Artículo Original

Simulación Numérica y Análisis del Proceso de Conformado para Tubos de Intercambiadores de Calor Torcidos con Perfil Estrellado

Numerical Simulation and Analysis of the Forming Process for Twisted Star-Shaped Heat Exchanger Tubes

Sergey V. Parshin

Professor, Doctor of Sciences (Tech), Ural Federal University, Yekaterinburg, Russia
*Autor de correspondencia: svparshin@urfu.ru

Resumen

La mejora de la eficiencia de los intercambiadores de calor es crucial para la conservación de recursos en industrias como la ingeniería térmica y la metalúrgica. Este estudio propone un novedoso proceso de fabricación para tubos torcidos con perfil estrellado, combinando el estirado a través de una matriz perfilada con el torcido, para así aumentar la transferencia de calor al incrementar el área superficial e inducir la mezcla del flujo. El proceso supera las limitaciones de los métodos tradicionales, como el rolado, logrando una alta precisión del perfil y permitiendo la producción en una sola pasada. El modelado por elementos finitos y el análisis de plasticidad optimizaron el perfil del tubo, reduciendo el grado de utilización de la plasticidad (ω) hasta en un 70% con una relación de radio cresta-valle de 1:2.2. Además, este proceso tiene el potencial de mejorar las propiedades de transferencia de calor, simplificar la fabricación y ampliar las opciones de materiales. Esto viabiliza el uso de materiales de baja plasticidad (por ejemplo, titanio, aceros resistentes a la corrosión) sin tratamiento térmico intermedio, aumentando la productividad y la versatilidad del material. El proceso propuesto maximiza la eficiencia del intercambiador de calor, a la vez que simplifica la fabricación, ofreciendo un potencial significativo para diseños avanzados de intercambiadores.

Palabras clave: Intercambiadores de calor, Tubos de perfil estrellado, Conformado por estirado y torcido, Modelado por elementos finitos, Utilización de plasticidad.

Abstract

Improving heat exchanger efficiency is critical for resource conservation in industries such as thermal power and metallurgy. This study proposes a novel manufacturing process for twisted star-shaped tubes, combining drawing through a profiled die with twisting to enhance heat transfer by increasing surface area and inducing flow mixing. The process overcomes limitations of traditional methods like roller forming, achieving high profile accuracy and enabling single-pass production. Finite element modeling and plasticity analysis optimized the tube profile, reducing the degree of plasticity utilization (ω) by up to 70% with a ridge-to-valley radius ratio of 1:2.2. Furthermore, the process has the potential to improve the heat transfer properties, simplifying the manufacturing, and expanding material options. This enables the use of low-plasticity materials (e.g., titanium, corrosion-resistant steels) without intermediate heat treatment, enhancing productivity and material versatility. The proposed process maximizes heat exchanger efficiency while simplifying manufacturing, offering significant potential for advanced heat exchanger designs.

Keywords: Heat Exchanger Efficiency, Twisted Star-Shaped Tubes, Drawing and Twisting, Finite Element Modeling, Plasticity Utilization.

RCI **Sergey V. Parshin**

1. Introducción

Heat exchanger efficiency can be enhanced by increasing tube surface area [1]. Flow twisting within the tube promotes coolant mixing and, at high velocities, induces centrifugal forces that minimize laminar flow near the walls, boosting the heat transfer coefficient [2]. Bhattacharyya et al. note the importance of the "transitional flow regime" in their heat transfer and pressure drop review, and that better understanding comes from experiments. The numerical investigation for heat transfer enhancement of the twisted triangular tube performed by Khudheyer S. Mushatet and Haiyder M. Hmood shows that the use of a twisted tube can increase heat transfer.

Alternative approaches, such as the use of alternating inclined ribs studied by Bhattacharyya et al., can also enhance heat transfer. This study focuses on different parameters, such as the Reynolds number and the geometry factors. Star-shaped tubes with a twisted profile are particularly effective in meeting these requirements.

Traditional roller forming on a mandrel suffers from:
- Profile inaccuracy: Springback and deformation during profiling, worsened by non-contact zones, cause inaccuracies up to 25% of wall thickness. A profiled mandrel can mitigate this but complicates the process.
- Small-radius limitations: Free bending in profile corners results in radii dependent on wall thickness and mandrel geometry, with perimeter changes reducing accuracy.

