3D numerical model of tube-tubesheet joint roller expansion process

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Abstract. The tube-tubesheet joint by roller expansion process is widely used for the manufacturing of heat exchangers. The industry experiences quality issues with the joint, due to over or under expansion of the tubes. The paper focuses on the numerical modelling of the rolling process, and verification by experiments. The numerical model is simulated using LS-DYNA, where the motion of the rollers is included to simulate the step-wise plastic deformation of the tube. The model is built in 3D, with plane strain assumption for a section of the tube-tubesheet. The tubesheet structure is included in the model to obtain a realistic and appropriate stiffness behaviour. The experiments are investigated using optical measuring equipment, where the Micro Vickers Hardness and the grain structure of the tube in the plastic deformed zone are evaluated. The paper investigates the validity of modelling the tube-tubesheet expansion process with inclusion of the rollers.

The input deck for LS-DYNA is available on request, from Karl Brian Nielsen.

1. Introduction
The tube-tubesheet roller expanded joint is commonly used in the heat exchanger industry due to its ability to provide and ensure a leak proof joint. The joint integrity is tested and determined by applying pressure to the system by running a fluid through it, if leakage in the heat exchanger is discovered the tubes will be reworked or re-tubed accordingly. The reworking or re-tubing can be a costly task that can eventually lead to expanding the tubesheet holes to levels that exceed the TEMA guidelines [1].

The mechanical tube roller expansion process was first documented in a scientific paper by Oppenheimer [2], and later Grimison and Lee [3] performed a parameter study where they established the foundation for the fundamental process parameters. Additionally, one of the earliest patents for the tool used in the process was developed in 1885 in the United States, where the patent itself was later approved in 1888 [4].

In figure 1 a sketch of a cross-section of a tube-tubesheet roller expansion process setup is shown. The roller expansion tool consists of a conical mandrel, rollers and a thrust collar, where the rotating mandrel pushes the rollers outwards.

Usually the numerical models, that are developed for the process, are axisymmetric, firstly proposed by Kasraie et al. [5]. Those models focus on determining the correct contact pressure, strength of the joint and other parameters. In addition, the axisymmetric models obtain an
uniform plastic deformation distribution. This is due to applying equally distributed pressure along the inner perimeter of the tube. This method assumes that there is an infinite amount of rollers expanding the tube at any given time. Depending on the purpose of the model this might have a negative influence on the validity of the corresponding results.

The numerical models developed in the recent years focus more on the kinematic modelling of the rollers in the tube-tubesheet expansion process. Merah et al. [6] developed a 3D numerical model including the rollers’ movement and compared it to an axisymmetric model. They found that the 3D model has a more realistic estimate of the deformation of the inner tube wall and the pullout force.

Al-Aboodi [7] developed a 2D planar numerical model with a realistic movement of the rollers and exact geometry of the tubesheet, in order to determine the strength of the joint by investigating the residual contact pressure. One of his observations was that the distribution of the stresses is not uniform around the tube, which can be caused by the geometry of the tubesheet.

Madsen et al. [8] made a comparison between a 2D axisymmetric, 2D planar and a 2D model with plane strain assumption with the inclusion of the rigid roller motion. The models were compared to a specific apparent wall reduction with springback taken into account. The results from the numerical models were compared to experimental findings, where metastable austenite underwent a martensitic transformation in the inner third of the tube wall. They found, that the results from the 2D model with the inclusion of the rigid rollers were closer to the experimental results. This was due to each roller pushing a wave of material in front of itself, therefore hardening the material locally.

Based on the above mentioned articles this paper will focus on developing a numerical model, with inclusion of the kinematics of the rollers. The model will be developed using LS-DYNA, while the articles [5, 6, 7, 8] use ANSYS. The numerical results will be compared to experimental findings.
Figure 2. A 3D representation of the numerical model. The presented parts are: Tubesheet (Red), Tube (Blue), Rollers (Yellow), Mandrel (Green) and Ring (Purple).

2. Numerical Model
The challenge of modelling the tube-tubesheet process with inclusion of the rollers’ kinematic motion is the contacts, which have a negative impact upon the CPU time.

The numerical model is a 3D model with 2D plane strain assumptions, modelled in LS-PrePost and solved in LS-DYNA. The model consists of 8 parts, which can be seen in figure 2. The 2D plane strain assumption is obtained by applying a mesh to the parts with one element in height and using an element formulation corresponding to this assumption. Therefore the tubesheet and tube’s element formulation is $\text{ELFORM} = 1$, which prescribes a constant stress formulation to the solid elements. Using this element formulation, the probability of zero energy modes is higher. This is avoided by using the hourglass control with Flanagan-Belytschko viscous form. All the tool parts are modelled as rigid shell parts, where the rollers and mandrel are modelled with a corresponding slope to give a smooth kinematic motion. To ensure the rollers’ 120° separation the u-shaped part in figure 2 is introduced.

