Parameter study and a numerical model of mechanical roller expansion of tube-tubesheet joint

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Abstract
The tube-tubesheet joint by roller expansion is commonly used in the heat exchanger production industry. This process has quality issues, due to over or under expansion of the tubes. This paper focuses on determining the parameters' influence on the joint's quality. A numerical model is made using LS-DYNA, where the rotation of the rollers is modelled to simulate the step-wise deformation of the tube. The model is made in 3D, with an assumption of plane strain for a section of the tube and tubesheet. Experiments are conducted and evaluated using pull-out force as a quality measurement. A multi linear regression analysis is conducted on the collected data from the experiments. This is done in order to investigate the four main parameters' influence on the joint's quality: Torque, rolling depth, clearance and tubesheet hole diameter. It was concluded that clearance has no effect on the quality of the joint, where torque and rolling depth have proven to be of significance. Furthermore, from the numerical model it was discovered that highly fluctuating hoop stresses result in the wave like plastic strain distribution throughout the tube's thickness.

Keywords: Tube-tubesheet joint, Mechanical roller expansion, Plastic strain, Numerical model, Parameter study, Multiple linear regression analysis

Nomenclature

$\%WR$	Apparent wall reduction $[\%]$
u_r	Radial displacement $[mm]$
c	Clearance $[mm]$
t	Wall thickness of the tube $[mm]$
F	Pull-out force $[N]$
d	Tubesheet hole diameter $[mm]$
l	Rolling depth $[mm]$
μ	Friction $[-]$
P^*	Contact Pressure $[MPa]$

1. Introduction

Heat exchangers work by the exchange of heat through tube walls. These tubes are expanded into tubesheet holes in order to form a leak proof joint. An illustration of a heat exchanger can be seen in figure 1. There are multiple expansion methods for creating the tube-tubesheet joint. However, in this paper only the mechanical roller expansion process is the object of investigation. In this process, the tubes are expanded by a tool, that consists of a conical mandrel that pushes the rollers outwards, towards the inner tube wall in order to expand the tube into the tubesheet hole and form contact between them, and with that create a leak proof joint.

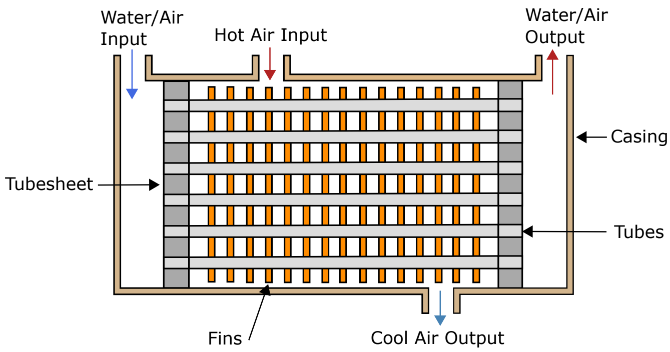

Fig. 1 Illustration of the components in a heat exchanger.

In production setups, a widely used indication for a tube-tubesheet joint's quality is the Apparent Wall Reduction (%WR). It is calculated using equation 1:

$$\%WR = \frac{u_r - c}{t} \cdot 100\% \qquad (1)$$

Here u_r is the radial displacement of the inner surface of the tube, c is the clearance between the tube and the tubesheet and t is the wall thickness of the tube.
Furthermore, %WR within the acceptable ranges does not guarantee a leak proof joint, and therefore all heat exchangers have to pass a leak proof test before being approved for use. Leakage is mainly caused by over or under expansion, and on a smaller scale, by stress

corrosion cracking. Leaking joints are costly to repair, because the heat exchanger has to be disassembled and the leaking joints undergo either re-rolling or re-tubing. In worst case scenario, the whole tubesheet has to be replaced, due to plastic deformation of the tubesheet holes.

The roller expansion process is an old method that is widely used in the industry. An early patent [1] approved in 1888 in the U. S. includes the same process principles as today, where as stated before, the rollers are forced outwards by a mandrel, expanding the tube.