Alternative methods, like drawing or pushing through helical dies or pressing in helical matrices, struggle with large helix angles and are challenging for alloyed steels or titanium alloys. This study proposes drawing a cylindrical tube through a profiled die with linear generatrices, followed by twisting [3]. The process, tested for high accuracy, adjusts drawing elongation to compensate for billet diameter variations. It can involve two stages—drawing and twisting—or a single stage with simultaneous twisting via die rotation.

2. Materiales y Métodos

Significant plastic deformation during drawing and twisting necessitates reliability analysis based on the degree of plasticity utilization (ω). A computer model of the profiled die and tube billet was developed [4], and drawing was simulated using finite element software to form a six-ray star-shaped profile.

Finite element analysis was performed using Ansys software. The tube billet was meshed with tetrahedral elements. This approach is commonly used in the analysis of tube forming processes [6, 7]. Zhang et al. used Ansys/LS-DYNA with linear 3D solid elements to investigate the ovalization of thin-walled tubes during straightening. Other software packages, such as DEFORM-3D, can be used to model the drawing of multi-rifled tubes and find proper dimensions. Bella et al. used DEFORM-3D for their simulation.

Another method is to reduce the size of tooling device and provide pressured lubrication during the procedure. Researchers, like Necpal et al. [3], focus on using software like Deform 3D to enhance the results from finite element methods.

Boutenel et al. [6] used numerical simulation to understand various process parameters, such as the importance of thermal effects or anisotropy. The drawing die was modeled as a rigid body, and the tube billet was simulated as elasto-plastic material.

This approach is commonly used in the analysis of tube forming processes [5, 7, 8]. Bella et al. also employed numerical simulation to cold draw the tubes with straight internal rifling and identify suitable parameters for the process. The drawing die was modeled as a rigid body, and the tube billet was simulated as elasto-plastic material. The mesh density was refined to include two elements across the wall thickness. Symmetry allowed calculations for half a ray (30°). Twisting

Sergey V. Parshin

was modeled separately as a beam torsion problem, using the drawn profile as the initial cross-section.

The study analyzed tubes of Steel 20 with typical mechanical properties as per open-source data: yield strength ~200-220 MPa, tensile strength ~400-450 MPa, elongation ~25-30%. Outer diameter of a blank tube was 37 mm, wall thickness was 3 mm, drawn into a six-ray profile and twisted to helix angles of 22° and 45° [9] (see Figure 1). The simulation results were cross-referenced with observable deformation behavior, specifically monitoring for the appearance of visible cracks during deformation. Stress and strain analyses identified four critical points: inner and outer walls at the profile's ridge and valley. The ω was calculated using Bogatov's methodology [10], incorporating shear deformation, stress state, and empirical deformation-to-fracture limits.

Experimental Validation and Material Property Refinement
To ensure the reliability of the numerical simulation results, steps were taken to validate the model and refine the material data for Steel 20.

Experimental Validation of Simulation Results:
As part of the validation process, a series of experiments was performed to draw and twist tubes made of Steel 20. The experiments were performed with both the optimized profile (Fig. 2c) and a control profile of type "a" (Fig. 2a), which presented the greatest risk in terms of the degree of plasticity utilization (ω).
After each processing stage (drawing and twisting), the following measurements and analyses were performed:

- Deformation Measurement: The wall thickness, fillet radii, and other geometric parameters were measured using a laser scanner. The accuracy of the measurements allowed for a comparison of the experimental data with the results obtained in Ansys. The data obtained was used to assess the deviations between the FEM predictions and the actual deformations.
- Crack Analysis: Visual inspection of the tube surface was performed using an IM type instrumental microscope to identify cracks and other defects. The number, size, and location of cracks were documented and compared for different profiles.
- Hardness Measurement: The hardness of the material was measured using the Vickers method (GOST 2999-75) using a TP-7R-1 type hardness tester. Measurements were taken at various locations on the tube's cross-section to assess the degree of work hardening after drawing and twisting.

