Engineering Manufacturing Letters, 2:1 (2024) 29-38
ISSN 2795-5168
DOI: 10.24840/2795-5168_002-001_2724

Received: 26 June, 2024
Accepted: 26 September, 2024
Published: 11 October, 2024

Comparative analysis of two rolling methods for producing rail axles

Grzegorz Winiarski
Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 38D, 20-618 Lublin, Poland (g.winiarski@pollub.pl) ORCID 0000-0001-5286-6285
Tomasz Bulzak
Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 38D, 20-618 Lublin, Poland (t.bulzak@pollub.pl) ORCID 0000-0002-0525-8321
Łukasz Wójcik
Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 38D, 20-618 Lublin, Poland (l.wojcik@pollub.pl) ORCID 0000-0001-8623-1835
Konrad Lis
Faculty of Mechanical Engineering, Lublin University of Technology, Nadbystrzycka 38D, 20-618 Lublin, Poland (k.lis@pollub.pl) ORCID 0000-0002-6461-4226

Author Keywords

Cross wedge rolling, skew rolling, rail axle, metal forming.

Type: Rapid communication

Open Access

Peer Reviewed

Abstract

This paper reports the results of a comparative analysis of two rolling methods that were used to produce rail axles. One was cross wedge rolling conducted with the use of flat plates, and the other was skew rolling conducted with the use of three rollers and one chuck. The analysis involved performing numerical calculations based on the finite element method. It was assumed that the part would be made of steel grade C35 and hot formed in a scale of 1:5 (due to planned experimental verification of the technologies under laboratory conditions). Numerical results were used to compare selected parameters of parts rolled by the two methods, including the distributions of stress, strain and Cockcroft-Latham ductile fracture criterion, as well as energy consumption of the two processes. It was found that all the analysed technological aspects primarily depended on the rolling method applied.

1. Introduction

Rolling processes are widely used in the production of a wide variety of products and semi-finished products. These techniques make it possible to manufacture a wide range of products such as bars, tubes and sheet metal plates, as well as parts with complex shapes. The most widely used forge rolling methods are cross wedge rolling (CWR) and skew rolling (SR).

Yang et al. used the CWR method to produce axle sleeves (Yang et al. 2017). As a result of many numerical simulations, the process was optimised to avoid axial movement and ovality of the workpiece. Another application of CWR is related to the formation of ball studs for automotive applications (Bulzak et al. 2017). Studies showed that the process could be conducted using tools with a large spreading angle. It was also found that the risk of material fracture increased with diameter increase. Another area where CWR can be applied is the production of railcar axles (Pater et al. 2023). Although rolling mills that would enable the production of parts with such large overall dimensions are unavailable on the market, the CWR process can be conducted in two operations, which makes it possible to use smaller-size machines. Lin et al. (2023) used the CWR method to produce a bimetallic shaft. The shaft consisted of a sleeve that had a core made of a different material inside. It was shown that the use of CWR with correct billet preparation led to permanent bonding of two materials on their interface. Pater et al. (2018) proposed two variations of the CWR technique: one involved constraining axial flow of material and the other consisted of rolling with upsetting. Results showed that the first variation of CWR was characterized by higher tangential loads than the classical CWR process, while the other made it possible to increase workpiece diameter by 50%. Both could be conducted with the use of shorter tools, which meant enhanced process efficiency and allowed for the use of smaller-size machines. Ji et al. used CWR to produce engine valves (Ji et al. 2015; Ji et al. 2017). Solid and hollow valves were analysed. For both cases, CWR was used to produce a preform that was later forged into a valve. Results showed that the key parameters were: forming angle, stretching angle and area reduction. If their values were selected incorrectly, this could lead to material fracture in workpiece axis or complete separation of material in a plane perpendicular to workpiece symmetry axis.

Another failure mode in CWR is related to inadequate thickness/inside diameter of a rolled part. For this reason, numerous studies addressed the problem of hole formation in CWR and material fracture. Studies investigating the aspect of wall thickness predominantly concern the use of a mandrel in hole formation. Shen et al. (2019) demonstrated that the use of a mandrel resulted in enhanced quality of the hole; nevertheless, the diameters of the hole and mandrel differed after the rolling process (Shen et al. 2020). To determine the required diameter of this tool, a model was developed based on a relationship between axial and radial flow of material (Shen et al. 2021). Numerous studies have been conducted on the problem of material fracture in CWR in order to develop a model or criterion of material fracture that would make it possible to predict the location and moment of material cohesion loss already at the stage of numerical simulations (Novella et al. 2015; Bulzak et al. 2022).