During the years, several scientific papers have been investigating the expansion process and its related issues. The first one to scientifically document the process was by Oppenheimer [2] in 1927, who experimentally investigated the influence of different process parameters. Later, in 1943 Grimison and Lee [3] performed a parameter study based on experimental data, which is still used as a basis for the process. During the 1990's, Updike et al. performed several parameter studies [4, 5], based on an advanced mathematical model, validated according to experiments. The findings from the model are still incorporated in the TEMA standards [6]. One of the findings by Kalnins and Updike [4] in 1991, was that the tube's material's tangent modulus in relation to the tangent modulus of the tubesheet material, determines at which %WR the highest contact pressure will be obtained. For example, if this ratio is less than 1, then the contact pressure will peak at 4-5 %WR.

A common approach for determining the integrity of this joint is to perform a pull-out test. In 2002, an equation for estimating the pull-out force as a function of the contact pressure was presented by Allam and Bazergui [7], see equation 2. Here d is the diameter of the tubesheet hole, l is the rolling depth, μ is the friction between the tube and tubesheet and P^* is the contact pressure.

$$F = \pi d l \mu P^* \tag{2}$$

In 2003, Shuaib et al. [8] found from experiments that the effect of over-enlarged tubesheet holes is of less importance than earlier assumed. The tested joints, which had 7 times the clearance recommended in TEMA [6], required the same pull-out force to break as the ones within the recommendations. Same year Merah et al. [9] found, using an axisymmetric model, that the contact pressure gets more sensitive to clearance with the increasing of the tangent modulus for the tube material.

Several numerical models simulating the expansion process have been used for the investigation of parameters' influence. The majority of the models are axisymmetric, where on the inside of the tube an equally distributed pressure is applied, which assumes an infinite amount of rollers. The modelling of the process as axisymmetric was first proposed by Kasraie et al. [10] in 1983. In 2016, Madsen et al. [11] conducted a comparison between three different finite element models which were compared to experimental data. The models were; a 2D planar model with plane strain assumption, a 2D axisymmetric model and a 2D model with inclusion of the rollers' motion and a plane strain assumption. The comparison showed that the 2D model with inclusion of the rollers' motion and plane strain assumption results in the best agreement with the conducted experiments. The model is simulating the accumulated plastic strain of the tube by including the rollers.

A deeper understanding of the influence of the process parameters are still of interest in order to assure leak proof joints, thereby avoiding expensive repairs. In this paper, the process parameters' influence will be investigated through a numerical model and experimental study.

2. Numerical Model

In order to obtain a correct plastic strain distribution, the model is formulated as a 3D numerical model with inclusion of the rollers' movement and plane strain assumption. The roller movement and the plane strain assumption are similar to that in the model proposed by Madsen et al. [11]. Due to the inclusion of the rollers and the extensive contact calculations, this can be considered as a multi-physics problem, for which LS-DYNA is found to be better suited.

The model consists of 9 parts in total. The parts in question are as follows; tubesheet, tube, mandrel, 3 rollers, a toolbase for separating the rollers and two rings for locking the tube in rotation. The parts can be seen in figure 2.