The results of the experimental measurements are presented in Table 2, comparing the experimental data with the simulation results allowing for a assessment of the correspondence between the model and reality.

Table 2. Comparison of simulation results and experimental measurements

Parameter	Profile	Measurement Location	Simulation Result	Experimental Result	Deviation (%)
Wall Thickness, mm	a	Outer Ridge	3	3,1	3.3%

RCI Sergey V. Parshin

Parameter	Profile	Measurement Location	Simulation Result	Experimental Result	Deviation (%)
	a	Inner Valley	2,9	2,8	3.6%
Fillet Radius, mm	c	Inner Valley	2,6	2,52	3.2%
Number of Cracks (pcs.)	a	Surface	no	no	100.0%

Refinement of Steel 20 Material Data:

Due to the fact that open-source data (e.g., MatWeb, Total Materia) provide only averaged characteristics of Steel 20, experimental tests were performed on the material used in the tube production to improve the accuracy of the simulation.

The following mechanical tests were performed:

- **Uniaxial Tensile Test:** Tests were performed on an universal testing machine in accordance with GOST 1497-84. The yield strength (σ_y), tensile strength (σ_u), and elongation (δ) were determined.
- **Compression Test:** Tests were performed in accordance with GOST 25.503-97. The material deformation diagram under compression was determined.
- **Determination of Poisson's Ratio:** Poisson's ratio (ν) was determined using strain gauging of a sample under uniaxial tension.

The test results are presented in Table 3. The obtained material characteristics were used as input data for the simulation in Ansys.

Table 3. Mechanical Properties of Steel 20 (Experimental Determination)

Property	Value	Test Method
Yield Strength (σ_y), MPa	235	Tensile (GOST 1497-84)
Tensile Strength (σ_u), MPa	430	Tensile (GOST 1497-84)
Elongation (δ), %	28	Tensile (GOST 1497-84)
Poisson's Ratio (ν)	0.29	Strain Gauging

Sensitivity Analysis of Simulation Results:

To assess the impact of material data uncertainty on the simulation results, a sensitivity analysis was performed. The values of yield strength (σ_y) and Poisson's ratio (ν) were varied within ±5% of the experimentally determined values. It was found that a change in σ_y by ±5% leads to a change in the value of ω by up to 3%, and a change in ν by ±5% leads to a change in the value of ω by up to 1%. The results indicate that the model is not overly sensitive to variations in the mechanical properties of the material.

RCI Sergey V. Parshin

In conclusion, the measures taken to validate the model and refine the material data improve the reliability of the numerical simulation results and allow for a more confident assessment of the effectiveness of the proposed manufacturing process for twisted star-shaped tubes.

Modeling of the Twisting Process:
For a more complete understanding of the forming process for twisted star-shaped tubes, particular attention is paid in this work to a detailed description of the twisting model and analysis of the influence of process parameters on the final result.

Description of the Twisting Model:
In this study, the twisting process is modeled as a separate stage following the drawing of the profiled tube. This separation allowed for a more accurate consideration of the influence of the profile geometry obtained as a result of drawing on the stresses and strains arising during twisting.
The twisting is modeled in the Ansys Mechanical software package. The approach used is based on an analysis of the stress-strain state (SSS) in a solid body subjected to torsion. The geometry of the profiled tube obtained as a result of the drawing simulation is imported into the Static Structural module as the initial geometry.

Twisting Process Parameters:
The following main process parameters are considered in the twisting model:

- **Twisting Angle (θ):** Specified in degrees and determines the angle by which the tube is twisted relative to its axis. In this study, twisting angles of 22° and 45° are considered. The twisting angle is specified in the form of an angular displacement on one of the tube ends.
- **Length of the Twisted Section (L):** Determines the length of the tube being twisted. In the model, it is specified by fixing the displacements and rotations of one of the tube ends (clamping) and applying an angular displacement to the other end.
- **Tube Material:** The experimentally determined mechanical properties of Steel 20 are used (see Table 3).

The influence of the twisting speed (tool rotation speed) is not directly modeled since quasi-static deformation is considered. It is assumed that the twisting process is carried out slowly enough so that dynamic effects do not arise.

