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Numerical simulation of cold drawing of steel tubes with straight internal rifling

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Abstract

In heat exchangers, steel tubes with straight internal rifling bring several benefits to the heat transfer process. However, production of such tubes by cold drawing brings considerable challenge in meeting strict dimensional criteria on a rifling geometry. Optimization of the whole production process naturally involves a numerical simulation of cold drawing, saving time and costs of pre-production plant trials. The key aspect of a multi-rifled tube production is the proper creation of internal rifling via gradual filling of plug grooves during drawing. It is this very mechanism where the benefit of numerical simulation steps in, providing us with qualitative and quantitative estimation of important state variables. In this article, four hollows have been compared as an input feedstock for cold drawing of Ø25.4 × 2.11 mm multi-rifled tube. The calculated state variables in a feedstock material (i.e. stresses, strains, and strain rates) uniquely determine the material flow during drawing. The results of numerical simulations helped us find the most suitable input hollow for given tube dimensions while meeting customer's strict dimensional tolerances on internal rifling. Additional tasks involved optimizing the axial position of the plug inside the die.

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Keywords: Finite elements method; Numerical simulation; Multi-rifled tube; Cold drawing; Tube forming

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1. Introduction

In Zeleziarne Podbrezova (ZP), production of precision seamless steel tubes via cold drawing has a long tradition dating back to 1968 with a new tube drawing plant being designed and erected in Podbrezova. The first batch of tubes left the drawing benches in 1971. As time went by, tube drawing process in ZP has undergone several significant changes. One of the main goals in today's research and development effort in ZP is to expand the range of products ZP offers to its customers. Therefore, our recent research has been focused on tubes with internal rifling/ribbing. This includes high-performance ribbed tubes with optimized material properties and ribbing design for better heat transfer [1–4]. Well-designed internal ribbing significantly improves the efficiency of heat exchangers in which refrigerant condenses or evaporates within the tube. Typical applications include fin and tube evaporator and condenser coils for air conditioners, freezers, and refrigerators. Usually, inner tube surface can have a helical or straight rifling pattern, depending on customer´s requirements.

The production of tubes with straight internal rifling consists of hot rolling and multiple cold drawing with intermediate heat treatment. The final drawing operation produces a typical grooving pattern on inner surface of the tube by means of a multi-rifled plug. This final drawing pass is very important in fulfilling all geometrical requirements of the rifling. Technological experiments via "trial-and-error" approach are very expensive in industrial conditions. In this case, it is possible to use numerical simulation to predict and evaluate certain technological problems. By numerical simulation it is possible to see the material flow, adding to a better understanding of the forming process as has been investigated in [5–8]. By numerical simulation it is possible to optimize the cold drawing process by predicting the limiting states of material plasticity that we must conform to. The simulation can also predict the load on the drawing bench, which is very important for its reliable long-term operation. For successful multi-rifled tube drawing it is very important to optimize the rib height, rib width, and lead angle. During production runs it is very important to establish and maintain four most crucial factors: dimensions of input tubular feedstock, drawing velocity, geometry of the multi-rifled plug, and the position (i.e. axial offset) of the plug with respect to the die.

The mail goal of this article was to develop a suitable numerical model of multi-rifled tube drawing (Fig. 1, Table 1) with output dimensions of Ø25.4 × 2.11 mm. As a secondary task, optimal position of the multi rifled plug with respect to the drawing die has been investigated. Both tasks have been elaborated using commercial FEM software package.

Table 1. Model dimensions of input feedstock for numerical simulations.

Feedstock model number	O.D. × W.T.
1	32 × 2.6
2	32 × 2.75
3	32 × 2.75
4	33 × 3.00

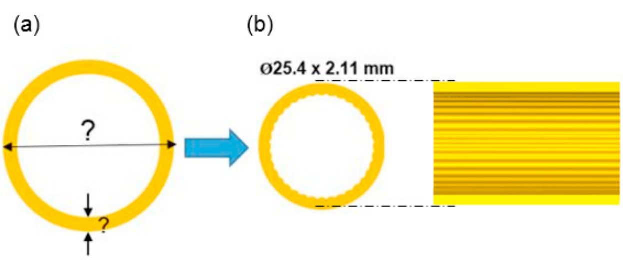

Fig. 1. (a) Input feedstock; (b) Multi-rifled tube in cross (left) and longitudinal (right) sections.