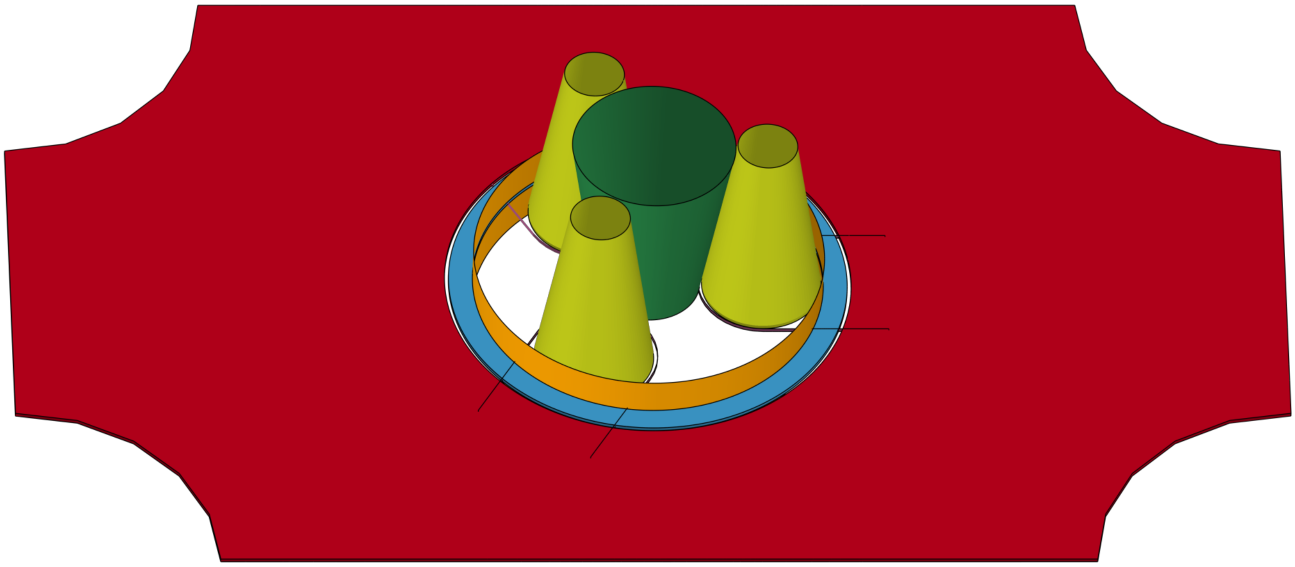

Fig. 2 Graphical representation of the numerical model.

The plane strain assumption is obtained by modelling the deformable parts with one element in height. Furthermore, the tube is constrained in translation in the Z-direction by a global bottom and top plane, and in rotation in Z by the rings. The rings' nodes are merged with the tube's corresponding nodes, and the rings' free nodes are locked in X and Y translation. The tubesheet is constrained at the edges in the respective direction as a cut-out. The rollers are only able to move in plane, and are kept separated by an angle of 120° by the toolbase. The top and bottom center nodes in the toolbase are constrained to only allow rotation around the Z axis.

The tube and tubesheet are the only parts which have a deformable material model. The model consists of a bilinear elasto-plastic material description with a isotropic assumption. Which requires Young's Modulus, Tangential Modulus, Poission's Ratio and the Yield Stress as inputs to describe the plastic behaviour. Since the deformable parts experience large deformations, the termination error negative volume space can occur. Here, this is avoided by using a constant stress element formulation. When using this element formulation, zero energy modes can occur, which is avoided by using Hourglass Control.

The moving parts are modelled as rigid shells, and the rings are modelled as elastic materials, but with a very low stiffness, so they do not influence the deformation of the tube during expansion.

All contacts defined in the model are penalty based, meaning that all penetrations of parts are penalised with equally sized opposite force. The contact models used are FORMING-SURFACE-TO-SURFACE for the shells element parts and AUTOMATIC-SURFACE-TO-SURFACE for the solids. The friction coefficients between the parts are included in the model. These coefficients are determined through multiple iterations, in order to obtain smoother contacts. In addition, a viscous damping of 50% is applied between the different parts, as a recommendation when modelling metal forming.

The mandrel motion is prescribed with a velocity curve for the rotation and translation. For the inclusion of springback, the mandrel is moved back to starting position after 3/4 of the simulation time. In order to obtain a stable result for the springback, mass damping is used by applying a time dependent damping force to all nodes in the deformable parts. The removal of the mandrel and the following mass damping, are relaxing the system and allows springback to occur.

The model build up is verified in a previous paper [12], accepted for the 36$^{\text{th}}$ IDDRG conference in Munich and publication in the Journal of Physics: Conference Series. The model verification is done by comparing the results from the model to experimental Micro Vickers Hardness results and grain structure investigations.

3. Experiments

The tube-tubesheet expansion process is performed using a Krais 797 tool driven by a Bosch GBS 18 V-EC electrical drill. The specifications for the tube and tubesheet are presented in table I. In order to avoid influencing the quality of the results, only every other tubesheet hole is utilised. Thus, twelve expansions are performed per tubesheet as seen in figure 3. Furthermore, nine different tubesheets are expanded, where the controlled parameters are rolling depth and torque. The experiments are performed by varying the rolling depth in two levels (12 and 20 mm) and the torque in three settings (1, 3 and 6).

Tab. I Specification for tubesheet and tube.

