Simulation of rifled tubes drawing process

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Abstract. Presented paper is focused on knowledge in the field of tube drawing process. The introduction consists of summarizing the current state of the art. In the material and methods section, it is a characteristic of the usability of rifled tubes for heat exchangers, which serve to better heat exchange between the medium and the tube. The following section describes the implementation of the experiment. This section shows the principle of pipe drawing using a grooved mandrel and a die. The result section is showing resulting a simulation of strength analyzes and the recorded values during the pulling tests. In conclusion, the aim of this paper is briefly explained, as well as the need to take into account the leading part of the mandrel, which may result in incorrect geometry and cavitation. In conclusion, the issue is mentioned, which is beneficial for science and research in the field of cold drawing of tubes. It is also about knowledge with internally shaped surface in energetic equipment.

1. Introduction

At the present time, steel forming has a number of established terms, which we use to designate and describe the ductile properties of a given material, forming processes, but mainly equipment and activities and their implementation. Forming technology is among the most economical method primarily due to increased quality molded parts and high labor productivity [1]. The rifled tubes are used in high pressure boilers to remove the vapor film effect on the inner surface of the tube and to increase the thermal effect in the furnace [2].

It is precisely the tubes with a shaped inner surface that are intended for the production of heat exchangers where, due to their special shape, they contribute to a better heat exchange between the medium and the tube. The inner shaped surface causes the vapor and liquid to separate due to the centrifugal forces, the liquid phase (water) being pushed towards the tube wall. In a detailed analysis of tubes with a shaped inner surface, their significant progress and benefits for the energy industry and for energy transmission processes are evident and noticeable [3–5].

Therefore, the R&D objectives in the energy industry are geared towards increasing the efficiency of energy installations, also by changing the shape of the inner surface of the tubes used in the construction of heat exchangers [6]. Nowadays, smooth-surface tubes are used for heat exchangers, despite the fact that tubes with a rugged inner surface contribute positively to the performance of these devices [7]. That is why this industry is one of the sectors that is under close scrutiny, as R&D (Research & Development) centers as well as interested manufacturing companies strive to improve the industry through the continuous development of new technologies and equipment.
2. Material and methods

2.1. Application of tubes
The use of these tubes is mainly used in heat exchangers and boilers, with a high energy benefit of heat. The presence of the groove induces centrifugal forces in the mass flow, whereby the water is separated from the steam fraction and forced water to the tube wall. As a result, this phenomenon occurs and the increase in the inner surface increases with the following advantages [8]:
• improved single transfer speed with higher steam quality,
• very good transmission even at given lower flow levels,
• decrease the average metal temperature of the pipe wall,
• they have the ability to optimize groove geometry.

2.2. Proposal of tool material
It is important for the individual design of the tool material to meet the given properties, which must be made of high resistance, wear and high compressive strength. The material to be tested for the simulation was chosen as the steel grade DIN – C15 (1.0401) [9].

Physical properties [10]:
• density: 7850 kg m^{-3},
• specific heat capacity: 460 J kg^{-1} K^{-1},
• thermal expansion coefficient: 11.1 \cdot 10^{-6} – 14.7 \cdot 10^{-6} K^{-1},
• thermal conductivity: 35.0–54.5 W m^{-1} K^{-1},
• resistivity: 150 \cdot 10^{-9} – 289 \cdot 10^{-9} Ohm.
Material properties for C15 are in table1.

| Property                      | Value               |
|-------------------------------|---------------------|
| Melting point                 | 1540 °C             |
| Density                       | 7.85 g cm^{-3}      |
| Young modulus, E              | 210 GPa             |
| Tensile strength, \sigma ts   | 500–650 MPa         |
| Poisson ratio                 | 0.303               |
| Fracture strength, K IC (plane strain) | 41–82 MPa |
| Thermal conductivity         | 64 W m^{-1} K^{-1}  |
| Thermal expansion, \alpha    | 12 E^{-6}/C         |