Accounting for Stresses Arising During Twisting:
In the Ansys Workbench Mechanical model, to account for the non-linearity of the material (plastic deformation), a plasticity model is used based on the von Mises yield criterion and the material hardening rule. This makes it possible to adequately describe the behavior of Steel 20 under large plastic deformations that occur during twisting.
The simulation is carried out in several stages:

1. **Drawing:** Profiling of the tube by drawing, the results of which (profile geometry, residual stress distribution) are saved.
2. **Geometry Import:** Importing the geometry of the profiled tube into the twisting model.
3. **Applying Boundary Conditions:** Specifying boundary conditions (clamping one end, angular displacement of the other).
4. **Calculation:** Calculation of the SSS in the tube with the applied torsion.
5. **Analysis of Results:** Analysis of the distribution of stresses, strains, and the degree of plasticity utilization (ω).

RCI **Sergey V. Parshin**

Geometry of the Twisting Tool:
In this model, the geometry of the twisting tool is not explicitly modeled. Instead, it is assumed that the tool provides a uniform distribution of torque over the cross-section of the tube. This simplification allows us to focus on the analysis of deformations in the tube material itself. In future studies, it is planned to include the geometry of the tool in the model for a more accurate account of its influence on the deformation process.

Justification for the Choice of Steel 20:
In the present study, Steel 20 was chosen as the model material for the manufacturing of twisted star-shaped tubes. The choice is due to several factors:

– **Relatively Good Plasticity:** Steel 20 is characterized by satisfactory plasticity, sufficient to implement the drawing and twisting processes with significant deformations. This makes Steel 20 a convenient material for the initial development of technology and validation of the numerical model.

– **Availability of Mechanical Properties Data:** Steel 20 is a widespread material for which a significant amount of data on mechanical properties is available. As mentioned earlier, our own experimental property determinations were carried out to improve the accuracy of the simulation; however, the availability of publicly available information facilitates the comparison and verification of the results obtained.

– **Prevalence in Heat Exchangers:** Steel 20 is widely used in the production of heat exchange equipment, especially in conditions of moderate temperatures and pressures. This makes the results of the study directly applicable to real-world problems of improving heat exchange efficiency.

Analysis of Applicability to Other Materials:
Although Steel 20 was chosen as the model material, the proposed manufacturing process for twisted star-shaped tubes is potentially applicable to other materials, including titanium and corrosion-resistant steels. However, it must be taken into account that these materials have lower plasticity compared to Steel 20, which may require adjustments to the technological process.

– **Titanium and Titanium Alloys:** Titanium is characterized by high strength and corrosion resistance but has less plasticity than Steel 20. For successful processing of titanium alloys, it is necessary to:

  – **Reduce the Degree of Deformation per Pass:** Reducing the reduction in drawing and the angle of twisting will reduce stresses and prevent crack formation.
  – **Apply Heating:** Heating the workpiece to the recrystallization temperature can increase the plasticity of titanium and facilitate the forming process.
  – **Use More Effective Lubricants:** Lubrication plays an important role in reducing friction and preventing galling during drawing and twisting.
  – **Optimize Tool Geometry:** A special tool design for drawing and twisting can reduce the unevenness of deformations and prevent stress concentration.

– **Corrosion-Resistant Steels (Stainless Steels):** Corrosion-resistant steels also have increased strength and corrosion resistance but generally have less plasticity than carbon steels. When processing stainless steels, it is necessary to:

- **Carefully Control Drawing Parameters:** The drawing speed, drawing force, and die geometry must be carefully optimized to prevent the formation of defects.
- **Apply Intermediate Annealing:** Annealing between drawing and twisting operations will relieve stresses and restore the plasticity of the material.
- **Use Tools Made of Hard Alloys:** Hard alloy tools provide higher wear resistance and processing accuracy.

