Numerical simulation of multi-rifled tube drawing – finding proper feedstock dimensions and tool geometry

P Bella¹, P Buček¹, M Ridzoň¹, M Mojžiš¹,², Ľ Parilák¹,³

¹ŽP VVC s.r.o., Kolkáreň 35, 976 81, Podbrezová;
²Ústav výrobných technológií, Materiálovotechnická fakulta STU (Trnava), Bottova 25, 917 24, Trnava;
³Katedra výrobných technológií, Fakulta výrobných technológií (Prešov), Technická univerzita v Košiciach

bella@zelpo.sk

Abstract. Production of multi-rifled seamless steel tubes is quite a new technology in Železiarne Podbrezová. Therefore, a lot of technological questions emerges (process technology, input feedstock dimensions, material flow during drawing, etc.) Pilot experiments to fine tune the process cost a lot of time and energy. For this, numerical simulation would be an alternative solution for achieving optimal parameters in production technology. This would reduce the number of experiments needed, lowering the overall costs of development. However, to claim the numerical results to be relevant it is necessary to verify them against the actual plant trials. Searching for optimal input feedstock dimension for drawing of multi-rifled tube with dimensions Ø28.6 mm × 6.3 mm is what makes the main topic of this paper. As a secondary task, effective position of the plug – die couple has been solved via numerical simulation. Comparing the calculated results with actual numbers from plant trials a good agreement was observed.

1 Introduction

Multi-rifled tubes, i.e. tubes with multiple inner grooving are used in heat exchangers and boilers. Over the last few years the effect of multi-rifled boiler tubes has been highly valued mainly in power generation at super critical pressures in coal-fired power plants. Rifled tubes are used in heat exchangers and boilers to provide highly efficient heat transfer.

In high pressure boilers, air bubbles are formed in the liquid close to the inner surface of the tubes. This is caused by the heat transfer from the tube walls and tends to create a steam film between the tube wall and the heated liquid. This steam film inhibits heat transfer between the tube and the liquid. If this exceeds a certain limit, the temperature of the tubes will increase rapidly, leading to the damage of the tubes. In order to prevent steam film formation on the tube walls, the mass flow rate of the liquid should be increased or the fluid should swirl to maintain a good contact between the liquid and the tube wall [1]. Rifled tubes in a conventional boiler provide a larger margin of safety for natural circulation and assisted circulation along with many economic advantages such as: reduction of weight for downcomers, headers, drum and connecting pipe, reduction of pumping power, and reduction of framework weight [2, 3]. The presence of internal rifling induces centripetal forces in the helical mass flow, thereby separating the water from the steam fraction and forcing the water towards the tube wall. As a result of this phenomenon, following advantages appear: improved heat
transfer rate even at higher steam quality levels, very good heat transfer even at low mass flux levels, reduction in mean metal temperature of the tube wall, ability to increase heat transfer rate by optimizing the rifling geometry.

The multi-rifled precision seamless steel tubes are produced in Železiarne Podbrezová by means of cold drawing, utilizing multiple drawing operations (sequences) 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. During production it is very important to optimize the following geometrical parameters: rib height, rib width, and lead angle. The rifling itself has a key effect on flow regime inside the tube.

During production runs it is very important to establish and maintain four most crucial factors:

- a) dimensions of input tubular feedstock,
- b) drawing velocity,
- c) geometry of the multi-rifled plug,
- d) position (i.e. axial offset) of the plug with respect to the die.

After the ribbing, the tubes are heat treated to meet the specified metallurgical requirements. Before cutting to final lengths, the tubes are 100% checked by eddy current method and/or ultrasonic test, depending on customer’s requirements. Resolving all these factors is time consuming and therefore expensive, therefore some preliminary decisions can be made with the help of numerical simulation [4, 5].

This main goal of this article was to develop a suitable numerical model (Figure 1) of multi-rifled tube drawing with output dimensions of Ø28.6 mm × 6.3 mm. As a secondary task, the optimum 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.