2.3. Steel DIN - C15 (1.0401)

Description
SIQUAL 0401 is a plain carbon steel with a nominal 0.15 % carbon content. It is a relatively low strength steel but it may be quenched and tempered for increased strength.
Soft Annealing: Heat to 850–950 °C, cool slowly. This will produce a hardness of 90–100 HB [11].
Forging: Hot forming temperature: 1200–950 °C
Machinability of SIQUAL 0401 steel is fairly good, especially in the cold drawn or cold worked condition. Based upon carbon steel AISI 1112 as a reference that is considered 100 % machinable (easily machined) the SIQUAL 0401 steel has a rating of 55 %.
Cold Working: SIQUAL 0401 is easily cold worked by traditional means. Following severe cold working a stress relief, or full, anneal should be performed.
Physical properties (average values) at ambient temperature [11]:

- modulus of elasticity ($10^3$ N mm$^{-2}$): 210,
- density (g cm$^{-3}$): 7.85,
- thermal conductivity (W m$^{-1}$ K$^{-1}$): 58.6,
- electric resistivity (Ohm mm$^2$ m$^{-1}$): 0.11,
- specific heat capacity (J g$^{-1}$ K$^{-1}$): 0.46.

Chemical composition of steel is in Table 2 and mechanical properties are in Table 3.

### Table 2. Chemical composition (%) of steel C15 (1.0401): EN 10277-2-2008 [12].

|   | C    | Si   | Mn   | P     | S     |
|---|------|------|------|-------|-------|
|   | 0.12–0.18 | Max. 0.4 | 0.3–0.8 | Max. 0.045 | Max. 0.045 |

### Table 3. Mechanical properties of steel C15 (1.0401) [12].

| Nominal thickness (mm) | $R_m$ – Tensile strength (MPa) (+C) | $R_{p0.2}$ – 0.2% proof strength (MPa) (+C) | $A$ – Min. elongation at fracture (%) (+C) | Brinell hardness (HBW): (+SH) |
|------------------------|-----------------------------------|-------------------------------------|----------------------------------|-------------------------------|
| 5–10                   | 500–800                           | 380                                 | 7                                | 98–178                       |
| 10–16                  | 480–780                           | 340                                 | 8                                |                              |
| 16–40                  | 430–730                           | 280                                 | 9                                |                              |
| 40–63                  | 380–670                           | 240                                 | 11                               |                              |
| 63–100                 | 340–600                           | 215                                 | 12                               |                              |

3. Realisation of experiment

A single principle consists in pulling through the die, which is mounted slotted mandrel. The hole may have a cone shape that determines the resulting tube cross section. The thrust bearing allows the mandrel to rotate and thus form the groove into the tube. An individual arrow indicates the direction in which the tube will be drawn. It is reduced during drawing, thus reducing the diameter of the tube while increasing its length (Figure 1).

![3D Configuration of die and mandrel for simulation.](image)

### Table 4. Input values entered into Deform 3D (initial) – Steel DIN – C15 (1.0401).

| Steel DIN – C15 (1.0401) |
|--------------------------|------------------|
| Flow stress:             | Tube             |
| Strain:                  | Strain: 0–0.8    |
| Strain Rate:             | 1.6–40           |
| Temperature:             | 20–1370 °C       |
| **Object:**              | Object temperature: 20–110 °C |
| **Object type:**         | Plastic          |
| **Mesh:**                | Number of elements: 200 000 |
| **Type:**                | Relative         |
| **Mesh parameters (size ratio):** | 2 |
| Thermal conductivity:    | Temperature: 0–1485 °C |
| Heat capacity:           | Temperature: 75–1460 °C |
Table 5. Input values entered into Deform 3D (initial) – Carbide (15% Cobalt).

|                | Carbide (15% Cobalt) | Mandrel |
|----------------|----------------------|---------|
| **Die**        | Object temperature: 20–43 °C | Object temperature: 20–39 °C |
|                | Object type: Rigid | Object type: Rigid |
| **Object**     | Number of elements: 50 000 | Number of elements: 50 000 |
| **Mesh**       | Type: Relative | Type: Relative |
| **Movement**   | Constant value: 60 mm s⁻¹ | Constant value: 60 mm s⁻¹ |
| **Mesh parameters (size ratio)** | 2 | 2 |

3.1. Simulation phase
This section analyzes the simulation analyzes that were created in DEFORM 3D. These show us the places of loading and the size of the tests given.