2.1. Contact
The contact definitions in this type of problem are very important. The generally unknown parameter is friction, which is selected based on experience with the model. For all the contact models the viscous damping is set to 50%, since oscillation is very likely in this type of problems.

The contact model for the solid parts is $\text{AUTOMATIC\_SURFACE\_TO\_SURFACE}$, which is a penetration based penalty and calculates penetration for both master and slave nodes.

For the contact between the shell elements, the contact model $\text{FORMING\_SURFACE\_TO\_SURFACE}$ is used. It has a more efficient contact definition, which makes the movements run smoothly. The contact between the mandrel and rollers is very important, because the kinematic motion is prescribed the mandrel, which moves downwards and has a constant rotation.
2.2. Material Model
The material models used are 20-RIGID and 112-FINITE ELASTIC STRAIN PLASTICITY. The rigid model is commonly used for tool parts in metal forming, therefore this model is used for the rollers and mandrel.

The material model for the tube and tubesheet is 112-FINITE ELASTIC STRAIN PLASTICITY, an elasto-plastic material model defined by a bilinear stress-strain model and assumes the material to be isotropic. The input parameters for the model can be seen in table 1, and are determined by Madsen et al. [8] for the material AISI 304L. These material parameters are used for both tube and tubesheet.

| Material          | Parameter       | Value   |
|-------------------|-----------------|---------|
|                   | Young’s Modulus | 193 GPa |
|                   | Yield Stress    | 325 MPa |
|                   | Poisson’s Ratio | 0.3     |
|                   | Tangent Modulus | 2.2 GPa |

3. Experimental Setup
In order to validate the numerical model, several experiments are performed. The apparent wall reduction is used as base for a comparison between the numerical model and experiments, measured with an equivalent method. The parameter for validation is hardening of the material compared to the plastic strain in the numerical model. For quantifying the hardening of the material, Vickers hardness is measured. For relating this to a larger area of the tube, the grain structure is inspected. The setup and procedures are presented in the following sections.

3.1. Tube and Tubesheet
The geometry and material of the tubes and tubesheets used in the experiments are presented in table 2.

| Tube                  | Tubesheet                  |
|-----------------------|----------------------------|
| Outer Diameter        | Length-Height-Width        |
| Tube Thickness        | Hole Diameter              |
| Material              | Material                   |
| 10 mm                 | 170-110-20 mm              |
| 0.6 mm                | 10.2 mm                    |
| AISI 304L             | AISI 316L                  |

The centers of the tubesheet holes are placed 19 mm apart along the length of the tubesheet. The next column’s holes are placed 16 mm from the first column along the height and directly in between the holes along the length. Each row consists of 7 holes. The total amount of holes in the tubesheet is 35. Only every other hole is used for these experiments to ensure that adjacent expansions do not influence the current expansion.
3.2. Procedure for Expansion of Joints
The tube expansion process is performed with a Krais 797 tool. Prior to expansion, each tube’s inner and outer diameter is measured, together with the diameter of the tubesheet’s holes. The measurement of the outer diameter of the tube is performed with a micrometer screw gauge, while the inner diameter is measured with a three point micrometer screw. After the expansion the inner diameter of the tube is measured again, and thereby the apparent wall reduction can be calculated by equation 1, where \( u_r \) is the radial displacement, \( c \) is the clearance and \( t \) is the tube thickness.

\[
\%WR = \frac{u_r - c}{t} \cdot 100\%
\]  

3.3. Sample Treatment
The joints of interest are cut out and the surfaces are wet polished to obtain a proper surface for electro polishing. Then 2 cm\(^2\) of the surface are electro polished using the automated Struers LectroPol-5. It is performed to get a required surface for measuring Vickers hardness and improving the visibility of the material structure. For revealing the grain structure the final surface treatment is etching. The etchant used is Carpenter 300 Series, which is a recommended etchant for stainless steel [9], allowing investigation of the grain structure in a microscope.

3.4. Micro Vickers Hardness
The hardness of the tube is measured to inspect the strain-induced martensite in the expanded tube. The hardness is measured with the Micro Vickers Hardness method, which uses a pyramid shaped diamond tip to indent the material. For the experiments the applied load is set to 110 g and a load time of 30 sec to ensure a static load. The indent is measured using the Internal/External Contact Collimation method as specified in the manual for indents under 0.05 mm in length. For the measurement a Galileo Microscan from 1989 is used. The Vickers hardness is calculated with equation 2, where \( F \) is the load and \( d \) is the diagonal length of the indent.

\[
\text{Vickers Hardness} = \frac{2Fd}{A}
\]

Figure 3. Indents with a 0.05 mm offset, the inner tube edge is on the left and the tube-tubesheet interface on the right.
The hardness is measured through the thickness of the expanded tube every 0.05 mm, to get an indication of how the expansion effects the tube throughout its thickness, the measuring points can be seen on figure 3. The measurements are conducted on two specimens: %WR = 6.6% and %WR = 33%.

\[ HV \approx \frac{1.8544 \cdot F}{d^2} \]  

(2)

4. Results and Discussion

4.1. Grain Structure

The grain structure investigations are performed using a AXIO ZEISS microscope with 20x lenses.