![Figure 1. Input feedstock → multi-rifled tube.](image)

2 Material, simulation and experiment

The drawing process was modelled in DEFORM-3D using a finite element model. The objects considered for modelling were: input feedstock, drawing die, multi-rifled plug, and the drawing carriage [6, 7]. The input feedstock dimensions were limited by the geometry of the preliminary forming tools. Five types of input feedstock were selected as candidates for numerical simulation (Table 1).

| Feedstock model number | [Outer Diameter] x [Wall Thickness] |
|------------------------|-----------------------------------|
| 1                      | 34 x 7.0                          |
| 2                      | 35 x 7.5                          |
| 3                      | 36 x 7.5                          |
| 4                      | 36 x 8.0                          |
| 5                      | 36 x 8.5                          |
Simulation parameters and settings were exactly the same for all models considered. The input feedstock was defined as a plastic object, which is suitable for modelling of cold forming processes under certain conditions. A piece of tube with $\frac{1}{4}$ symmetry was 70 mm long and described by 30 000 linear tetrahedrons. Smaller elements were created on the inner tube surface where high intensity of plastic deformation is takes place. After the drawing simulation the number of elements was increased 10-folds. This was necessary to ensure the strict dimensional requirements on inner grooving of the tube (ribs, grooves, rounded edges, etc.) This approach is very effective and less time consuming, as it requires fewer elements to describe less important regions, placing finer elements to the more important regions according to the meshing weights [8, 9]. The forming tools (die, plug, carriage) were considered rigid and wear-free objects. Initial model setup is shown in Figure 2. During drawing, the multi-rifled plug revolves around its own axis due to the helical shape of the grooves, determining the flow of the material. The Coulomb 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 Lagrangian incremental type [10]. The drawing carriage has its velocity of drawing ($v = 30$ mm/s). The drawing carriage and the tube were connected through non-separable (so called “sticking”) condition. The position of the plug with respect to the die was so that the plug face flushes the end of the bearing length.

3 Results and discussion

3.1 Models of input feedstock

Final dimensions of multi-rifled tubes from numerical simulation were measured in cross and longitudinal sections, as specified in Figure 3. The results are in Table 2.

![Figure 2. Initial model setup for numerical simulation of multi-rifled tube drawing.](image)

![Figure 3. Key dimensions of multi-rifled tube – cross and longitudinal section.](image)

| Label | Description     | Units | Nominal value | Tolerance | (34x7.0) | (35x7.5) | (36x7.5) | (36x8.0) | (36x8.5) |
|-------|----------------|-------|---------------|-----------|----------|----------|----------|----------|----------|
| A     | Outer diameter | mm    | 28.60         | $\pm$ 0.15| 28.44    | 28.35    | 28.43    | 28.50    | 28.41    |
| B     | Inner diameter | mm    | 16.06         | $\pm$ 0.15| 16.04    | 16.02    | 16.01    | 16.02    | 16.03    |
Model No. 1 (34×7.0):
The grooving profile showed the worst filling up. The rib height was just 0.3 mm and other dimensions (K, L, L’) were well off the tolerance, too. Larger diameter and thicker wall of the feedstock are necessary to achieve desired dimensions.

Model No. 2 (35×7.5):
A slightly better material flow was observed, but we still haven’t reached all the dimensions specified. The rib height, rib radius and other dimensions were out of tolerance (red font values in Table 2).

Model No. 3 (36×7.5):
Similar results as in model No. 2. The rib height was at the lower tolerance limit. The rest of the dimensions were acceptable.

Model No. 4 (36×8.0):
All dimensions are within the tolerances.

Model No. 5 (36×8.5):
The material flow was similar to the model No. 4, but the rib angle and rib radius were just below the tolerance limit. Other dimensions were out of tolerance.

Figure 4. Cross section of multi-rifled tube for model No. 1 (left) and model No. 4 (right).

3.2 Position of the plug with respect to the die
The position of the plug has a profound effect on the material flow because of the change in contact area between the plug and the tube. We have evaluated 3 different plug positions (Figure 5) to obtain the best material flow. Simulation settings were the same as in previous cases and the input feedstock used came from model No. 4 (36×8.0).
0mm plug-die axial offset: 
The contact length was 11 mm (Figure 6, left). This seemed to be the ideal position for all the dimensions were within tolerances (see Table 3). The material flow (and thus deformation) was rather uniform (see Figure 7, centre).

5mm plug-die axial offset: 
The contact length was 16.5 mm (Figure 6, centre). Dimensions were outside the tolerances.

10mm plug-die axial offset: 
The contact length was 22 mm (Figure 6, right). The material flow is depicted in Figure 7 (top). This particular configuration position is again undesirable for there was the “rib radius” violation: the material flow (and thus deformation) at the inner tube surface was quite heterogeneous. Higher deformation was observed in location L’ whereas insufficient deformation (thus insufficient groove filling) was observed in location L.

Figure 5. Position of the plug with respect to the die.