2. Numerical simulation methodology

The geometrical input for numerical simulation consisted of the following objects: input tubular feedstock (i.e. the hollow), a drawing die, a multi-rifled plug and a drawing carriage. Forming tools were defined as rigid objects fixed in space. The tube object was defined as a plastic material made of steel grade ASTM A179 (ASME SA179). The corresponding flow stress was estimated by tensile testing of tube samples Ø31.8 × 2.6 mm according to [9]. While the tensile test considers true strain up to $\varepsilon = 0.2$ only, the flow stress curve was extrapolated up to $\varepsilon = 0.7$ (see Fig. 2). Friction boundary condition between the feedstock and the tools has been estimated according to a plant trial during which we recorded the electrical power of the bench and calculated the corresponding drawing force. A single pass smooth drawing of Ø31.8 × 2.6 to Ø28 × 2 mm was selected for the job and served the purpose well. In tab. 2 there is a comparison of drawing force obtained from the plant trial and from DEFORM-3D simulation. Detailed results of this study were published in [10]. A good agreement between experimental and simulation results confirmed that the material data and the friction coefficient were estimated correctly. We have thus obtained valid input parameters that were used for simulation of drawing with a multi-rifled plug.

Table 2. Comparison of selected parameters of smooth tube drawing process.

Parameter	Technology	Simulation	Difference [± %]
Drawing force [kN]	54.00	54.21	0.39
Outer diameter [mm]	28.00	28.00	0.00
Wall thickness [mm]	2.00	1.99	0.50

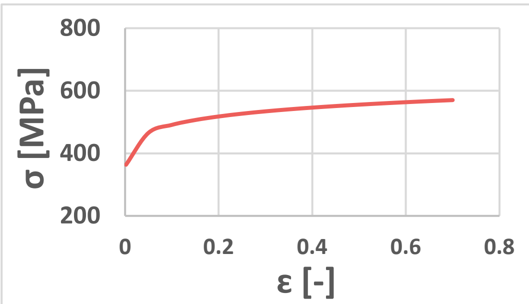

Fig. 2. Flow stress model for given steel grade.

The initial temperature of the material was $T = 20$ °C. Shear friction coefficient between the die and the tube and between the tube and the plug was estimated to be 0.08. The FEM formulation was of a Lagrangian incremental type. The drawing carriage was given the drawing velocity of $v = 30$ mm/s. The position of the plug with respect to the die was so that the plug face flushes the end of the bearing length. The initial simulation setup is illustrated in Fig. 3.

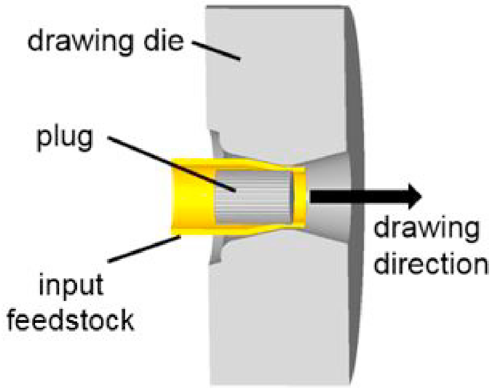

Fig. 3. Setup model of die drawing process.

The tube domain was filled with 100000 tetrahedrons. The cross section of the mesh is illustrated in Fig. 4. Only 1/36 of full geometry (i.e. one rib) was modelled with mirror symmetry boundary condition on cut faces. The tube domain was divided into 4 mesh subdomains for optimum meshing with the rib filling subdomain having the smallest elements. Just in this subdomain the groove filling was compared for given input hollows. The gradual element size transition from ribbing domain up to the outer surface proved to be effective for good convergence of the calculation while allowing us to compare individual dimensions with high accuracy. The calculation algorithm was based on a conjugate gradient iterative method.

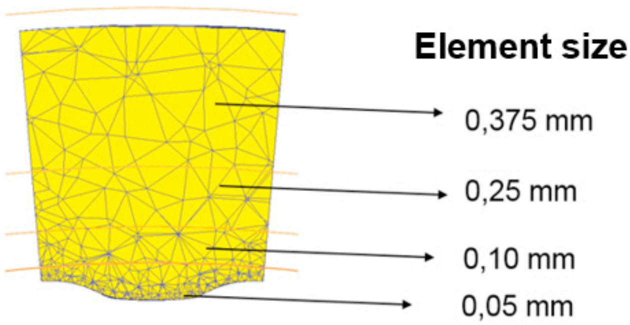

Fig. 4. Cross section of tube filled with tetrahedral FEM mesh.

