QFX simulations

Simulation of piercing processes in a helical rolling mill using the QForm software

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Cross roll piercing is a process for producing hollow tubes from initially cylindrical billets. Typically, a two-pass process is used in cross roll piercing, but with the use of computer simulation it may be possible to identify a one-pass procedure that reduces machine time and increases productivity. QForm is a commercially available finite element code that can be used to handle large-deformation forming processes. This paper details the development of a QForm computer simulation of a one-pass piercing process, and compares the simulation results with results obtained experimentally. This approach to the development of the production process can reduce try out costs when designing new piercing regimes in order to implement them at the present production facilities.

Introduction

Currently, the finite element method (FEM) is widely used by industrial plants to simulate manufacturing operations, including metal forming operations. For forming processes that involve large contact forces between workpiece and tooling, the accuracy of the predicted stresses and strains is typically increased when the tooling is considered to be deformable. As such, finite element codes that can handle deformable tooling have wider application. Using such systems makes the development of new products easier and reduces costs, allows forecasting out-of-specification conditions and identification of possible risks in the forming operations.

The QForm software package is a finite element code used in JSC VMZ for solving a wide range of technological problems including the cross roll piercing process. The software was created by QuantorForm Ltd., a Russian company that has been developing software for computer modelling of metal forming processes since 1991. Their products are being used in various branches of industry all over the world [1].

QFORM uses a Lagrangian mesh for predicting the deformation of deformable bodies. The inclusion of deformable tools in the simulation should increase the accuracy of the predictions compared to simulations where the tools are considered to be rigid. Several authors have reported that QFORM predictions for metal forming process agree favourably with practical data [2, 3].

Finite-element model of cross roll piercing process

The simulation process in QForm may generally be divided into three stages.

At the first stage, three-dimensional models of the tools and the workpiece are created in an appropriate CAD-system and stored in IGES or STEP file formats. The CAD data is read into QFORM which can be used to further prepare the model by:

1. initially positioning the solid bodies relative to each other
2. eliminating any existing geometric defects
3. meshing the models
4. specifying the axes and the rotation directions of rolls, rollers, etc.,
5. setting symmetry properties if any

For this work, we used Compas 3D package as a CAD system for constructing the geometry of all the bodies involved (see Figure 1).

At the second stage, additional material properties and parameters that define the forming process are input. These include boundary conditions and initial conditions such as temperatures and velocities. Once all of the information has been supplied, the analysis can be launched. During the simulation, the computer solves a system of partial differential equations that simulate a plasticity problem.

In the last stage the model predictions are examined using the post-processor. Typical parameters to be observed include:

1. contact areas,
2. stress and strain tensors,
3. velocity fields for deformable materials,
4. temperature of the workpiece and/or tools,
5. tool reaction forces,
6. the final workpiece shape,

The post-processor can also be used to identify any reasons for failure of the calculation (if applicable).

For simulations of the piercing process in cross rolls, the calculation results of interest include:

1. geometric parameters of shells,
2. helicoid line steps on the outer workpiece surface,
3. piercing machine time,
4. twist of the billet in the roll gap, and
5. predictions of surface waviness.

Figure. 1. a) Preparation of 3D models of tools in the CAD system; b) Finite element mesh generation, building up the deforming zone in QForm

The computer model of the piercing stand «TPA 70–270» was built for simulation purposes. This stand is located in JSC VMZ shop No 3, and is