Martensite is observed in the inner part of the tube, which is consistent with the findings by Madsen et al. [8]. The martensite is in the form of needle like structured grains. The highest density of martensite is focused mainly around the expansion contact area and its vicinity, as it is shown in figure 4. The red arch indicates the border of the martensite band, which has a width of approximately 150 µm and is formed in the inner part of the tube. It should be noted, that the formation of martensite in austenitic stainless steel is a function of multiple factors such as temperature, strain rate and plastic deformation [10]. It can be speculated that the transition from austenite to martensite is caused by the concentration of plastic deformation in the inner part of the tube. In addition, it should be noted that martensite is observed in the grain structure of the tubesheet, which indicates plastic deformation.

In an extreme case of over-expansion, with apparent wall reduction of 33% the observed density of martensite is higher as shown in figure 5.

![Figure 4. Observation of the grain structure, with %WR = 6.6%, 20x zoom. The red line indicates the border of the martensite band.](image1)

![Figure 5. Observation of the grain structure of an over-expanded tube, with %WR = 33%, 20x zoom.](image2)

The grain structure from figures 4 and 5 is compared to the numerical results of the corresponding expansion, in figures 6 and 7. The plastic strain distribution for the %WR = 6.6% is similar to the martensite formation in the sense of locating the more concentrated plastic strain. For the over-expanded numerical model, %WR = 33%, the plastic strain is, throughout the tube, at a much higher level which is also indicated by the grain structure, where the martensite is formed throughout its thickness.
4.2. Vickers Hardness Results

The results show that in the tube expanded to %WR = 33%, the maximum hardening is located at the inner edge, and the least effected area is at the interface between tube-tubesheet, which is shown in figure 9. Furthermore the results show that in the tube expanded to %WR = 6.6%, the hardening is distributed in a wave like pattern throughout the thickness. The hardness of a tube before expansion is measured to approximately 175HV consistently through the thickness. According to experiments performed by Shirdel et al. [11] on 304L steel, the measured hardness can be used as an indicator for plastic strain concentration. The specific ratio of hardness to strain requires further experiments on the material due to non-linearity, therefore only the distribution is used. The hardness is compared to the plastic strain through the thickness of the tube, and here the indications of the wavelike structure seem to be similar to the hardening, which can be seen in figure 8. The problem when comparing these two results is the non-linear behaviour of the hardness and strain relation. The hardening and plastic strain through the thickness can only indicate the curvature of the strain distribution.

4.3. Discussion

The grain structure investigation and the hardness measurements parameters indicate some source of error. Shirdel et al. [11] stated that hardness measures are highly affected by the specific grain, i.e. measuring martensite shows increased hardness. Since the heat distribution/temperature is unknown when performing the roller expansion, the austenite-martensite transformation can be caused by heat development.

In addition, during the grain structure investigation, martensite grains were observed in the tubesheet, which could be an interesting base for further examination of the impact it has upon the joint quality. This also occurs in the numerical model, where plastic strain (that reaches up to 0.08) in the interface’s vicinity of the tubesheet might be the cause. It should be noted that, the prescribed material model for the tubesheet, has a lower yield stress compared to AISI 316L.

The validation method used in this paper, focuses solely on the strain distribution through the tube thickness. Another method to validate the model could be to measure the applied torque on the mandrel, which can be related to a better process control understanding.
5. Conclusion

In this study the aim is to develop a valid numerical model, that includes the kinematic motion of the rollers, in order to simulate the multi-pass rolling process and its influence on the resulting plastic straining of the tube material using LS-DYNA.

The model’s validity is achieved by comparing the plastic strain distribution in the model to Micro Vickers Hardness measures across the tube thickness. Afterwards, its relation to a larger area of the tube is attained, by investigating the austenite-martensite transformation. The model successfully predicts that the plastic strain concentration will be in the inner third (~150 μm) of the tube, which is confirmed by the experiments on a specimen with a %WR = 6.6%. However, additional work is required to reach better quantitative relations between the numerical model and the experiments.

From a computational point of view, the numerical model is sufficiently stable. This constitutes the basis for an extensive study of the relation between geometric and material properties, in order to ensure the specification of the optimal process parameters. Finally, it is evident that the rule of thumb in relation to the relative wall thickness reduction is not sufficient to ensure a good quality.

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