Similarly to CWR, the SR method has been extensively studied and applied in practice. It can be employed in the production of e.g. rail axles (Pater et al. 2015), hollow axles (Wang et al. 2023) and hollow shafts (Zhang et al. 2020). This process is conducted with the use of three identical rollers that make the workpiece rotate. The process can also be conducted with the use of a chuck to aid movement of the workpiece in the axial direction. The tool kinematics in this process makes it possible to produce shafts of varying lengths and diameters using only one tool set. Hollow parts can also be rolled with the use of a mandrel. This method can also be used for rolling bimetallic materials, where individual components are bonded (Ji et al. 2024). Another variation of SR is a rolling process conducted with the use of two rollers. This technique can be used to manufacture e.g. bearing steel balls (Bulzak et al. 2022). In this process, additional guides are used in order to maintain the position of the workpiece between the rollers. A new variant of skew rolling is flexible skew rolling (FSR) (Lin et al. 2022; Cao et al. 2021). This process is conducted with two rollers and two tube guides. Both rollers have three degrees of freedom, which allows them to rotate about their symmetry axis, move in the radial direction and rotate about the axis that is perpendicular to that of the workpiece. This rolling process is divided into four stages: radial rolling, rollers inclining, skew rolling, and rollers levelling in which the rollers perform specified movement. This method is universal and can be used to manufacture a wide range of solid and hollow products using one tool set.

The literature review has demonstrated that CWR and SR methods are employed to manufacture a wide variety of products. This results from high efficiency and universality of these techniques. Consequently, studies are conducted to investigate new groups of parts that can be produced by these techniques. In addition, new processes and tools are designed. In light of the above, research has been undertaken to determine the viability of using CWR and SR processes for producing rail axles. This study is a comparative analysis of the two rolling methods in terms of their suitability for producing rail axles. Numerical calculations are performed to determine forces and energy parameters in these processes, as well as distributions of stress, strain, temperature and damage function in rolled parts. Results show that values and distributions of these parameters significantly depend on the type of rolling method used for producing rail axles.

2. Materials and Methods

A schematic design of a CWR process for producing rail axles is shown in Figure 1. The process was conducted with the use of two plates and a billet in the form of a section of bar that was put between these plates. On their surface, the plates had wedge-shaped impressions in which individual area reductions were made. During the rolling process, the bottom tool was stationary while the top tool performed translation. Consequently, the workpiece performed both translational and rotational motion.

The SR process for producing a rail axle was conducted with three rollers and a chuck (Figure 2). The rollers were spaced at uniform distance around the workpiece (bar section), with their axes set askew relative to that of the workpiece. The rollers were rotated about their own symmetry axes and at the same time performed translational motion in the radial direction. The chuck moved along the axis of the workpiece and rotated freely about this axis. Such kinematics of the rollers and chuck made it possible to deform areas on the workpiece to the required diameter and length.

The rolling processes of rail axle forgings were carried out on a scale of 1:5, for the product shown in Figure 3. This scale was chosen because of the planned experimental verification of the technologies under laboratory conditions. These tests must be performed for the parts in a reduced size due to the limited rolling mills working spaces available by the authors. Both processes were conducted with the same parameters. FEM-based numerical calculations were performed using *SimufactForming*. The tools were modelled as rigid objects while the workpiece was rigid-plastic. The workpiece was assigned the properties of steel AISI 1035, the material model of which was taken from the material library database of the simulation program. The initial temperature of the workpiece and tools was set to 1150 and 50°C, respectively. The workpiece was discretized using hexagonal elements. Contact relations between the rigid tools and the rigid-plastic workpiece were described by a shear friction model (with the friction factor set to 0.9 due to lack of lubrication in hot rolling processes) and a heat transfer coefficient of 20 kW/m2K. In CWR, the velocity of the top plate was set equal to 300 mm/s. In SR, the rotational speed of the rollers was 60 rev/min, while their linear velocity in the radial direction was varied in the range of 0-5.5 mm/s and made dependent on the dimensions of area reduction. The chuck velocity was varied in the range of 5-25 mm/s.

Numerical results were used to assess the suitability of the two rolling methods for producing rail axles by comparing selected parameters of rolled parts. The geometry of the obtained forgings, force and energy parameters, as well as the distributions of stress, strain, temperature and damage functions in the rolled parts were analyzed. It should be noted that for other process parameters the results may be different from those presented in the further part of the paper.