![Figure 5](image)

Figure 6. Calculated contact area between the tube and the forming tools for various plug-die axial offsets.

![Figure 6](image)

Table 3. Comparison of calculated tube dimensions according to various plug-die axial offsets

| Label | Description       | Units | Nominal value | Tolerance     | 0 mm | 5 mm | 10 mm |
|-------|-------------------|-------|---------------|---------------|------|------|-------|
| K     | Rib side angle    | °     | 54            | -10 / +15     | 50 - 56 | 42 - 50 | 31 - 45 |
| L     | Rib radius        | mm    | 0,3           | min 0,13 max 0,60 | 0,37 | 0,62 | 1,1   |
| L’    | Rib radius        | mm    | 0,3           | min 0,13 max 0,60 | 0,27 | 0,45 | 0,43  |
3.3 Model validation

Based on simulation results the obvious winner of the contest is the model No. 4. The plug-die axial offset was set to 0mm. To validate our numerical results, experimental tube drawing took place in Železiarne Podbrezová tube drawing plant.

As an input feedstock, Grade-T12 steel tube with dimensions of Ø36 × 8 mm was used. The drawing velocity was 1.85 m/min. The experiment was conducted at room temperature. The tube dimensions after drawing on a multi-rifled plug were measured with 3D optical scanner GOM ATOS II and the data obtained were processed in order to obtain reverse-engineered CAD model of the tube [11, 12]. Dimensions of the multi-rifled tube, both experimental and simulated, were measured in the cross and longitudinal section of the tube, as specified in Figure 3. Experimental and simulated values are compared in Table 4.

| Description     | Units | Nom. value | Tolerance | VALIDATION                  | Difference [mm] | Difference [%] |
|-----------------|-------|------------|-----------|-----------------------------|-----------------|----------------|
| A Outer diameter | mm    | 28,6       | ±0,15     | 3D scanning: 28,52 | 28,50           | -0,02          | -0,07          |
| B Inner diameter | mm    | 16,06      | ±0,15     | Num. simulation: 16,00 | 16,02           | 0,02           | 0,13           |

Figure 7. Longitudinal section of a multi-rifled tube: 10mm plug-die offset (top), 0mm plug-die offset (centre).
### Table

|        | Description                  | Unit | Min     | Max     |
|--------|------------------------------|------|---------|---------|
| D      | Wall thickness               | mm   | 6.27±0.57 | 6.3     |
|        |                              |      | 6.17    | -0.13  |
|        |                              |      | -2.06   |         |
| F      | Rib width (cross)            | mm   | 4.8±0.6  | 4.34    |
|        |                              |      | 4.51    | -0.17  |
|        |                              |      | -3.92   |         |
| S      | Rib width (longitudinal)     | mm   | 8.3±1.04 | 9.38    |
|        |                              |      | 8.98    | -0.4   |
|        |                              |      | 4.26    |         |
| H      | Rib height                   | mm   | 0.7±0.15 | 0.71    |
|        |                              |      | 0.71    | 0      |
|        |                              |      | 0.00    |         |
| K      | Rib side angle               | °    | 54      | 67      |
|        |                              |      | 50 – 56 | 6       |
|        |                              |      | 8.96    |         |
| L      | Rib radius                   | mm   | 0.3 min 0.13, max 0.60 | 0.33 |
|        |                              |      | 0.37    | -0.06  |
|        |                              |      | 18.18   |         |
| L'     | Rib radius                   | mm   | 0.3 min 0.13, max 0.60 | 0.34 |
|        |                              |      | 0.27    | -0.13  |
|        |                              |      | 17.65   |         |
| M      | Rib pitch                    | mm   | 21.85±3.18 | 22.26 |
|        |                              |      | 22.57   | + 0.31 |
|        |                              |      | 1.39    |         |
| P      | Lead angle                   | °    | 30      | 25.20   |
|        |                              |      | 26.30   | + 1.1  |
|        |                              |      | 4.37    |         |

### 4 Conclusion

Solving technological optimization problems by means of numerical simulation proves to be a vital approach towards further innovations in tube production. In this paper, numerical simulation approach was used to estimate the most suitable input feedstock dimensions along with optimum plug-die position for production of multi-rifled tubes with given dimensions. Furthermore, calculated dimensions from numerical simulation were compared with the actual tube dimensions from experimental drawing trials. The results agreement was acceptable, further promoting the idea of numerical simulation as the vital part of production technology design process in Železiarne Podbrezová.

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