Tube		**Tubesheet**	
Outer Dia.	$10mm$	L*H*T	170 * 110 * 20 mm
Thickness	$0.6mm$	Hole Dia.	$10.2mm$
Material	AISI304L	Material	AISI316L

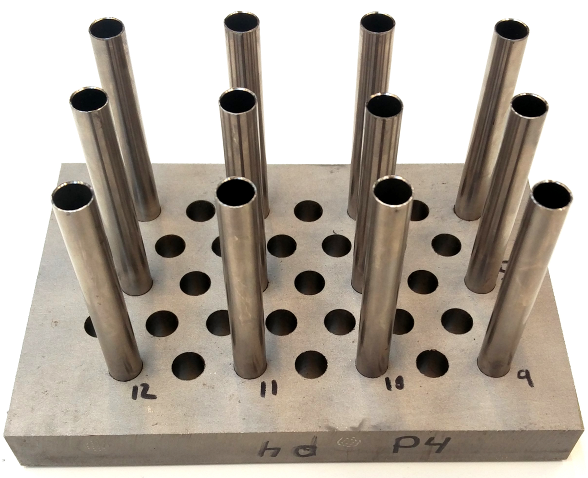

Fig. 3 Example of the a tubesheet after expansion.

3.1 Pull-Out Test

The pull-out tests are performed using a Zwick Tensile machine, for which an appropriate setup is devised, which can be seen in figure 4.

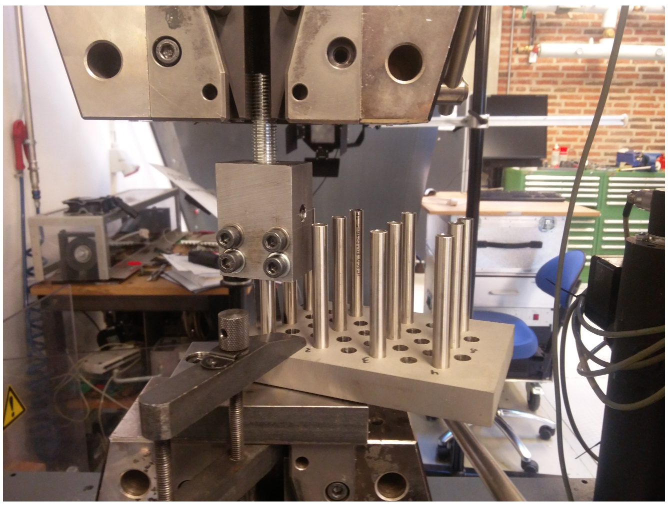

Fig. 4 The experimental setup for the pull-out test.

As seen in figure 5, joints that have a rolling depth of 20 mm, require a larger force to fail, due to the larger contact area. Furthermore, in this paper, the pull-out force is identified as the maximum tensile force.

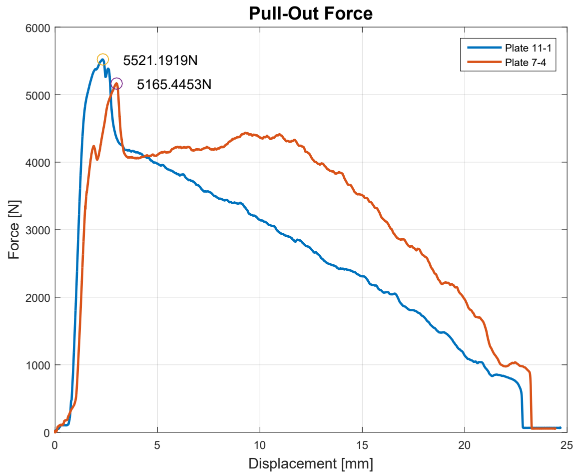

Fig. 5 Two tests with high torque setting, but plate 11-1 has a rolling depth of 20 mm, while plate 7-4 has 12 mm.

Through the experiments it is observed that when applying a high torque in a low rolling depth, the expansion from the conical front part of the rollers, increases the rolling depth. The tube and rollers can be seen in figure 6.