Figure 2. Tube initial position a); Tube during simulation process b).

In Figure 2 it is shown the tube and mandrel, where option a) tube before drawing and option b) tube during drawing. During the drawing process, there is a given taper of the tube, as well as the dimensions when its diameter decreases and the length of the tube will increase. The forming die is placed in the stool (not moving) and the inserted mandrel in the pipe is rotated. The individual tube is drawn by the tapered end and thus changes in dimensions and the resulting shape and diameter of the tube occur. The outside diameter of the pipe before drawing was 36 mm and the inside diameter was 19.5 mm.

Figure 3 option a) shows a tube in cross-section prior to drawing, which will subsequently be used in the drawing process through the drawing. The single die is firmly seated in the stool and the mandrel is positioned in one place where it performs only a rotational movement. The sliding movement will be performed by the drawn tube through the die. Option b) shows the tube in cross section, but during drawing, when the deformation state of the tube and the occurrence of single grooving by the mandrel in the pipe cavity and its dimensions can be noticed.
Table 6. Basic parameters used in simulations.

| Drawn tube               | Mandrel                        | Die              |
|-------------------------|-------------------------------|-----------------|
| Diameter (mm)           |                               |                 |
| (external/internal)     | Diameter (mm) (external/internal) | Input diameter (mm) |
| 36/19.5                 | 16/14.5                       | 40              |
| Length (mm)             | Length of the forming groove (mm) | Output diameter (mm) |
| 300                     | 33                            | 28.6            |
|                         | Length of the whole tool (mm) | Bevel from the axis (°) |
|                         | 127                           | 16              |

Table 6 recorded dimensions for part of our model kits consisting of pipe, the mandrel and die. It is a part of the basic dimensional parameters set for our models of the entire assembly needed to simulate the program Deform 3D.

4. Results and discussion

Figure 4 shows the strain effective but with the given die and mandrel. Here you can see in which direction the pipe pulls and how the mandrel behaves in the cavity of the pipe. The values for strain effective have changed since the start of the simulation, where the initial value was set to 0. The highest value of 1.19 was measured during the pulling of the tube. This greatest value was at the point where the forming mandrel pushed the groove into the pipe. This is the place where the largest volume change occurred. On the outer walls of the tube during drawing, which occurred to the outer diameter of the pipe reduction was measured value of 0.447. In the initial drawing, where the mandrel first enters the tube material, the stress efficiency is 0.238, which is a minimum value with just a comparison of the entire drawing simulation.

Figure 5 shows the efficiency of the mechanical stress effective that is shown during the grooving inside the tube. The figure shows us the minimum and maximum value measured by the analysis that was already recorded during the simulation run, and its status does not change. It is a state that arises in the oven if it is affected by the individual effects of forces. The initial mechanical stress effective value was recorded as 0 MPa. This is the value that is taken as the input (that is, before running the simulation for the resulting analysis). During the whole simulation to the very conclusion, the analysis recorded the maximum measured value of 926 MPa. This mechanical stress was recorded precisely at the point of initial start-up mandrel, where for the first time pushed into the inner pipe wall. Also this maximum value was recorded also in the area where occurred a change in the outer diameter of the pipe, but also a change in the diameter of a slotted pipe from the inside.
Figure 5. Stress – effective of the drawn tube simulation.

In Figure 6 shows the amount of deformation. Here we can notice the individual deformation of the oven during the simulation. This simulation is used in the composition of the die, mandrel and pipe. The initial value that is recorded as the input value before the simulation was set to 0. At the point where the internal grooving was created, the largest deformation recorded was 0.557. In the area when changing the outside diameter of the pipe, the value was 0.186. The maximum measured value did not exceed the upper limit of the 0.742 interval, which allows us to say that this deformation process in the selected area meets the required conditions. It is pointed out in the figure that this value was recorded at the place where the grooving is created. Each technology is not without damage and therefore it is possible to see the analysis, which points to pipe damage recorded as damage that still fulfils the stress conditions.

Figure 6. Deformation of the draw tube.