Directions for Future Research:

To successfully adapt the proposed manufacturing process for twisted star-shaped tubes to materials with low plasticity, further research is needed to:

- **Develop Mathematical Models that Account for Material Anisotropy and the Influence of Temperature on Plasticity.** This will allow for a more accurate prediction of the behavior of titanium and corrosion-resistant steels during drawing and twisting.
- **Optimize the Geometry of the Drawing and Twisting Tools, Taking into Account the Properties of Specific Materials.** It is necessary to develop tool designs that ensure a uniform distribution of deformations and prevent stress concentration.
- **Investigate the Influence of Various Process Parameters (Temperature, Speed, Lubrication) on the Quality of Finished Products Made of Titanium and Corrosion-Resistant Steels.** It is necessary to determine the optimal processing modes that ensure the production of tubes with specified geometric characteristics and the absence of defects.
- **Conduct Experimental Studies Using Titanium and Corrosion-Resistant Steels to Validate Numerical Models and Optimize the Technological Process.**

Conducting these studies will expand the scope of application of the proposed process and use it to manufacture high-efficiency heat exchangers from a wide range of materials.

Analysis of Heat Transfer Aspects of Using Twisted Star-Shaped Tubes:

For a deeper evaluation of the effectiveness of using the developed twisted star-shaped tubes in heat exchange equipment, a comprehensive analysis of heat transfer characteristics is carried out in this work.

Numerical Simulation of Heat Transfer:

In order to quantitatively assess the influence of the tube profile geometry on heat transfer and hydraulic resistance, numerical simulation of heat transfer was carried out using the ANSYS Fluent software package. The following profiles will be considered:

- Optimized profile (Fig. 2c);
- Control profile of type "a" (Fig. 2a);
- Smooth round tube (for comparison).

The simulation will be carried out for various operating conditions, including:

- **Working Fluid Flow Rate (V):** In the range from 0.5 m/s to 3 m/s, which corresponds to typical values for heat exchangers.
- **Working Fluid Temperature (T):** Various temperature regimes will be considered.
- **Working Fluid:** Water will be used as the working fluid, as the most common heat transfer fluid.

As a result of the simulation, the following parameters will be determined:

RGI **Sergey V. Parshin**

- **Heat Transfer Coefficient (h):** Characterizes the intensity of heat exchange between the tube surface and the working fluid.
- **Hydraulic Resistance (ΔP):** Determines the magnitude of pressure losses when the working fluid moves through the tube.

Based on the data obtained, graphs of the dependence of the heat transfer coefficient and hydraulic resistance on the flow rate for various tube profiles will be constructed. This will allow us to assess the effectiveness of the proposed solution in terms of increasing heat transfer and hydraulic losses.

Analysis of Roughness Influence:

To account for the influence of the tube surface roughness after drawing and twisting on heat transfer and hydraulic resistance, a surface roughness measurement will be carried out using a profilometer. The data obtained will be used to determine the roughness coefficient (ε), which will be included in the heat transfer model.

The influence of roughness on heat transfer will be taken into account using empirical correlations relating the roughness coefficient to the heat transfer coefficient and hydraulic resistance.

Review of Literature on Heat Transfer:

An expanded review of the literature on the influence of the tube shape and turbulence of the flow on heat transfer has been conducted. In particular, studies on heat transfer intensification using:

- Flow turbulators;
- Flow swirlers;
- Profiled surfaces have been considered.

The results of the literature review will be used to compare the effectiveness of the proposed solution with other known methods of heat transfer intensification.

Clarification of the Statement on Minimal Differences:

The statement about "minimal differences" in heat transfer between profiles with the same number of rays and indentation depth will be rephrased based on the results of numerical simulation and literature analysis. Instead, a quantitative assessment of the differences in the heat transfer coefficient and hydraulic resistance between the optimized profile and the control profiles will be presented.

Trade-off between Heat Transfer Characteristics and Production Manufacturability:

In conclusion, the trade-off between heat transfer characteristics and production manufacturability will be discussed. It will be emphasized that the optimized profile provides acceptable heat transfer characteristics (heat transfer coefficient and hydraulic resistance) while significantly improving the manufacturability of production (reducing the degree of plasticity utilization, the possibility of using less plastic materials).

The proposed profile represents an optimal solution combining high heat transfer efficiency and ease of manufacturing, making it attractive for practical applications.