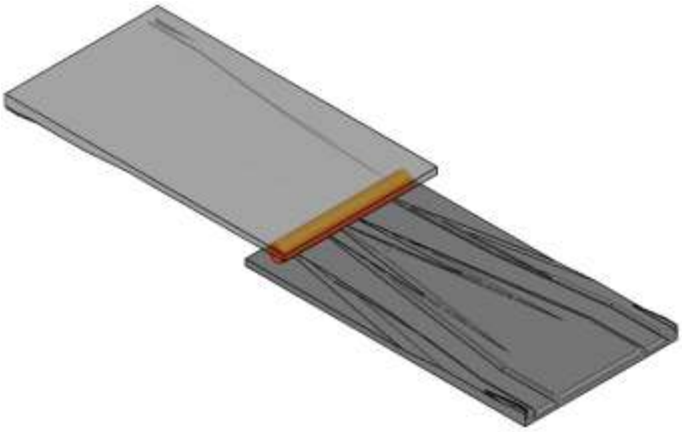

Figure 1: Schematic design of cross wedge rolling (CWR) for producing rail axles

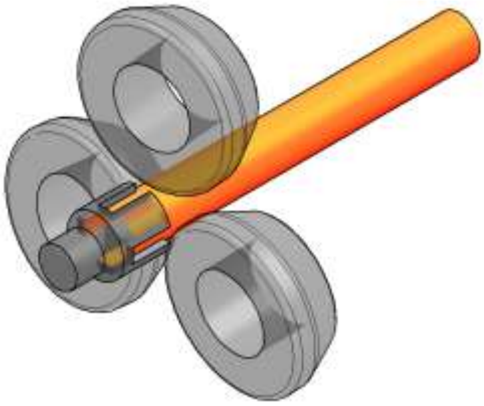

Figure 2: Schematic design of skew rolling (SR) process for producing rail axles

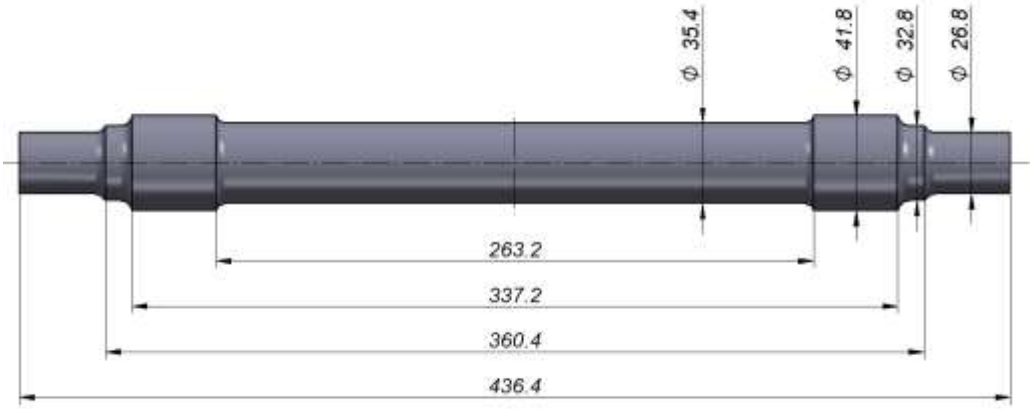

Figure 3: Key dimensions (in mm) of a rail axle in scale 1:5

3. Results and Discussion

Given the differences between the two rolling techniques, the rolled parts have different geometries (Figure 4). Unlike the CWR-produced part, the skew-rolled part does not have the area reduction with the desired diameter Ø32.8 mm. For both cases, the rolled parts have material allowance on their ends. The allowance on the ends of the CWR-produced part is symmetric and will be cut off in the final stage of the rolling process. In contrast, one end of the SR-produced part is undeformed because it was fixed in the chuck, while the other makes part of the smallest diameter area. Nevertheless, in both cases the outline of the forging is compatible with that of the finished part.

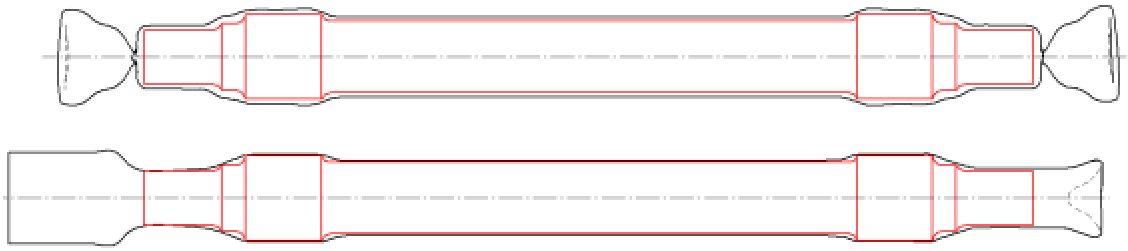

Figure 4: Geometry of a rail axle produced by cross wedge rolling (top) and skew rolling (bottom) with an outline of the finished part