3. Results and discussion

The results were evaluated in DEFORM-3D postprocessor after the simulations reached steady state. Four input hollows were compared in cross and longitudinal section as is illustrated in Fig. 5. Comparison of the grooving profiles in cross sections is shown in Fig. 6. The rib filling was evaluated based on the gap between the tube and the plug in steady state.

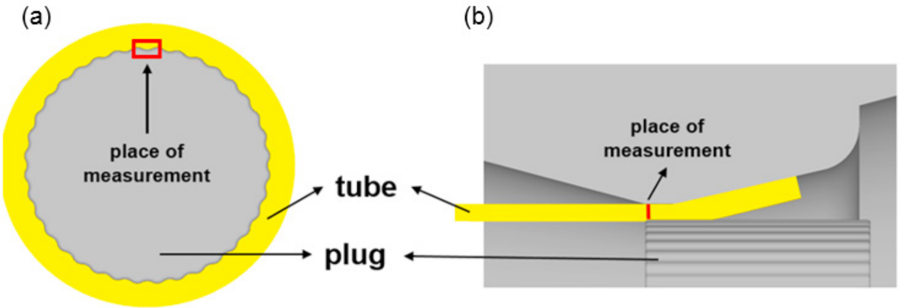

Fig. 5. Highlighted place of measurement in: (a) cross; (b) longitudinal section.

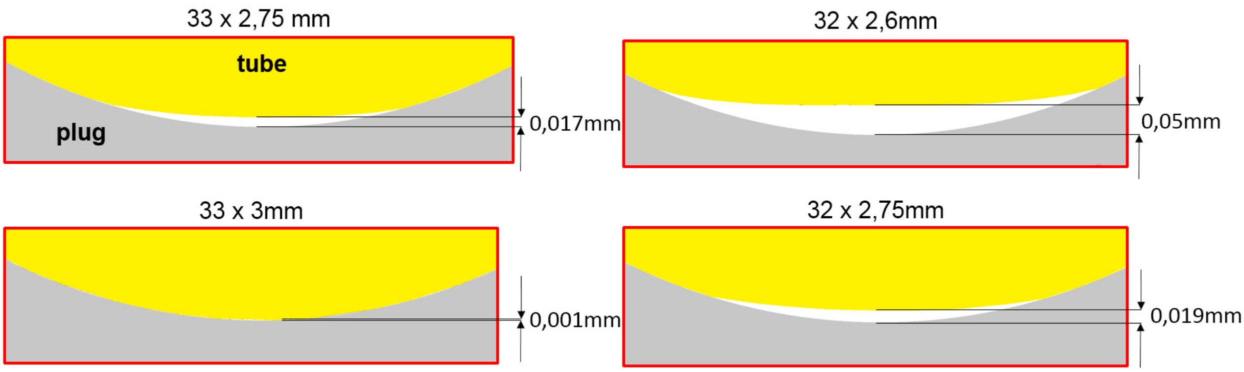

Fig. 6. Cross section of multi-rifled tube for input models.

Hollow (32 × 2.60 mm):

The grooving profile showed the worst filling. The required rib height was not met, yielding 0.05 mm underfilling. A larger diameter and thicker wall of the feedstock are necessary to achieve the required dimensions.

Hollow (32 × 2.75 mm):

Although the wall thickness was increased for this dimension, the rib height remained insufficient.

Hollow (33 × 2.75 mm):

The increase in the outer diameter improved the filling in the grooving profile, but it is still necessary to use higher wall thickness for input feedstock.

Hollow (33 × 3.00 mm):

The desired rib height and grooving profile were achieved.

Sufficient compressive strain in radial and tangential direction is the necessary factor for optimal filling of the groove. Fig. 7(a) shows definition domain of wall thickness for analysis strain components in cross sections. Higher compressive strain in radial and tangential direction is observed for (33 × 3.00 mm) hollow (Fig. 7(b)).

The drawing forces were evaluated by means of the drawing carriage (Fig. 8). The steady state was achieved after 0.6 s, giving the drawing distance of 18 mm. The highest drawing force was measured for input hollow (33 × 3.00 mm) as a result of the highest compressive strain in radial and tangential direction during reduction of the cross section. The lower the reduction of the cross section, the lower the drawing force during cold drawing.

Besides, we should mention that using numerical simulation, optimal input feedstock for production of a multi-rifled tube with helical grooves was found as in [11]. The resulting tube obtained by "numerical" drawing was compared with the actual tube using optical 3D scanning. A good agreement of eleven grooving dimensions in cross and longitudinal section of the tube was observed.