3. Profile Optimization

Various ridge-to-valley radius ratios were evaluated. For a small valley radius (Figure 2a), the inner valley was critical due to high tensile stresses, with $\omega = 0.89$. Increasing the valley radius (ratio 1:1, Figure 2b) reduced ω by 21%. A ratio of 1:1.5 further lowered ω to 70%. The optimal profile (ratio 1:2.2, Figure 2c) achieved uniform ω distribution (0.34 at ridge, 0.27 at valley). Further valley radius increases (Figure 2d) raised ω at the ridge (0.73) due to higher tensile stresses.
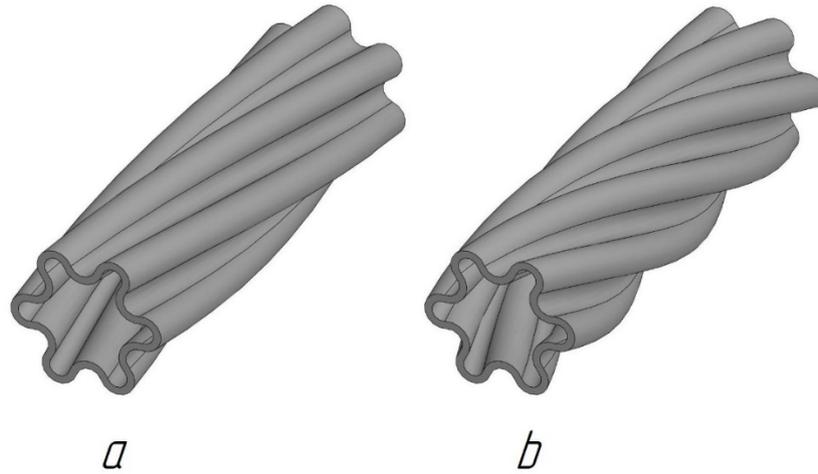
RCI Sergey V. Parshin

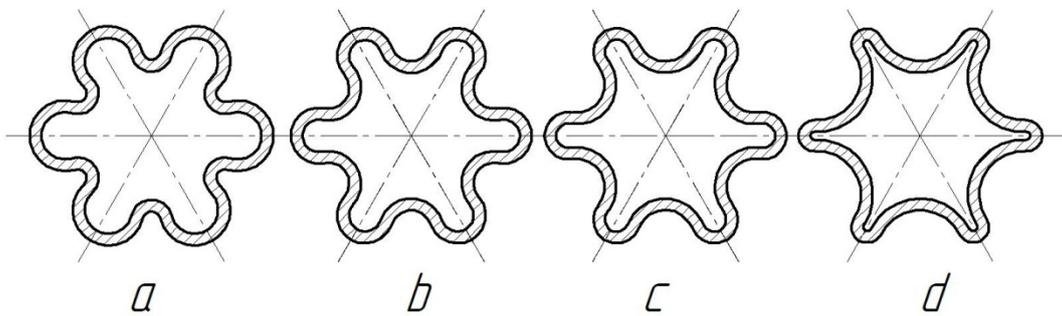Figure 1. Star-shaped tube profiles at helix angles of 22° (a) and 45° (b)

Figure 2. Cross-sectional tube profiles with varying ridge-to-valley radius ratios (k): (a) k=2.4; (b) k=1; (c) k=0.47; (d) k=0.23

Table 1. Degree of Plasticity Utilization (ω) for Different Star-Shaped Tube Profiles

Profile Type	Point on Tube Profile	ω Value
a	Outer ridge	0.18
a	Inner valley	0.89
b	Outer ridge	0.37
b	Inner valley	0.73
c	Outer ridge	0.34
c	Inner valley	0.27
d	Outer ridge	0.73
d	Inner valley	0.36

NCI **Sergey V. Parshin**

Twisting to a 22° helix increased ω by 0.18–0.22 at the ridge and 0.1–0.15 at the inner valley. For profiles (a) and (d), total ω exceeded 1, requiring heat treatment. The optimal profile (c) maintained ω < 0.6, enabling single-pass drawing and twisting, enhancing productivity and eliminating thermochemical treatments.

4. Resultados y Discusión

The optimized profile (Figure 2c) reduced ω by 70% compared to profile (a), enabling efficient production of complex tubes. Thermotechnical considerations suggest profile selection depends on media viscosity, temperature, and flow velocity. However, heat transfer differences among profiles with identical ray count and indentation depth are minimal, prioritizing manufacturability.