Views of the axial sections of the parts produced by cross wedge rolling and skew rolling together with the distribution of effective strain are shown in Figure 5. The rolled parts differ in terms of effective strain distribution. In the CWR process, the lowest strain values are located in the greatest diameter areas of the workpiece. This results from the fact that the workpiece has no contact with the tools in these areas and that the diameter of the workpiece is slightly increased due to material flow in the adjacent zones. In the centre of the workpiece and on its ends the strain values are similar and their distribution is relatively uniform. In the SR process, the highest strains are located in the smallest diameter area, near the chuck. This results from the fact that this area of the workpiece carries the force applied to the chuck from the very beginning of the rolling process. It can be observed that the effective strain is distributed in layers, i.e. the highest values are located on the surface of the workpiece and they decrease with the distance to the axis of symmetry. This probably results from the kinematics of the tools, which causes a more rapid axial flow of material on the workpiece surface rather than in its centre, i.e. around the axis of symmetry (which is confirmed by the presence of a distinctive funnel on the right side of the part).

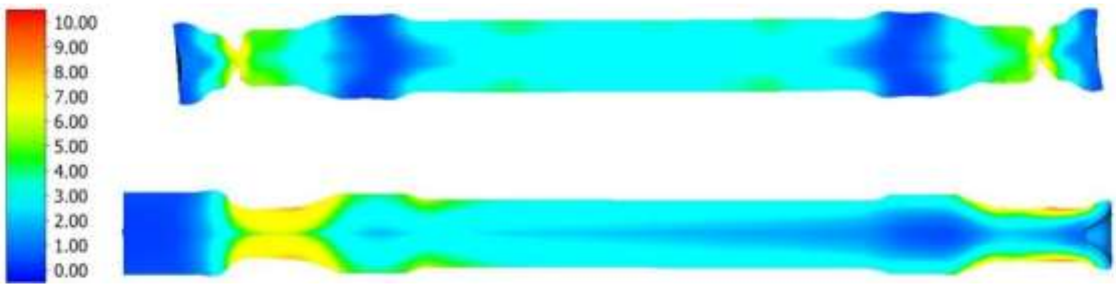

Figure 5: Effective strain in the axial section of a rail axle produced by cross wedge rolling (top) and skew rolling (bottom)

Figure 6 shows the effective stress in the axial section of rolled parts. In the CWR-produced part, the effective stress has a non-uniform distribution, both in the axial and radial directions. Three characteristic regions can be distinguished in the workpiece: the centre, the ends, and the largest diameter area. In the first region, the effective stress has a non-uniform distribution. The highest values (also in relation to the entire part) are located on the surface and decrease towards workpiece symmetry axis. In the second and third regions, the stress distribution in the radial direction is more uniform than in the first region, but the stress values are lower in the largest diameter areas. The skew-rolled part is characterized by a more uniform distribution of effective stress. The differences in the radial and axial stresses are considerably smaller than those observed for the CWR-produced part. Also, the stress values are lower and similar to those observed for the largest diameter areas in the CWR-produced part.

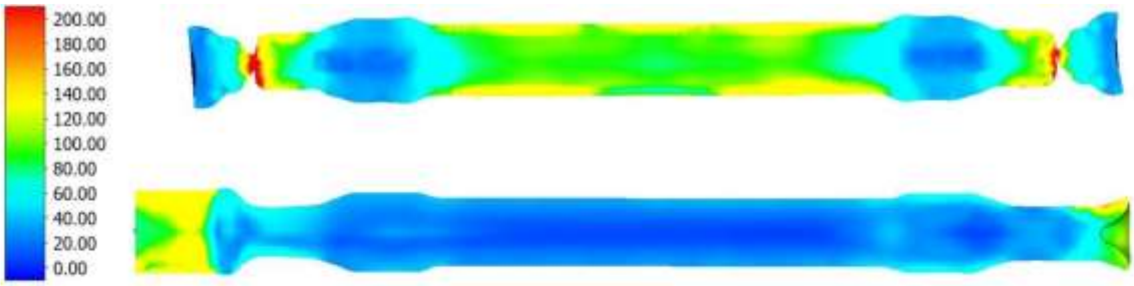

Figure 6: Effective stress (in MPa) in the axial section of a rail axis produced by cross wedge rolling (top) and skew rolling (bottom)