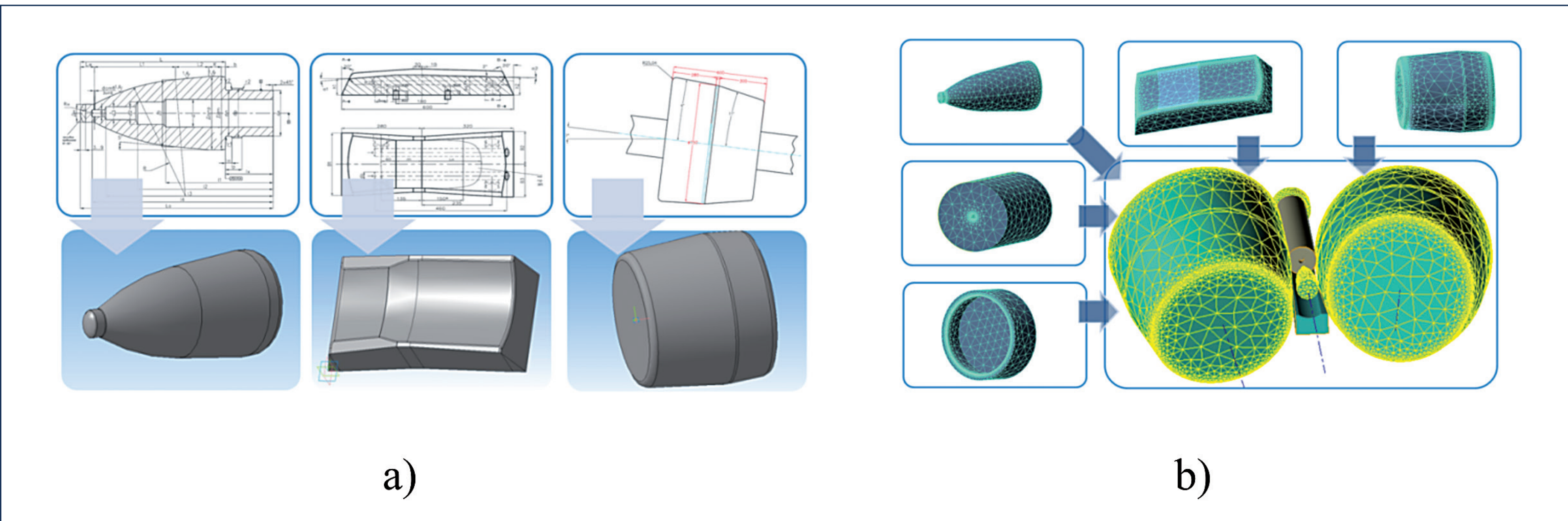


Figure 1.