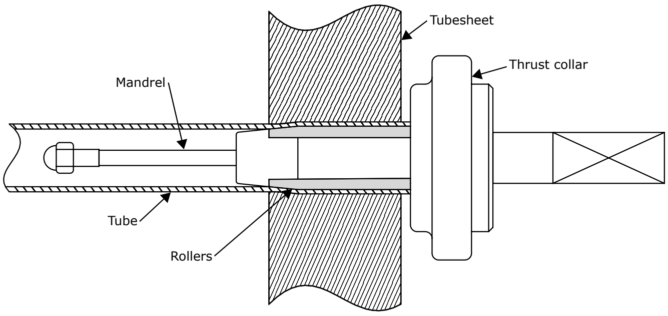

Fig. 6 A sketch of the roller expansion for the tube-tubesheet joint process.

3.2 Data Collection

While conducting the experiments, data for the parameters of interest is collected. More specifically, the inner diameters of the tube and the tubesheet holes together with the outer diameter of the tube are measured and documented before expanding, together with the inner diameter of the tube after expansion. This is done in order to calculate the %WR. From the pull-out experiments, the required pull-out force is documented. Other notable parameters documented are: The rolling depth, clearance, torque and the tubesheet hole diameter after pull-out. The collected data is used in a statistical analysis in order to determine their individual influence

on the joint's quality. In this study, the joint's quality will be defined as the pull-out force.
A summary of the experiments can be seen in table II.

4. Statistical Analysis

The statistical analysis method used for investigating and describing the relationship between the pull-out force and the variables of interest is multiple linear regression analysis. As stated previously, the influence of the rolling depth, torque, diameter of the tubesheet hole and clearance, on the pull-out force are investigated. The data had to be checked for compliance with the prerequisite assumptions of the method, before conducting the actual analysis.

The analysis yields $R^2 = .568$, which roughly translates into: 57% of the pull-out force's variability is explained by the model's independent variables. Furthermore, in table III, each independent variable's significance value, regression coefficient, and corresponding standardised regression coefficient value are presented. In the table it can be observed that torque, rolling depth and diameter of the tubesheet hole contribute significantly to the regression model, while the clearance does not. In order to state that a variable is statistically significant, it must have a significance value smaller than 0.05.

Positive regression coefficients yield a positive relationship between the regressor and the outcome variable, thus the increase of the first results in an increase in the latter. The opposite applies for negative coefficients, which signify a negative relationship between the variables. A comparison between the magnitude of the influence each predictor variable has on the outcome variable, can be achieved by contrasting their respective standardised regression coefficients. Here it can be observed, that torque exhibits the highest value (and consequently the largest influence on the pull-out force) followed by the rolling depth. This is further supported by the results from the pull-out test, where the tube-tubesheet joints that were expanded with a higher torque and larger rolling depth required the highest pull-out force.

The unstandardised regression coefficients from table III can be used to determine the equation that describes the relationship between the pull-out force and the independent variables. However, this has to be interpreted with caution, because each variable's contribution is computed when all other independent variables are held constant. Thus, for example, the pull-out force increases 30.706 N for each millimetre of rolling depth, while all other independent variables are held constant.

Tab. III Results of the multiple linear regression analysis.

	Unstandardised Coefficients	Standardised Coefficients	Sig.
	B	Beta	
(Constant)	172343.349		0.004
Rolling Depth	30.706	0.228	0.001
Kliks - Torque	183.667	0.722	0.000
I. Diam. Tubesheet	-16628.900	-0.207	0.004
Clearance	7915.238	0.130	0.063

5. Comparison

The findings from the numerical model show a wave-like pattern of the plastic strain throughout the tube's thickness. This plastic strain is very important when estimating the contact pressure of the joint [11]. In figure 7, the accumulation of plastic strain over time throughout the thickness of the tube can be seen.

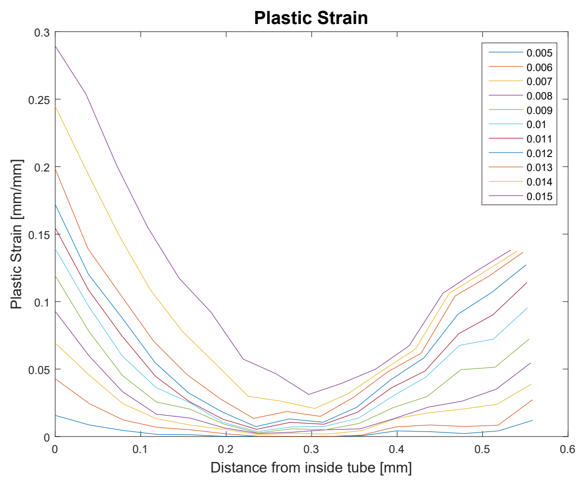

Fig. 7 Plastic strain throughout the tube's thickness over time.