Figure 7 shows the distribution of temperature in the axial section of rolled parts. Both parts differ in terms of this parameter. In the CWR-produced part, the lowest temperature values are located on its ends and in the centre. In the largest diameter areas of the workpiece, the temperature values are more uniform albeit higher than in other regions of the part. Similarly, to effective strains, this results from the lack of workpiece/tool contact in this region. In the skew rolled part, the duration and contact between the material and the tools were similar in all regions of the workpiece. As a result, the temperature values are similar over the entire volume of the rolled part. The temperature in the chuck-fixed region of the workpiece is considerably lower. Nevertheless, this region makes part of the material allowance that is later cut off. It can therefore be claimed that in SR the temperature value remains almost constant over the entire volume of the workpiece. Also, the temperature is similar to the value observed in the largest diameter areas of the CWR-produced part.

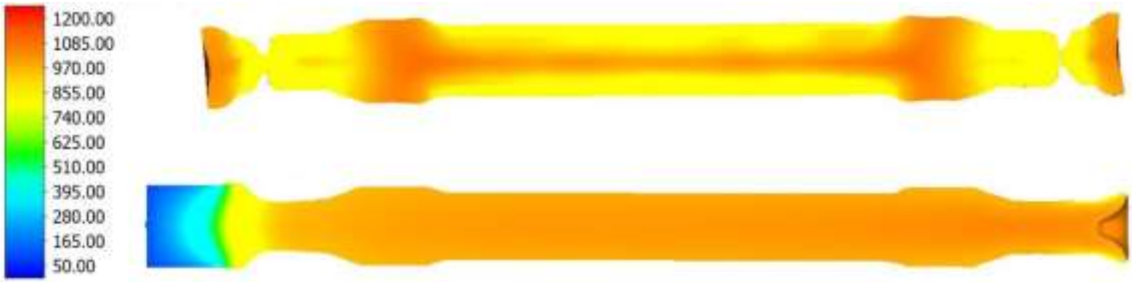

Figure 7: Temperature (in °C) in the axial section of a rail axle produced by cross wedge rolling (top) and skew rolling (bottom)

Figure 8 shows the distribution of the Cockcroft-Latham integral in the axial section of rolled parts. In the CWR-produced part, the highest Cockcroft-Latham integral values are located in the centre, close the axis of symmetry. This is connected with the occurrence of alternate compressive and tensile stresses in this region. This may lead to material fracture due to low-cycle fatigue. The values of the integral in the skew rolled part are considerably lower and their radial distribution is uniform. This is due to the fact that during skew rolling, the forging is in contact with three rollers, which provide three support points for the rolled cross section of the workpiece. Such tool kinematics prevents the Mannesmann phenomenon, which in the CWR process using two flat plates has favorable conditions for its formation. Therefore, considering the risk of material cohesion loss, the SR technique seems to be more suitable for rolling rail axles than CWR.

Figure 8: Distribution of the Cockcroft-Latham integral in the axial section of a rail axle produced by cross wedge rolling (top) and skew rolling (bottom)

Figure 9 shows the force parameters in cross wedge rolling of rail axles. The behaviour pattern of the radial force acting on the top plate differs from that of the tangential force that moves the tool. The radial force value shows a steady increase throughout the duration of the rolling process, which is connected with forming reduced diameter areas on the workpiece. Toward the end of the process, i. e. in the product calibration stage, the force value remains stable. The tangential force becomes stable after approx. 30% of the process duration. A ratio of the maximum radial force to the tangential force is more than four-fold.