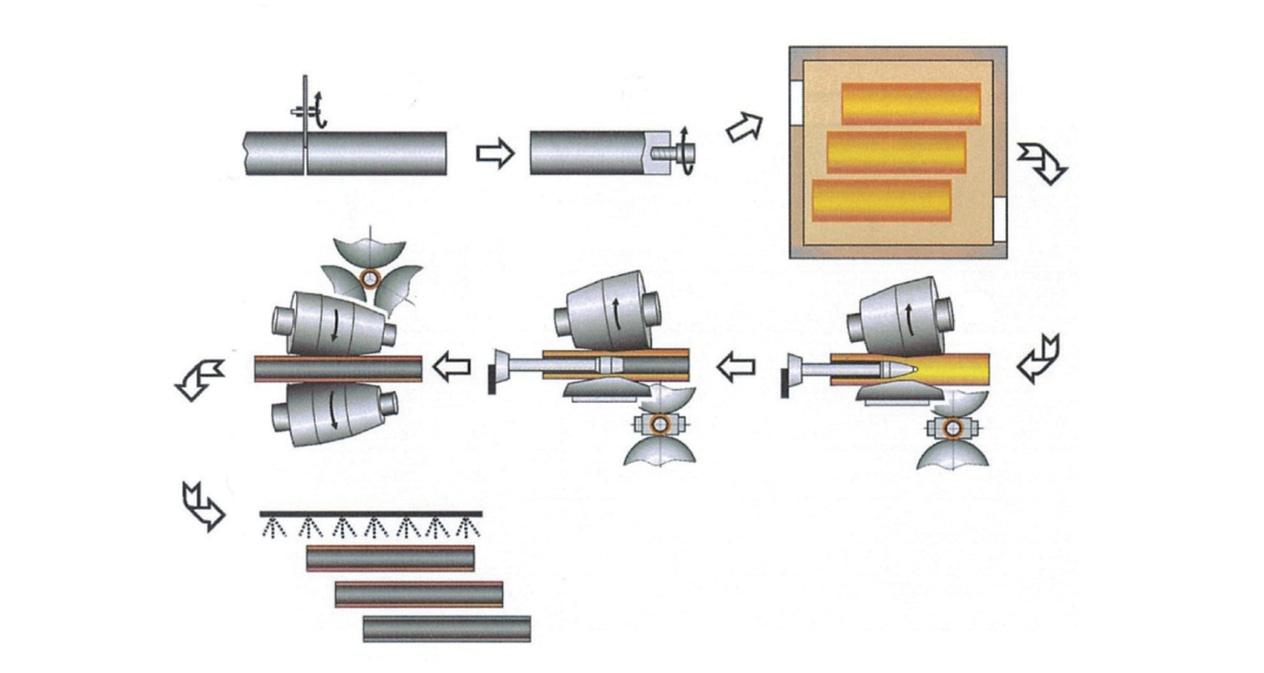


Figure 2.

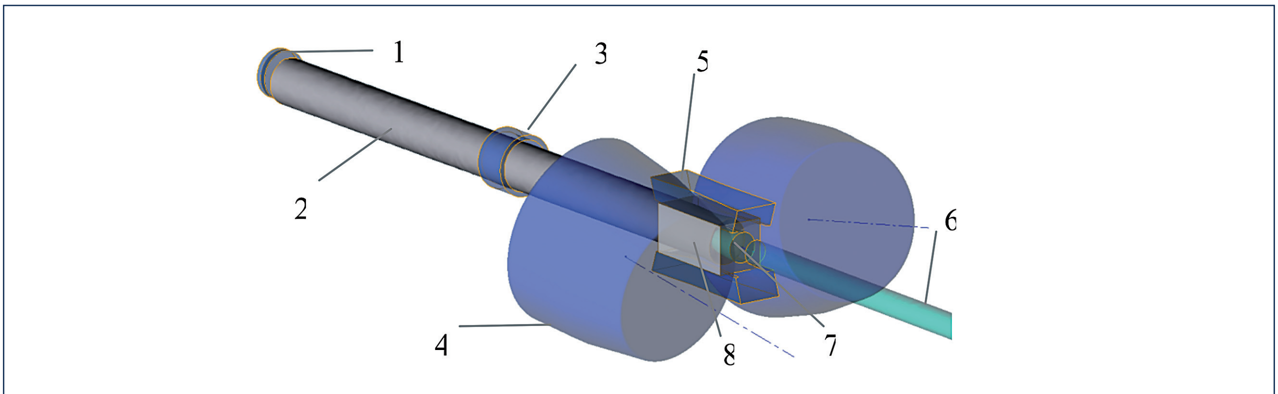
used for the production of hot-rolled seamless pipes to be used for pipe couplings (casing and tubing). A hot-rolled or continuously-cast round billet with diameter from 80 mm to 250 mm is utilized as an initial workpiece for production of pipes from 70 mm to 270 mm in diameter and wall thickness from 8 mm to 28 mm. Normally, piercing of a solid bar in this stand is made in two passes. In the first pass the solid billet is rolled and contacts a plug mounted on a rod. As the workpiece moves forward under the force of the cross rolls, the workpiece makes contact with, and is pierced by, the plug, thus forming a hollow tube (or shell) from the originally solid workpiece. After the first pass, the plug is replaced with a different plug, and the distances between the rolls and guides are adjusted for the second pass. During this time, the half-rolled shell is supplied to the front side of the stand for the next pass.

Fig. 2. Process flow diagram of production of tubes on the TPA 70-270

The 3D CAD models of the working rolls, the guide shoes, and two plugs are made according to the actual sizes of the TPA 70-270 tools. The assembled model of the aggregate is shown on Fig. 3.

Fig. 3. Geometrical model of the workpiece and the tools of piercing stand TPA 70-270 for QForm simulation

Figure 3.