The plastic strain development is a product of the rollers' kinematic motion, where the continuous loading and unloading accumulates plastic strain. This fluctuating behaviour can be seen in figure 8, where the hoop stress in the tube has high amplitudes in the inner and outer elements of the tube. Whereas, the middle element does not experience as large amplitudes in the hoop stresses, which is also the case for the plastic strain at that element.

Tab. II Summary of the results from the experimental investigation, with varying torque and rolling depth.

Settings		Pull-Out Force			%WR			Tubesheet Hole
Torque	Rolling Depth [mm]	Mean [N]	SD [N]	CV [%]	Mean [%]	SD [%]	CV [%]	Expanded [%]
1	12	4038.75	515.99	12.78	3.55	1.40	39.30	0.175
3	12	4265.93	345.79	8.11	6.10	1.54	25.27	0.141
6	12	4773.81	289.05	6.05	13.16	2.02	15.31	0.247
1	20	3897.50	254.89	6.54	2.14	0.90	41.86	0.061
3	20	4625.83	202.38	4.37	2.23	1.37	61.25	0.102
6	20	5185.83	207.34	4.00	5.33	1.29	24.21	0.110

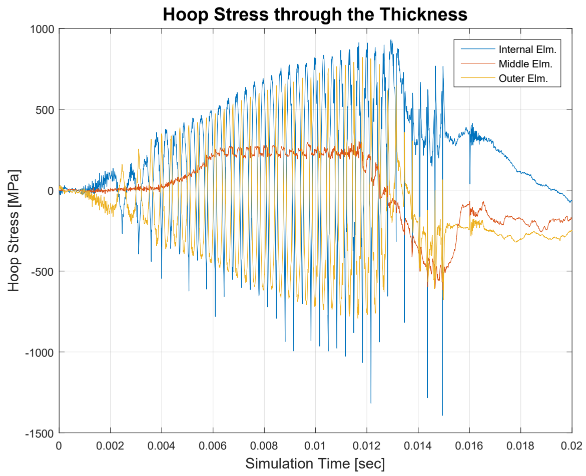

Fig. 8 Hoop stress shown for three elements throughout the tube's thickness.

This finding shows that it is very difficult to estimate the plastic strain, since it is highly influenced by the kinematics of the rollers, which also includes the inertial response in the model.

6. Discussion

The findings from the statistical analysis and experiments should not be considered as generic, and should therefore not be considered as valid for other cases.
The statistical findings show that the torque is the most significant factor because it has the largest influence on the pull-out force. The pull-out force increases with an increase in torque, however measurements of the tubesheet holes after expansion indicate that, so does the deformation and hardening, which are related to over expansion.
The second most influencing parameter is found to be the rolling depth. Increase in the rolling depth will increase the pull-out force. However, long term effects should be investigated, before expansions beyond the depth recommended by TEMA [6] are used in production.
The results for tubesheet hole size show a negative influence on the pull-out force with increasing size. Intentionally, the size was not changed, and the maximum difference between the smallest and the largest hole is $50\mu m$. In the linear regression method clearance and tubesheet hole diameter are independent variables, while in reality, the tubesheet hole size has an influence on the clearance. Thus, the results are of questionable applicability in a production setup.
The clearance's effect on the pull-out force can not be evaluated, since it was not found to be statistically significantly. Supported by the findings in the paper by Shuaib et al. [8] where clearances 7 times the ones stated in TEMA [6], the clearance is found to have no effect on the joints, within the investigated range.
An investigation of the %WR as a quality gauge is of relevance, due to its extensive use in the industry. The measurements for %WR in the experiments show that the %WR increases with the torque beyond the expected percentage of an optimal joint. However, the required pull-out force continues to increase with the torque beyond this percentage. This, together with the far larger standard deviation for the %WR than for the pull-out force, indicates that the %WR is unreliable as a quality measurement. The %WR results should be related to the tolerances of the measurements, which due to the small sizes of the tubes and tubesheet holes have a significant influence on the %WR.