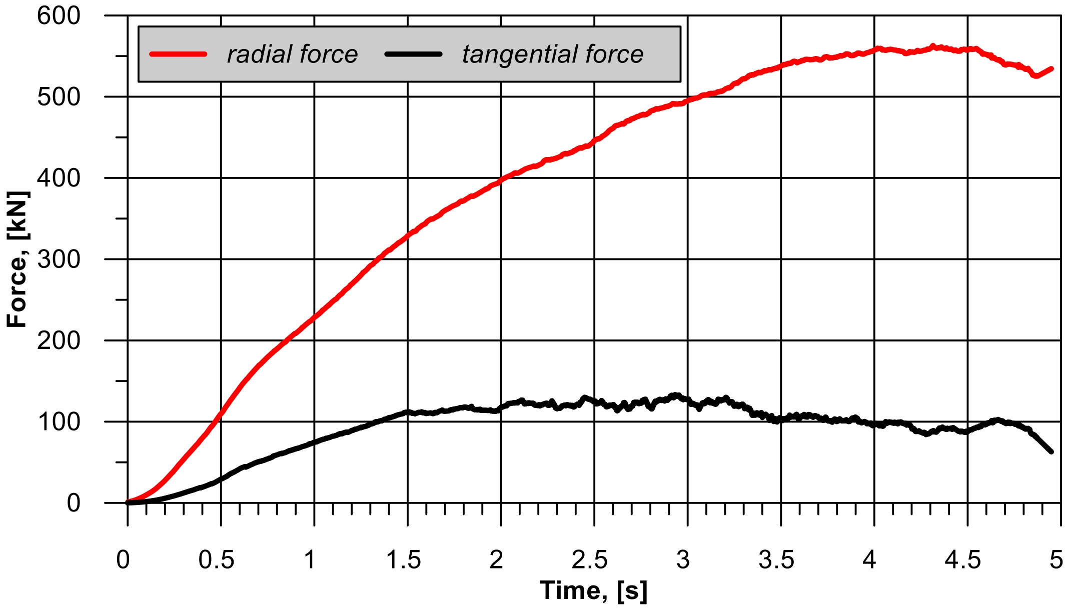

Figure 9: Force parameters in cross wedge rolling

Figure 10 shows the force parameters in skew rolling of rail axles. The chuck force, roller force and roller torque have similar behaviour patterns, which is strongly connected with the geometry of the workpiece. As the rollers move closer to the axis of the workpiece, the values of all force parameters increase. In contrast, when the translation of the rollers is stopped to make the reduction in area, the values of the roller forces and torque remain almost constant. Compared to the forces in CWR, the maximum values of the forces in SR are many-fold lower.

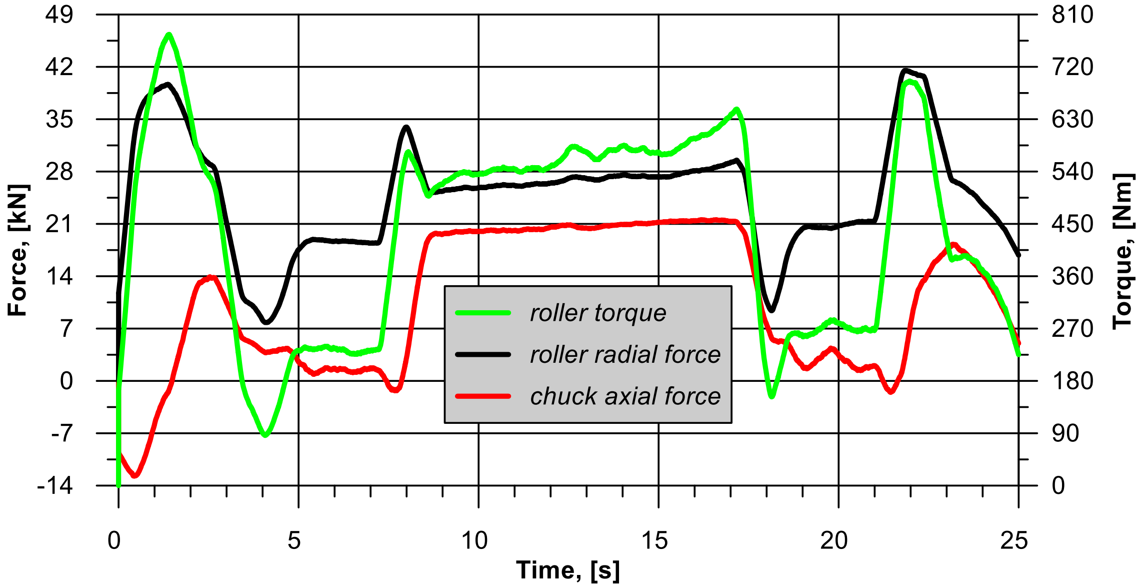

Figure 10: Force parameters in skew rolling

Given the differences in the analysed rolling techniques, any attempt at comparing force parameters in these processes will be unreliable. For this reason, a comparison was made of energy consumption in both processes. Figure 11 shows the energy consumption in cross wedge rolling and skew rolling. In CWR, the only energy-consuming work is performed by the tangential force on the top plate. In SR, on the other hand, the total energy consumption is a sum of the energy supplied to the chuck and three rollers. The rotation of the rollers is the most energy-consuming work, while their motion in the radial direction requires the least energy. The total energy consumption comparison demonstrates that considerably less energy must be supplied to the tools in CWR than in SR.