1 pusher; 2 workpiece (billet); 3 entry guide; 4 working rolls;
5 guide shoes; 6 plug rod; 7 plug; 8 box for refining the FE mesh

The workpiece material C45 (plain carbon steel C 0.45 wt %) was selected from the QForm database of deformable materials. An isotropic hardening model was used for simulating the plasticity of the workpiece. The contact friction between the workpiece and tools is taken into account by the Coulomb law. The "pusher" moves towards the main tools at a constant speed that is apparently lower than the rolling speed of the shell and is used for initially pushing the workpiece into the rolls. Thus the "pusher" action terminates as soon as the workpiece head is captured (gripped) by the working rolls. A forced surface mesh refinement on the workpiece and the tools has been implemented in the deformation zone, which contributes to a more accurate solution of the contact problem. The size of surface FE was no more than 7 mm for simulations described below.

The following assumptions have been made for simulation purposes:

- The tools were assumed to be rigid;
- Friction coefficient is isotropic and constant throughout the entire simulation process;
- Heat transfer between the workpiece and tool does occur; however, it is significantly simplified (thermal conductivity takes place only in a thin layer of the workpiece — a few transverse elements' size thick).

Preliminary calculations of two pipe sizes have been performed: ø 270 x 44.7 mm (diameter x wall thickness) from the round billet of ø 250 x 2800 mm (diameter x length, for a total mass of 1080 kg) and ø 200 x 31.8 mm from the round billet of ø 190 x 2850 mm (657 kg).

The simulation was conducted in order to determine the piercing mill deformation zone settings (distance between pairs of rolls and guide shoes, the front distance of the plug, rotation speed of the rolls), that would provide satisfactory values of outer diameter and wall thickness of the finished tube in a single pass. The limit deviation for the outer pipe diameter is ± 1 % of the nominal value, for the wall thickness is ± 10 %. Variations in wall thickness of the pipe should not exceed 3 mm (variations in wall thickness is the difference between the maximum and minimum wall thickness in the same cross-section of the pipe).

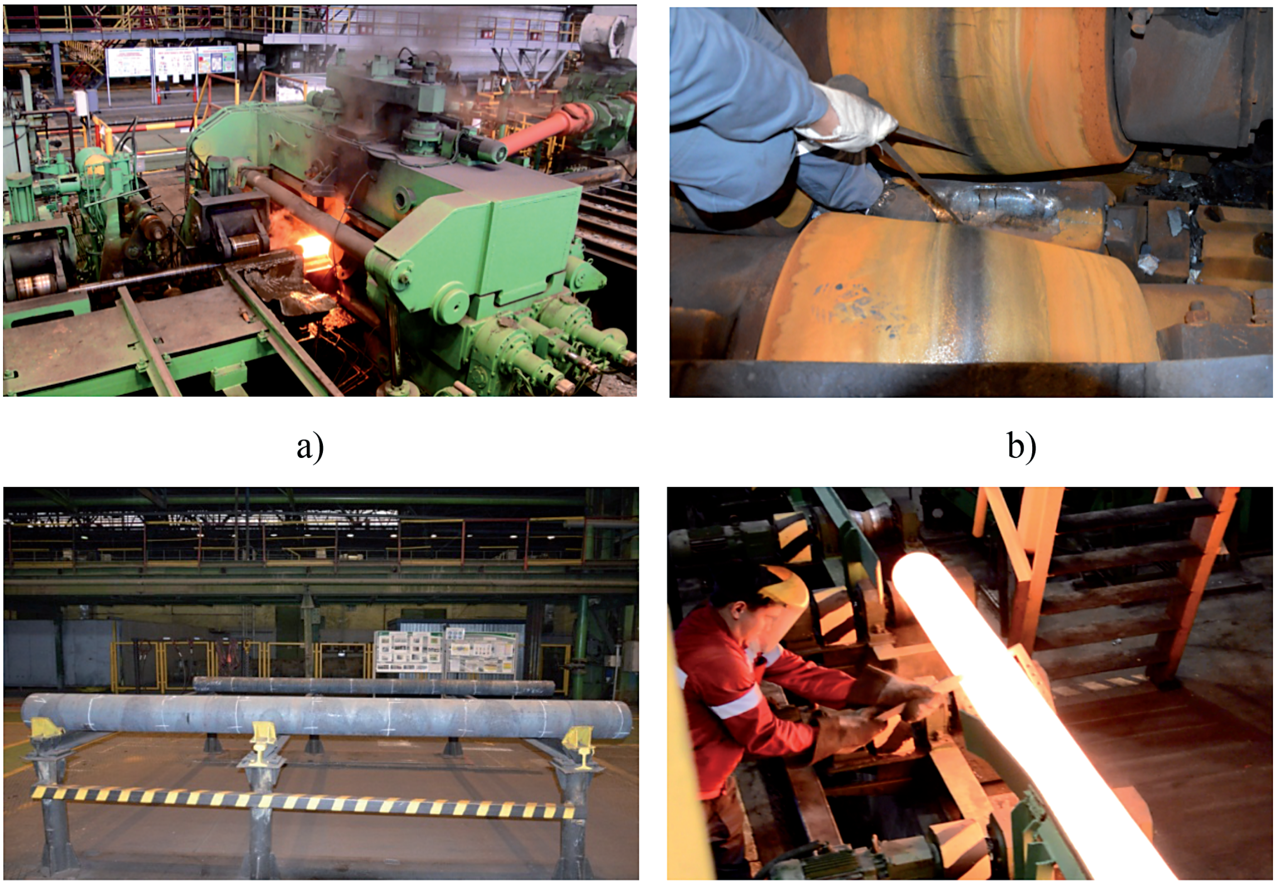
The outer diameter of the simulated rolled shells was chosen so as to take into account their subsequent reduction in the sizing stand and thermal shrinkage due to cooling. To obtain the predefined outer dimension of the virtual shell, the location of the tools has been adjusted in the same manner as if it were done in the real stand.