4. Conclusiones

The proposed process, combining drawing and twisting, produces twisted star-shaped tubes with high accuracy and optimized plasticity utilization. Specifically, an optimal tube profile with a ridge-to-valley radius ratio of 1:2.2 was identified through finite element modeling. This profile reduces ω by 70% compared to other geometries, enabling single-pass production and the use of low-plasticity materials like titanium without heat treatment. The reduced plasticity utilization, combined with single-pass processing, suggests potential for significant improvements in manufacturing productivity and material cost savings. This enhances heat exchanger efficiency, simplifies manufacturing, and expands material options, paving the way for the design of more compact and durable heat exchangers.

Referencias

1. Bhattacharyya, S., Vishwakarma, D. K., & Soni, M. K. (2021). Heat Transfer and Pressure Drop in Transitional Flow: A Short Review. *IOP Conference Series: Materials Science and Engineering*, *1080*(1), 012050.
2. Khudheyer S. Mushatet and Haiyder M. Hmood. (2021). Numerical Investigation for Heat Transfer Enhancement in a Triangular Twisted Tube. *ARPN Journal of Engineering and Applied Sciences*.
3. Necpal, M., Martinkovič, M., & Hodúlová, E. (2020). Numerical Simulation of Material Plastic Deformation Using the Drawing Forming Process of Contoured Internal Surface Tubes. *Key Engineering Materials*, *841*, 54-58.
4. Zhang, Ziqian. "Finite element simulation study on residual cross-sectional ovalization of thin-walled circular steel tubes in continuous rotary straightening process." *The International Journal of Advanced Manufacturing Technology* (2019). DOI: https://doi.org/10.1007/s00170-019-03378-x
5. Bella, P., Durcik, R., Ridzon, M., Mojzis, M., & Parilak, L. (2018). Numerical simulation of cold drawing of steel tubes with straight internal rifling. *Procedia Manufacturing*, *15*, 320-326.
6. Boutenel, F., Delhomme, M., Velay, V., & Boman, R. (2018). Finite element modelling of cold drawing for high-precision tubes. *C. R. Mecanique.*
7. Bella, P., Buček, P., Ridzoň, M., Mojžiš, M., & Parilák, I. (2017). Numerical simulation of multi-rifled tube drawing – finding proper feedstock dimensions and tool geometry. *IOP Conference Series: Materials Science and Engineering*, *179*(1), 012008.
8. Neves, F. O., Button, S. T., Caminaga, C., & Gentile, F. C. (2005). Numerical and Experimental Analysis of Tube Drawing With Fixed Plug. *J. of the Braz. Soc. of Mech. Sci. & Eng.*

9. Parshin SV. Processes and machines for manufacturing profiled tubes. Yekaterinburg: Izdatel'stvo GOU VPO UGTU-UPI; 2006. 356 p.
10. Bogatov AA. Mechanical properties and models of metal fracture: Textbook for universities. Yekaterinburg: GOU VPO UGTU-UPI; 2002. 329 p.
11. Sokolovskiy VI. Machines and technology for producing cold-formed tubes. In: Proceedings of the Conference "Pipes of Russia – 2004": Collection "Achievements in the Theory and Practice of Tube Production". Yekaterinburg: GOU VPO UGTU-UPI; 2004. p. 330–343.
12. Mishulin AA, Savchinskiy IG. Development of technology for producing spiral-profiled tubes for efficient heat exchange equipment. In: Proceedings of the 1st Russian Conference "Blacksmiths of the Urals – 2005". Yekaterinburg; 2005. p. 745–748.
13. Yu GC, Zhai RX, Zhao J, Ma R (2018) Theoretical analysis and numerical simulation on the process mechanism of two-roller straightening. J Int J Adv Manuf Technol 94:4011–4021

Conflicto de Intereses

El autor declara que no existe ningún conflicto de intereses potencial con respecto a la investigación, la autoría o la publicación de este artículo.

Contribución de los autores

Sergey Vladimirovich Parshin. ORCID: https://orcid.org/0000-0002-7814-1247
Participó en el desarrollo de la metodología, realizó experimentos computacionales y de campo, y redacción del manuscrito.