Figure 7 shows the temperature analysis of the tube. The temperature differences in stress and drawing of the tube by the forming technology are as follows. The initial values before drawing were 20 °C (normal operating temperature), but as the oven was pulled to give the groove, the temperature rose and reached a maximum of 159 °C. This temperature has always occurred in places where a change in the outside diameter of the pipe, together with the change of the inside diameter of the pipe and grooving. The figure shows a pin with a mandrel where it is possible to see in which places these tools are most stressed. Due to higher temperatures, e.g. however, the coatings to be used for lighter and more transient dragging also help to maintain optimum temperatures. That is why the right choice of tool material is
needed. It can be seen in the figure that the structure of the tube changed in several analyzes, but the main differences were in the initial grooving.

**Figure 7.** Temperature analysis of draw tube.

In Figure 8 it is possible to see the final analysis of the total extrusion at the individual effect of drawing the tube through the die. The figure shows the individual values that can be used to judge that the pipe is still gaining value that indicates the pipe shift. The final state can be much larger than our maximum, depending on the length of the tube. Prior to pulling, the value was 0 but increased to 16.7 mm during the pulling process. During the pulling process at 80mm, the pipe lengthened by 16.7 mm. This extension depends on the inlet pipe diameter and shape of the pipe before pulling up to desired.

**Figure 8.** Displacement – total displacement of the drawn tube simulation.

**Table 7.** The recorded values of simulations (initial and maximum measurement).

|                           | Minimal | Maximum |
|---------------------------|---------|---------|
| Strain – effective (mm mm⁻¹) | 0       | 1.19    |
| Stress – effective (MPa)   | 0       | 926     |
| Deformation of the tube – Damage | 0     | 0.557   |
| Temperature (°C)           | 20      | 159     |
| Displacement – Total displacement (mm) | 0    | 16.7 (at length 80 mm) |
Table 7 includes information on the minimum and maximum values that were recorded in the simulations. In our case the minimum values are taken as initial values. These were determined before the simulation was run. At maximum measured values it comes to values that meet our requirements. These maximum values are still below the upper limit allowed, which was given to the program for the test material DIN C15 (1.0401).

5. Conclusion
The aim of this paper was to express the essence of cold tube drawing with internal grooving. By producing cold grooved tubes, it was explained in the final field by the level of safety, the natural circulation, and the steam circulation itself for safety.

Rifled tubes are used in the energy industry, which have contributed significantly to the reduction of pump performance and efficiency in removing the film effect. The economic evaluation of current and alternative materials represents a strong cost-saving potential in the case of successful introduction of new mandrel materials into manufacturing practice.

After evaluating the individual strength analysis in the DEFORM program, we see some stress, temperature, strain, mechanical stress, stress strain and individual displacement in the given analyzes. In particular, the design of the tool geometry must take particular account of the leading portion of the mandrel, which may result in incorrect geometry, cavitation. These are individual micro-cracks that arise in the given production of the rifled tube, where the so-called. Vacuum bubble – cavity and a given micro-explosion that mainly damages the inside of the oven. The conclusion of the paper was to show a tube with a dowel and a mandrel in the tested analyzes, during the production of grooves in the tube cavity.

Just in the final evaluation it can be seen that for the selected material DIN C15 (1.0401) the simulation shows that the resulting tests met the requirements. These are the requirements that are given maximum limits specified program Deform 3D. They are set for a chosen material. The measured maximum values did not exceed the maximum allowed values. Such a simulation can predict the material's pulling tubes behavior and avoid the shortcomings that may occur during the operation. When using the assembly composed tube, die and mandrel is a comprehensive simulation, which will be subsequently deployed into production for clarification of the final test.

The paper has a contribution to the science of cold-drawing pipes. Other benefits may also be deepening and broadening of the knowledge of the use of tubes with an internal shape-rugged surface in power installations such as tubes serving for the transfer of media. It is mainly about knowledge in the field of software environment Deform 3D and its use for tested material. It is also a benefit for practice, where is the simulation part of the tool geometry of tool steel and drawn tube is of steel DIN - C15 (1.0401). The use of this simulation will also serve for the following investigations in the field of the functionality of the parts of the forming tools in the tube forming to the required dimension, which will be determined by the customer.

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