Calculation time for simulation of a piercing pass came to 33–35 hours for a billet originally 600 mm long.

The setup parameters for piercing these billets by only one pass in contrast to normal two passes (piercing itself and kind of reeling) were determined. Use of a single pass saves machine time, increasing productivity and reducing production costs providing that the geometry of the obtained shells is satisfactory.

Parameter	Simulation	
	Billet ø 250 mm	Billet ø 190 mm
Nominal dimensions of the pipe to be produced	ø 270 x 44.7	ø 200 x 31.8
Minimal distance between rolls, mm	228	173
Minimal distance between guide shoes, mm	273	200
Ovalization ratio	1.2	1.16
Reduction at the point of roll neck, %	8.8	8.9
Reduction in front of the plug nose, %	6.4	6.1
Plug front distance, mm	50	45
Plug diameter, mm	168	126
Rolls rotational speed, rpm	40	
Feed/rolling angle, °	12/7	
Friction coefficient: between the workpiece and the rolls	0.4	
Friction coefficient: between the workpiece and the guide shoes, the plug, etc.	0.25	
Initial temperature of the tools, °C	150	
Initial temperature of the billet, °C	1180	
Workpiece – tool heat transfer model	simplified	

Table 1. Configuration parameters of the model for rolling experimental pipes



a) b) c) d)

Fig. 4. a) Piercing of the rough tube ø200 x 31.8 mm at the TPA 70-270; b) Adjustment of the deformation zone; c) Pipe on the examination table before the measurement of wall thickness d) Pipe measuring in a hot condition after the piercing mill

No. of pipe	Diameter of pipe the "head", mm	Pipe diameter the "mean", mm	Diameter of pipe the "tail", mm	Wall thickness the "head", mm	Wall thickness the "tail", mm	Length, mm
1	198.5/198.65	198.33/198.65	199.6/199.2	35.0/36.5	35.0/35.2	4670
2	199.7/199.95	198.9/199.0	198.7/199.35	29.0/29.5	33.5/34	4840
3	271.35/270.93	-	271.07/271.4	48.0/50.2	49.2/50.0	4050
4	271.4/271.72	-	270.82/270.37	47.2/49.0	47.8/50.2	4170
5	271.2/271.63	-	269.93/270.35	44.8/47.5	47.5/48.0	4360
6	270.95/270.08	-	269.58/269.83	46.7/45.3	45.8/46	4260
Note: Tools for measuring of geometrical parameters: Vernier calliper with division value of 0.1 mm, micrometre with division value of 0.05 mm, pipe wall thickness gauge with division value of 0.05 mm (max. distance of measuring points from pipe end is 250 mm);						

