + 28mm \approx 90\ mm \qquad (5)$$

where Pr_{scrap} – profile scrap, $B_{\mathrm{b-e}}$ – length of butt-end, B_s – additional length to consider skin contamination. Billet loss can be calculated according to the formula:

$$B_{loss} = \left(\frac{B_{scrap}}{B_L}\right) * 100\% = \left(\frac{90}{635}\right) * 100\% = 14{,}17\% \qquad (6)$$

Thus, industrial efficiency is:

$$Pr_{ef} = 100\% - B_{loss} = 100\% - 14{,}7\% = 85{,}3\% \qquad (7)$$

Therefore, for each extruded billet, of the billet length is transformed in «good» profile. Therefore, for each extruded billet (except 1st one), 85,3% of the length is transformed to a «good» profile. The total batch length is:

$$B_{length} = \frac{B_{mass}}{density_{Al} * A_{profile}} * 100\% = \qquad (8)$$

$$= \frac{35000kg}{2710\frac{kg}{m^3} * 560{,}05 * 10^{-6}m^2} = 23060\,m$$

where B_{mass} – batch mass from the initial data. The number of billets to complete the order:

$$N_B = \frac{B_{length}}{(1 - B_{loss}) * B_L * \lambda} = \frac{23060m}{0{,}853 * 635mm * 37{,}9} = 1124 \qquad (9)$$

5. Heat treatment

Figure 35 shows the differences in the required cooling rates to ensure quenching in order to create a solid solution of magnesium and silicon by preventing the precipitation of Mg_2Si particles [5].

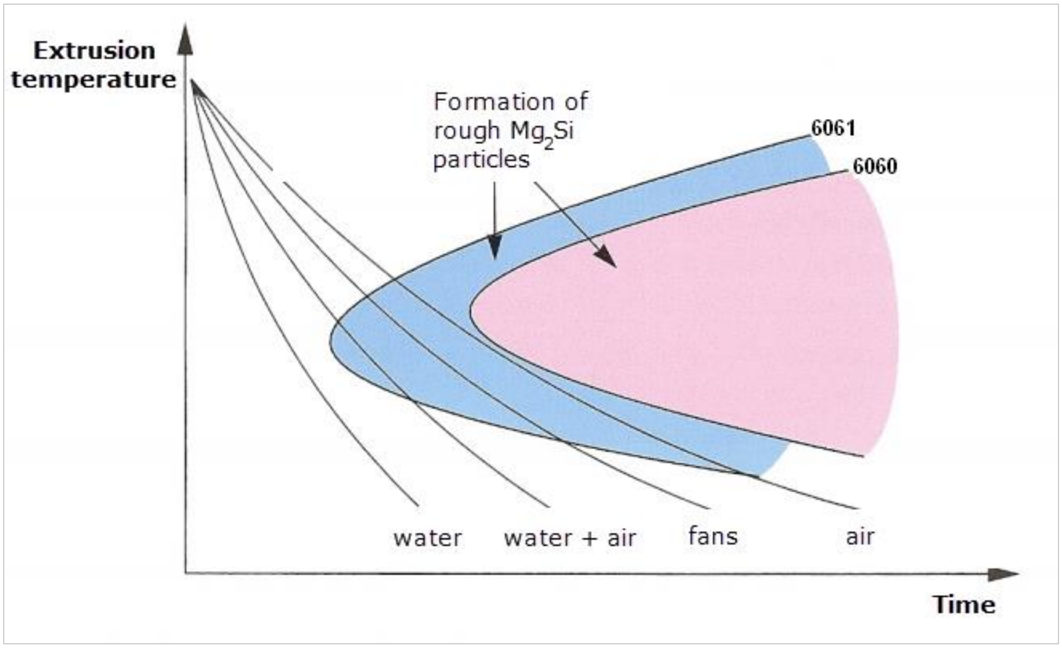


Fig. 35. Formation of particles

Recommended cooling methods and minimum cooling rates for Alloy 6061 as are shown in Table 5.

Alloy ASTM	minimum cooling rate ºC/min	Cooling method	
		Solid profile thickness less than 10 mm	Solid profile thickness more than 10 mm
6061	300	Air or fans / Water + air	Water spray cooling

Table 5 – Recommended Quenching Rates and Cooling Methods for alloy 6061.