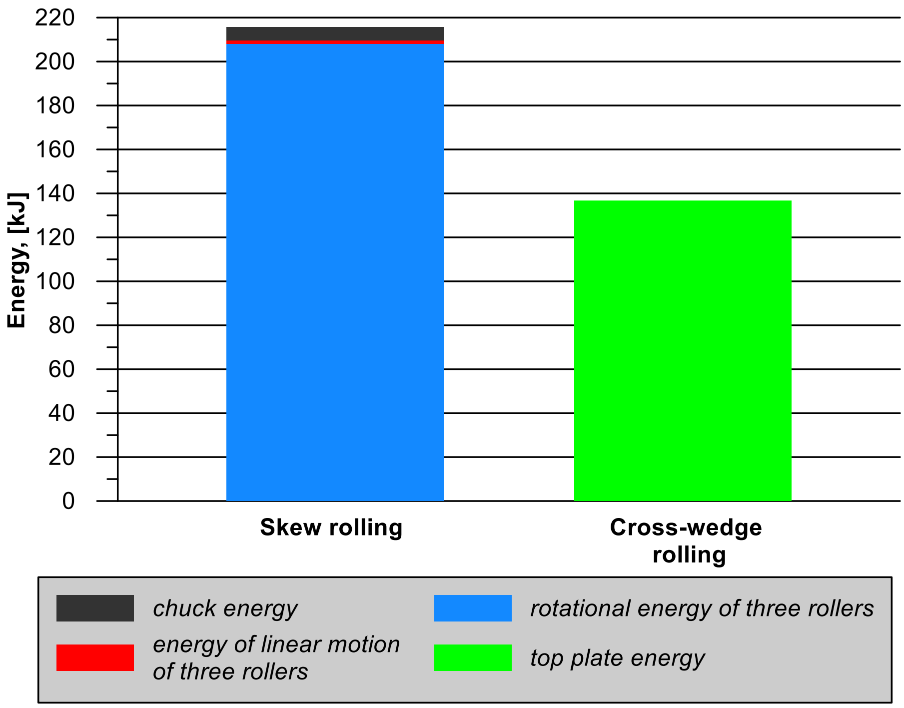

Figure 11: Comparison of energy consumption in the analysed rolling processes for producing rail axles

4. Conclusions

The results of the comparative analysis of two rolling processes for producing rail axles lead to the following conclusions:

- given the differences between cross wedge rolling and skew rolling, the produced rail axles differ in terms of geometry, both in relation to the part itself and allowance;
- due to the different geometries and kinematics of the tools in the analysed rolling processes, the rolled parts differ in terms of effective strain and stress as well as temperature;
- the Cockcroft-Latham ductile fracture criterion analysis has shown that the skew rolling method is less likely to cause material cohesion loss;
- the cross wedge rolling process for producing rail axles is less energy consuming than skew rolling;
- to determine which method is more suitable for rolling the analyzed part, further experiential research of the technologies and quality tests of the forgings are required.

References

Bulzak, T., K. Majerski, J. Tomczak, Z. Pater, and Ł. Wójcik. 2022. "Warm skew rolling of bearing steel balls using multiple impression tools". C*IRP Journal of Manufacturing Science and Technology* 38: 288–298. https://doi.org/10.1016/j.cirpj.2022.05.007.

Bulzak, T., Z. Pater, and J. Tomczak. 2017. "Numerical and experimental analysis of a cross wedge rolling process for producing ball studs". *Archives of Civil and Mechanical Engineering* 17: 729–737. https://doi.org/10.1016/j.acme.2017.02.002.

Bulzak, T., Z. Pater, J. Tomczak, Ł. Wójcik, and A. Murillo-Marrodan. 2022. "Internal crack formation in cross wedge rolling: Fundamentals and rolling methods". *Journal of Materials Processing Technology* 307: 117681. https://doi.org/10.1016/j.jmatprotec.2022.117681.

Cao, X., B. Wang, J. Zhou, J. Shen, and L. Lin. 2021. "Exploratory experiment and numerical simulation investigation on a novel flexible skew rolling of hollow shafts". *The International Journal of Advanced Manufacturing Technology* 116: 3391–3403. https://doi.org/10.1007/s00170-021-07360-4.

Ji, C., H. Niu, Z. Li, T. Wang, and Q. Huang. 2024. "Deformation law and bonding mechanism of 45 carbon steel/316L stainless steel cladding tubes fabricated by three-roll skew rolling bonding process". *Journal of Materials Processing Technology* 325: 118277. https://doi.org/10.1016/j.jmatprotec.2023.118277.