Table 2. Measurements of the geometrical parameters of experimental pipes after cooling

Industrial experiment

Two billets of 190 mm diameter and four billets of 250 mm diameter on the TPA 70-270 (Fig. 4) were pierced according to the setup parameters presented in Table 1. In order to adjust these parameters, the outside diameter (fig. 4, d) and the wall thickness (table 2) of the hot shell were measured every time after piercing the next billet on the run-out table of the stand. The measurements were made by a vernier caliper on the head part of the shell at about 500 mm from the butt.

The final dimensions (diameter, and wall thickness) of all 6 pipes after sizing and cooling were measured on the examination table in 3 cross-sections (head, middle, tail) along the length of the tube. The measurements were made in two perpendicular directions. Results are presented in Table 2.

To assess the thickness variations of the obtained pipes throughout its length, diameters and wall thickness of two rolled workpieces (one for each size) were measured on the examination table at 9 or 10 cross-sections separated by 0.5 m (Fig. 4, c) after the shells had been sized and cooled. The diameter was an average of two perpendicular directions and the wall thickness — of four. The thickness in this case was measured by an ultrasonic thickness gauge. The results on thickness variations are presented in Fig. 5 (discussed later).

Analysis of the results

Measured values of the outer diameter and the wall thickness of the tubes (Table 3) agree well with predictions obtained with QForm software. The relative errors of the outer diameter and the wall thickness do not exceed 1.5 % and 2.9 % respectively. It should be noted that the estimated shell thickness is always a bit thinner than the actual one.

The lengthwise average wall thickness variations of the experimental pipes ø 200 x 31 and ø 270 x 44.7 came to 1.5 and 3.8 mm, respectively. For the pipe ø 200 x 31.8, these values do not exceed the established tolerances, although in some cross-sections of the pipe, they are significantly high (Figure 5). Rather, for the ø 270 x 44.7 tube, the average wall thickness variation exceeds the permissible limit.

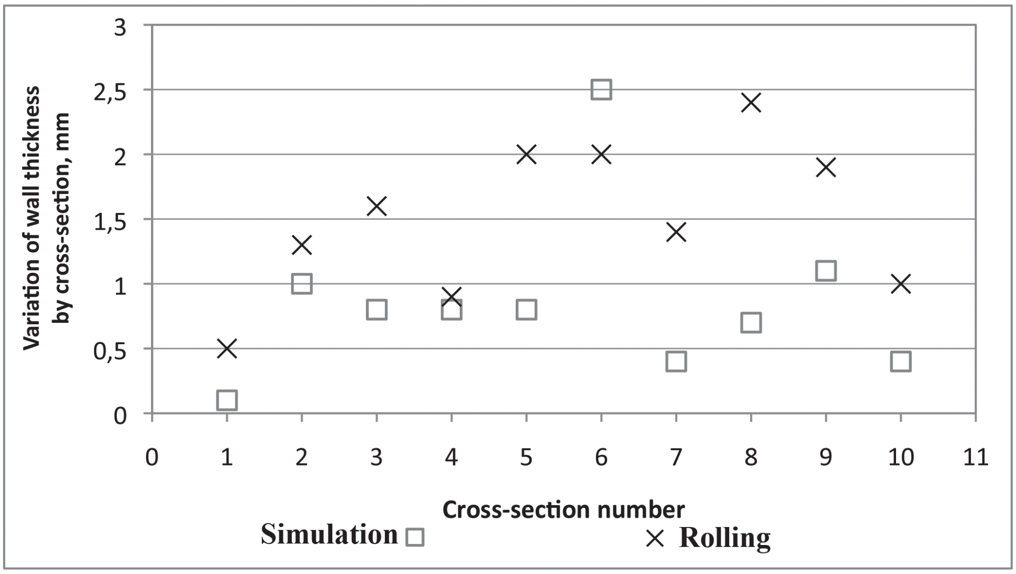
The value of wall thickness variation estimated by the results of calculations using the computer model is approximately 1.5–2.0 times lower than the actual values (Figure 5). This can be explained by idealizations inherent in the computer models. Such conditions include:

1. An ideal geometrical shape of workpiece and tools. While the actual production tools would exhibit wear, elastic deformation, and tool backlash, these are not considered in the model;
2. Stability of the friction coefficient;
3. Assumed uniform heating up to the given temperature;
4. Isotropic mechanical properties.

An important factor is also the relative positioning of the tools and the workpiece in the deformation zone (rolls, guide shoes, plug). Linear positioning errors may be of the order of a millimetre. It should be added that significantly lower vibration amplitudes of interacting bodies and, consequently, reduced forecast values of shape problems like waviness and thickness variations are expected during the simulation process. In actual practice, the position

Pipe size	Experiment			Model			Deviation (Experiment – model) / model, %	
	Shell diameter, mm	Wall thickness	Drawing	Shell diameter	Wall thickness, mm	Drawing	Diameter	Wall thickness
ø200 x 31.8	202	34.9	1.542	203	33.9	1.557	0.5	2.9
ø270 x 44	278	48.0	1.420	273.8	46.8	1.500	1.5	2.5

Table 3. Comparison of the computed and experimental results



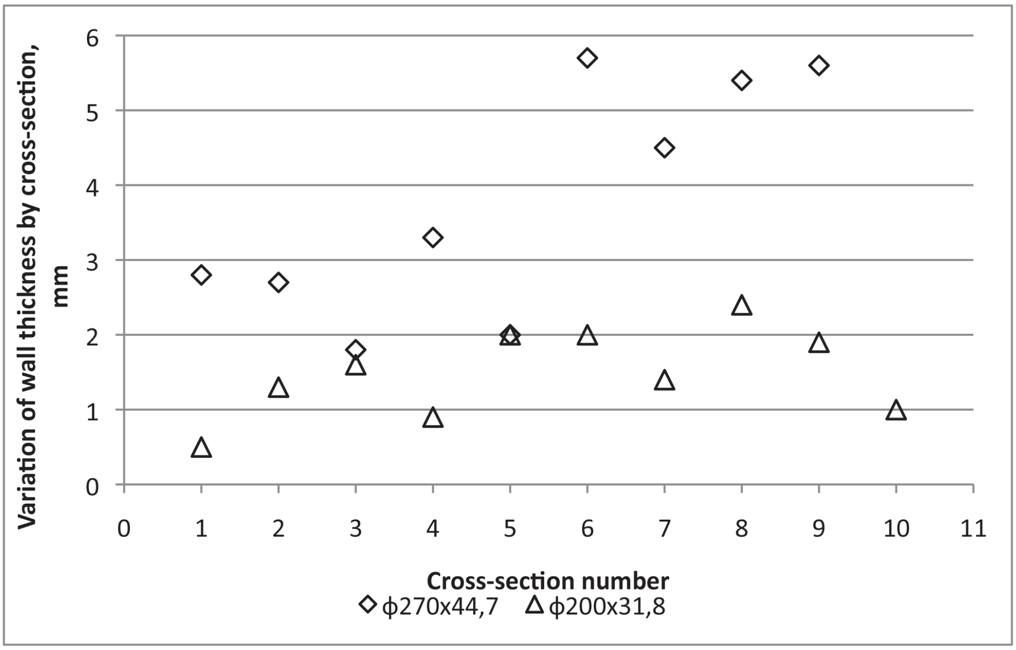


Fig. 5. The variation of wall thickness value for a) the pipe ø 200 x 31.8 mm (values obtained by simulation and rolling); b) the pipes, obtained by rolling at the mill