In the current state of the numerical model, it is not possible to make an exact assessment of the joint's quality, as a relation to the contact pressure. From the statistical analysis, it was determined that torque has a high influence on the joints' quality. Therefore, it would be of interest to be able to calculate it using the numerical model. However, some difficulties were experienced while trying to model the torque, for example, when the motion of the mandrel is at the same time a rotation and a displacement in the Z axis. A possible solution to this problem could be to apply a vector force in the nodes of the mandrel.
In its current state, the model can determine the wave-like plastic strain distribution. There, it was discovered that, the fluctuating hoop stresses in the tube are

the cause of the plastic strain throughout the tube's thickness. As stated before, these stresses are highly influenced by the kinematics of the rollers. Thus, the kinematics for the model are of high importance, when it comes to determining the plastic strain distribution to obtain the contact pressure [11].

7. Conclusion

The focus of the study presented in this paper, has been to investigate different parameters' influence on the quality of the roller expansion process. This is done in order to achieve a greater understanding of the process. This in turn, could enable avoidance of expensive re-rolling, re-tubing and replacement of tubesheets. The findings presented in this paper have led to the following conclusion:

- %WR is an unreliable quality measurement.
- Clearance has no effect on the quality of the joints investigated.
- Torque is the parameter with the most influence on the joints' quality. The torque should be increased to a maximum, while still avoiding over expansion issues.
- Rolling depth is the second most influencing parameter. The rolling depth should be in full depth, up to the limit set by general recommendations.
- The numerical model is able to determine the plastic strain distribution. However, it is not currently able to relate the real pull-out force to the contact pressure, and is therefore, not able to predict the true quality of the joint.

Acknowledgement

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References

[1] C. Robinson, Tube-expander. No. US Patent 381583 A, United States Patent and Trademark Office, 1888.

[2] P. H. Oppenheimer, "Rolling tubes in boiler plates," American Society of Naval Engineers, vol. 39, no. 2, pp. 417–426, 1927.

[3] E. D. Grimison and G. H. Lee, "Experimental investigation of tube expanding," Transactions of the ASME, 1943.

[4] A. Kalnins and D. P. Updike, "Contact pressure in rolled tube-tubesheet joints," Nuclear Engineering and Design, vol. 130, no. 2, pp. 229–234, 1991.

[5] D. P. Updike, A. Kalnins, and S. M. Caldwell, "Residual stresses in transition zones of heat exchanger tubes," Journal of Pressure Vessel Technology, vol. 114, no. 2, pp. 149–156, 1992.

[6] T. E. M. Association, Standards of the tubular exchanger manufacturers association. Tubular Exchanger Manufacturers Association, Inc., ninth ed., 2007.

[7] M. Allam and A. Bazergui, "Axial strength of tube-to-tubesheet joints: Finite element and experimental evaluations," Pressure Vessel Technoly, vol. 124, no. 1, pp. 22–31, 2002.

[8] A. N. Shuaib, N. Merah, M. K. Khraisheh, I. M. Allam, and S. S. Al-Anizi, "Experimental investigation of heat exchanger tubesheet hole enlargement," Journal of Pressure Vessel Technology, vol. 125, no. 1, pp. 19–25, 2003.

[9] N. Merah, A. Al-Zayer, A. N. Shuaib, and A. Arif, "Finite element evaluation of clearance effect on tube-tubesheet joint strength," International Journal of Pressure Vessels and Piping, vol. 80, no. 12, pp. 879–885, 2003.

[10] B. Kasraie, J. S. Porowski, W. J. O'Donnell, and A. Selz, "Elastic-plastic analysis of tube expansion in tubesheet," ASME Pressure Vessel and Piping Conference, vol. 71, 1983.

[11] S. B. Madsen, B. Gervang, C. H. Ipsen, and A. S. Kristensen, "An improved numerical model of the tube-tubesheet joint roller process," in Journal of Materials Processing Technology, vol. 246, August 2017.

[12] D. Alexouli, D. Bøjesen, L. R. Bøystrup, C. R. Klose, G. N. Nikolov, and K. B. Nielsen, "3d numerical model of tube-tubesheet joint roller expansion process," in Journal of Physics: Conference Series and the IDDRG 2017 conference proceedings, IOP Publishing, 2017.