Ji, H., J. Liu, B. Wang, X. Fu, W. Xiao, and Z. Hu. 2017. "A new method for manufacturing hollow valves via cross wedge rolling and forging: Numerical analysis and experiment validation". *Journal of Materials Processing Technology* 240: 1–11. https://doi.org/10.1016/j.jmatprotec.2016.09.004.

Ji, H., J. Liu, B. Wang, Z. Zhang, T. Zhang, and Z. Hu. 2015. "Numerical analysis and experiment on cross wedge rolling and forging for engine valves". *Journal of Materials Processing Technology* 221: 233–242. https://doi.org/10.1016/j.jmatprotec.2015.02.007.

Lin, L., B. Wang, J. Zhou, and J. Shen. 2022. "Manufacturing large shafts by a novel flexible skew rolling process". *The International Journal of Advanced Manufacturing Technology* 118: 2833–2851. https://doi.org/10.1007/s00170-021-08079-y.

Lin, L., W. Peng, V. Titov, M. Oleksandr, X. Wu, and H. Li. 2023. "Interface phenomena and bonding mechanism in the new method of cross wedge rolling bimetallic shaft". *Journal of Materials Research and Technology* 24: 1132–1149. https://doi.org/10.1016/j.jmrt.2023.03.049.

Novella, MF., A. Ghiotti, S. Bruschi, and PF. Bariani. 2015. "Ductile damage modeling at elevated temperature applied to the cross wedge rolling of AA6082-T6 bars". *Journal of Materials Processing Technology* 222: 259–267. https://doi.org/10.1016/j.jmatprotec.2015.01.030.

Pater, Z., J. Tomczak, and T. Bulzak. 2015. "Numerical analysis of the skew rolling process for rail axles". *Archives of Metallurgy and Materials* 60: 415–418. https://doi.org/10.1515/amm-2015-0068.

Pater, Z., J. Tomczak, and T. Bulzak. 2018. "New forming possibilities in cross wedge rolling processes". *Archives of Civil and Mechanical Engineering* 18: 149–161. https://doi.org/10.1016/j.acme.2017.06.005.

Pater, Z., J. Tomczak, and T. Bulzak. 2023. "Novel cross wedge rolling method for producing railcar axles". *The International Journal of Advanced Manufacturing Technology* 128: 3403–3413. https://doi.org/10.1007/s00170-023-12142-1.

Shen, J., B. Wang, C. Yang, J. Zhou, and X. Cao. 2021. "Theoretical study and prediction of the inner hole reduction and critical mandrel diameter in cross wedge rolling of hollow shaft". *Journal of Materials Processing Technology* 294: 117140. https://doi.org/10.1016/j.jmatprotec.2021.117140.

Shen, J., B. Wang, J. Zhou, X. Huang, and J. Li. 2019. "Numerical and experimental research on cross wedge rolling hollow shafts with a variable inner diameter". *Archives of Civil and Mechanical Engineering* 19: 1497–1510. https://doi.org/10.1016/j.acme.2019.08.003.

Shen, J., B. Wang, L. Lin, J. Li, and C. Zhu. 2020. "Investigation on the hole evolution and forming dimensions during cross wedge rolling hollow shaft with mandrel". *Procedia Manufacturing* 50: 143–147. https://doi.org/10.1016/j.promfg.2020.08.027.

Wang, J., X. Shu, C. Ye, Z. Li, S. Li, H. Xu, Y. Wang, Y. Deng, and Q. Chen. 2023. "Study on forming quality of three-roll skew rolling hollow axle". *The International Journal of Advanced Manufacturing Technology* 128: 1089–1100. https://doi.org/10.1007/s00170-023-11893-1.

Yang, C., J. Ma, and Z. Hu. 2017. "Analysis and design of cross wedge rolling hollow axle sleeve with mandrel". *Journal of Materials Processing Technology* 239: 346–358. https://doi.org/10.1016/j.jmatprotec.2016.09.002.

Zhang, S., X. Shu, C. Xu, J. Wang, and Y. Xia. 2020. "Simulation and experiment of reduction of equal-diameter hollow shafts with three-roll skew rolling". *Procedia Manufacturing* 50: 183–186. https://doi.org/10.1016/j.promfg.2020.08.034.

Acknowledgments

The research was financed in the framework of the project: Development of new rolling technologies for rail axle forgings, No. LIDER/9/0060/L-12/20/NCBR/2021. Total cost of the Project: 1 466 831.25 PLN. The project is financed by the National Centre for Research and Development under the 12th edition of the LIDER Programme.