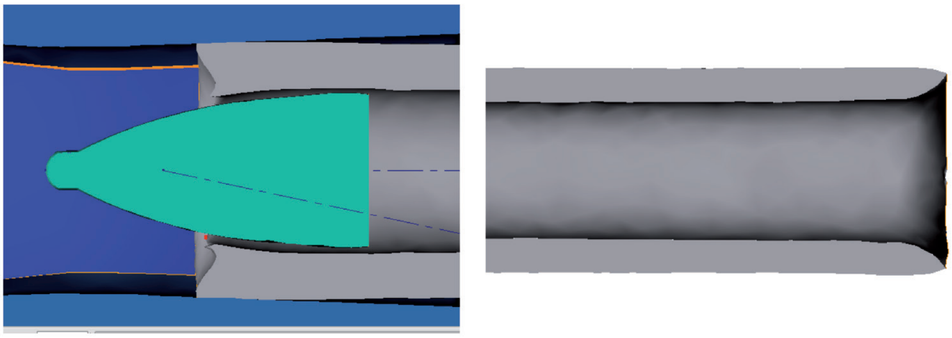


Fig. 6. The shape of the front and rear end of the hollow shell during the QForm simulation

along the length of the workpiece has been shown to have a significant impact on the magnitude of such defects, which is not seen as strongly in the computer simulations (see Fig. 5, b for example).

An optimal element size in the finite element discretization of the model and optimal integration time step may improve the accuracy of the simulation results. However, mesh refinement and reduction of the time step can lead to a dramatic increase in the overall computational cost for such problems, which may become unacceptable in some cases.

The calculated and actual values of piercing torques and power at the steady-state phase of deformation were also compared. A relative difference between values obtained in the piercing mill and the computer model (for two sizes of the shells) are: for the torque — 15–20 %, for the piercing power — 5–7 %. Calculated values of these parameters are higher than for the experimental ones. Comparison of rolling forces was not possible because the stand of TPA 70-270 is not equipped with measuring cells.

The differences between predicted and measured values of these parameters are most likely a result of inaccurate representation of the properties of the workpiece, including its temperature, friction coefficient values and by the law of friction, utilized for the simulation. It must also be taken into account that the rolling torque at the mill is estimated through the main drive current. This contributes a significant error in evaluation of the rolling torque on the rolls.

Non-steady-state deformation conditions of the end sections of the workpiece are represented by the model very realistically from a qualitative point of view. Formation of shape deviations from a regular-shaped cylinder at cross-roll piercing like flare and sink mark on the front and rear ends of the hollow shell is shown on Fig. 6. An imperfection like a "snout" appears in the model when the plug exits from the shell

Conclusions

1. The simulation of piercing solid billets of diameter 190 and 250 mm to hollow shells ø 270 x 44.7 and ø 200 x 31.8 at two-high screw rolling mill TPA 70-270 JSC VMZ using the QForm software package was carried out. Piercing was made by one pass instead of the two passes, normally used at this mill. The advantages of this mode are obvious, but the risk of exceeding energy and force parameters of deformation also increases as well as the likelihood of producing shells with unsatisfactory geometry. Metal forming simulation allows estimating such risks.
2. The calculated and actual values of energy and force parameters of the piercing operation, geometrical parameters of the shells and its deviations are compared. It is found that the systematic deviations of geometrical parameters and their tolerances are of the same order. The value of the systematic deviations has to be determined in trial rolling and should be taken into account while determining the final technological regime. The estimated values of energy and force parameters for the observed cases are approximately 20% higher than actual values. Such error is acceptable, and more especially it provides a safety factor.
3. The main reason for these errors is the uncertainty of the model input data that are unlikely to be diminished at the existing conditions. The typical finite element size must be of the same order as the tolerance for the linear dimensions of pipes.
4. Using the QForm software for verifying technological settings in seamless pipes production looks reasonable. This approach to the development of the production technology allows avoiding economic losses while designing new technological tools, testing new piercing regimes in order to implement them at the present production facilities.

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