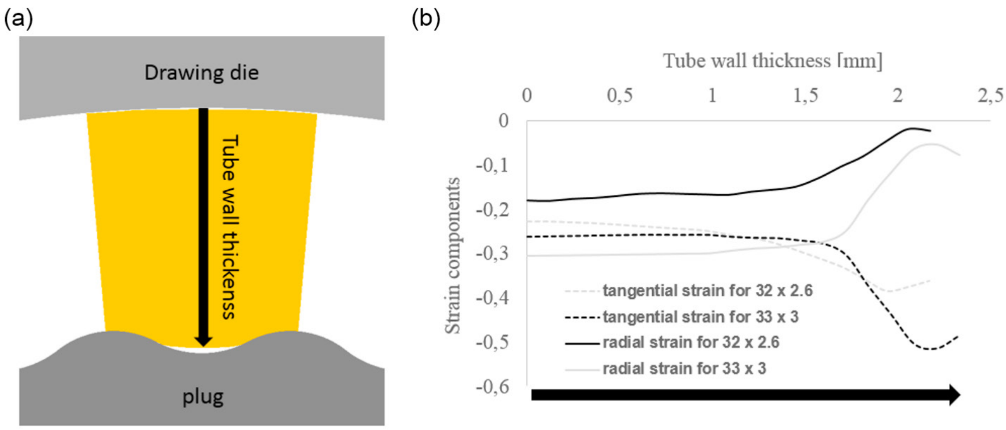

Fig. 7. (a) Cross section with definition domain; (b) Distribution of strain components for feedstock dimensions: 32 × 2.60, 33 × 3.00.

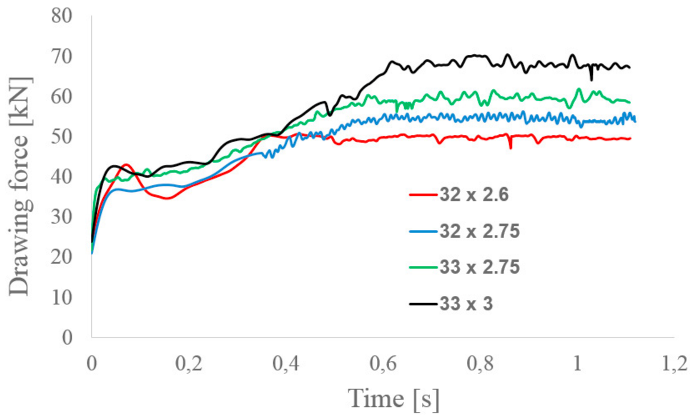

Fig. 8. Drawing force for all input hollows.

We expected that the position of the plug had a profound effect on the material flow because of the change in contact area between the plug and the tube. We have therefore evaluated 3 different plug positions (Fig. 9) to obtain the best material flow for input hollow (33 × 3.00 mm). However, the results showed an insignificant impact of the axial plug position on the profile filling and subsequent drawing force. That‘s why we stuck to the original 0 mm plug offset (in the actual drawing process the plug is axially held in place by means of flexible steel rod that is stretched 1 ÷ 2 mm after drawing has started).

If the ribs were helical, the position of the plug would have a significant effect on the material flow and the final dimensions of the ribbing geometry [11].

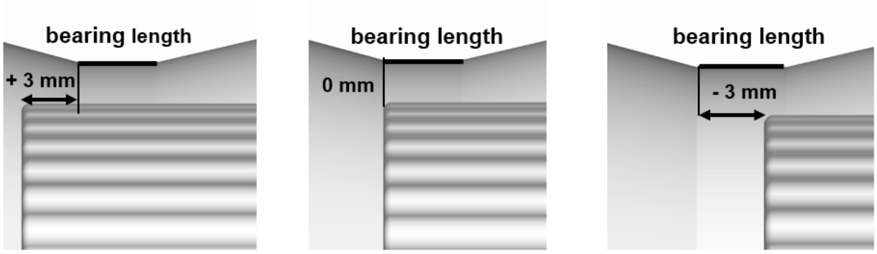

Fig. 9. Position of plug with respect to die.

4. Conclusions

This paper describes the methodology of a numerical simulation of multi-rifled tube drawing with emphasis on the high precision of the final product. The most suitable feedstock dimensions for proper filling of the grooves were found. A sufficient compressive strain in radial and tangential direction makes a necessary factor for optimal filling of the groove. Using the same numerical model the drawing force was analyzed, too. It has been found that the axial position of the plug does not have significant effect on the final tube dimensions when compared to input hollow dimensions. We can say that the results from such numerical simulations can facilitate initial technology design and tuning, giving useful insights into other parameters in production technology as well.

Acknowledgements

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