As can be seen, for Alloy 6061:

• with a thickness of up to 10 mm, cooling with air or fans, water-air mixture (considering the thickness) is sufficient

• with a thickness of more than 10 mm thick water spray cooling is required

Natural aging provides the best strength properties as well as optimal rust resistance for the end product. However, using artificial aging makes possible to achieve even higher strength at the cost of rust resistance reduction. Consequently, depending on the sphere of application and environmental reasons it is up to the production engineer to decide what type aging is appropriate to use.

The initial profile has a thickness of 2 mm. Based on production experience, for such profiles it will be sufficient to use only air cooling or fans. The cooling system parameters considering the profile cross-section can be assigned after cooling-quenching simulation in QForm.

6. Resulting process parameters

Attribute / Object	Diameter, mm	Length, mm	Geometry type
Container	166	-	-
Billet	162	700	-
Die set	240	165	STEP
Die holder	400	-	-
Bolster	400	110	IGS
Sub-bolster	400	110	-
Pressure ring	200		

Table 6

Attribute / Object	Temperature, °C	Material
Billet	475	AA6061
Die set	435	H13
Bolster/Sub-bolster	200	
Ram	410	
Container	435	
Temperature taper	75	-

Table 7

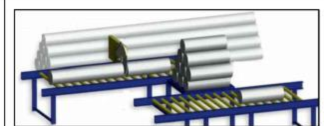
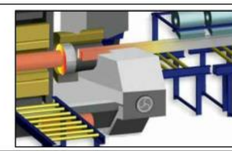
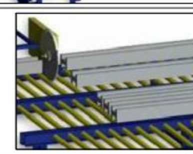
Ram velocity	5 mm/s

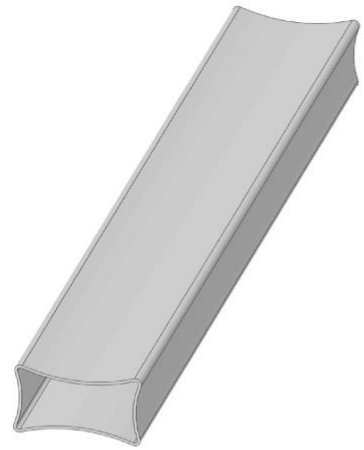
Table 8

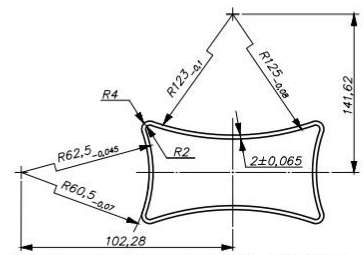
7. Reference list

1. Library of Congress Cataloging-in-Publication Data - Extrusion / editors, M. Bauser, G. Sauer, K. Siegert. — 2nd ed.
2. Library of Congress Cataloging-in-Publication Data – Saha, P. (Pradip) Aluminum extrusion technology / Pradip K. Saha.
3. Intermet Engineering – Extrusion of aluminium alloys / Scherba V.N. (in Russian).
4. QForm Extrusion user’s manual.
5. ASM Specialty Handbook – Aluminum and Aluminum Alloys / J. R. Devis

Attachment A

Operation Nº	Operation Name	Equipment	Operation parameters	Illustration
1	Billet heating	Open gas furnace	Heating temperature: 480°C	
2	Billet cutting	Hot shears	Load ≈ 150 kN	
3	Boron nitriding	Equipment for hot boron notriding		
4	Extrusion	Horizontal extrusion press 20 MN	Ram velocity – 5 mm/s Cooling: Fans or water mist quenching	
5	Shearing	Circular saw		
6	Stretching	Stretching machine		
7	Artificial aging	Aging furnace	Aging temperature: 200°C Aging time: 6 hours	





TOLERANCES UNLESS OTHERWISE SPECIFIED:
ALL DIMENSIONS ±0,05
ALL DIMENSIONS ARE IN MILLIMETERS

Cross-sectional area (mm^2)	Theoretical mass of 1m of product (gr)	Circumscribed circle diameter (mm)	Outside perimeter (mm)
560.05	1490.6	101.57	282.3

1. Other requirements according to GOST 22233–2001
2. Temper designation – T5

The International Students Olympiad in Extrusion Technologies 2021

AA6061

Attachment B