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Innovative method of rolling railcar axles using segmented tool assemblies

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ABSTRACT

This paper presents a novel method for rolling railcar axles using wedge tools of considerable length (about 8 m). The tools are divided into 28 components which are mounted in a tool assembly that moves in a way resembling caterpillar drive. The advantages of the proposed method include no tool idling and relatively low forming loads. A design of a segmented rolling mill with two identical tool assemblies is presented. The feasibility of the proposed solution is verified via numerical simulations conducted in Simufact.Forming. A rolling process for producing a BA3002 type railcar axle from both a cylindrical and a rectangular billet is analysed in detail. Maps of effective strain, temperature and damage function in the workpiece are shown for both cases considered. These maps clearly show that a rail axle of good quality is obtained in both rolling processes. In addition, by analysing the forming load distributions, the power of the rolling mill drive system was also estimated, which was found to be significantly higher in the case of rolling from a rectangular billet.

Keywords: railcar axle, cross wedge rolling, segmented tools, FEM.

INTRODUCTION

Railcar axles are large-size parts that are manufactured in batches of thousands of pieces [1]. Nowadays parts of this type are manufactured by open die forging and rotary forging processes. Open die forging is conducted on hydraulic presses with a load range of 8 to15 MN, which are coupled with two manipulators. Round or square section ingots are used as the starting material for forging, and the manufacturing time for a single axle is several minutes. Open die forging requires large machining allowance, and the noise level in this process is over 100 dB. In contrast, the use of rotary forging reduces both the manufacturing time for a single axle (to about 4 minutes) and the required machining allowance. Rotary forging is usually conducted on machines equipped with four forging hammers, each having a load of 6.5 MN.

To increase manufacturing efficiency and reduce energy consumption of railcar axle production, extensive research is currently conducted on the application of skew and cross rolling methods in fabricating these parts. In skew rolling, an axisymmetric part is formed simultaneously by three rollers and an axially moving chuck in which one end of the workpiece is fixed. The motion of these tools is coupled [2, 3]. Preliminary numerical simulations [4, 5] showed that this process requires relatively low loads and torques. A great advantage of skew rolling is that parts with different shapes can be produced using the same set of rollers and that there is low susceptibility to internal crack formation [6, 7]. A shortcoming of this process is the unavailability of numerically controlled machine tools for producing railcar axles. Nevertheless, it was shown that a laboratory rolling mill installed at the Lublin University of Technology [8] made it possible to produce solid and hollow railcar axles in a scale of 1:5, with the required quality [9, 10], which confirmed the validity of the developed technique. Cross wedge rolling (CWR), which has been widely used in the industry since the 1960s, poses completely different problems. In this process, the main problem is related to the size of railcar axles, implying the use of machines and tools with large overall dimensions [11, 12]. In the standard CWR process where various diameters are created across the length of the workpiece successively, one after another, using typical tool angles, the tools can be up to 8 m in length, which is currently unfeasible to apply. Therefore, alternative solutions have been sought. Among others, it was proposed that railcar axles be produced in two stages, where they would be rolled using either two sets of tools [13] or one tool set [14]. This solution ensures that the diameter of the rollers can be reduced to an acceptable value of 1200 mm. A drawback of this method is that the workpiece has to be displaced between the forming operations, which can result in lower quality of the finished product. Another proposed solution was that railcar axles be formed by multi-wedge rolling [15, 16], a process in which the workpiece is deformed by several pairs of wedge tools simultaneously. This solution allows for the nominal diameter of the rollers to be reduced to acceptable values. At the same time, however, this method entails a higher probability of internal crack formation in the axial zone of the product, which is considered the primary failure mode in CWR [18–20]. Therefore, further studies should be conducted to develop new methods for forming railcar axles, which would ensure that the finished products are defect-free.

This study presents a new concept of a CWR process for producing railcar axles that is conducted with segmented tools consisting of 28 components working in a closed system. The validity of the proposed method is verified via numerical simulations. Both the proposed rolling method and the rolling mill design are innovative on a world scale.

Object of the study

The new method for forming railcar axles is explained through the example of a BA3002 type axle shown in Figure 1. This part has a length of 2200 mm, a maximum diameter of 216 mm and a weight of 445.6 kg. For this axle to be formed by CWR from a cylindrical billet, the tools must be approximately 8 m in length. These tools, one of which is shown in Figure 2, have wedges described by the forming angle α and the tool angle β. The first of the wedges (α = 22.5° and β = 9.4°) is responsible for creating the central cross-sectional reduction with a length of 1302 mm, while the other two wedges (α = 25° and β = 7.5°) create cross-sectional reductions on the ends of the workpiece. In this rolling process, a cylindrical billet with specially shaped conical ends is used in order to prevent the formation of end face cavities on the workpiece ends. The use of a cylindrical billet with conical ends facilitates the CWR

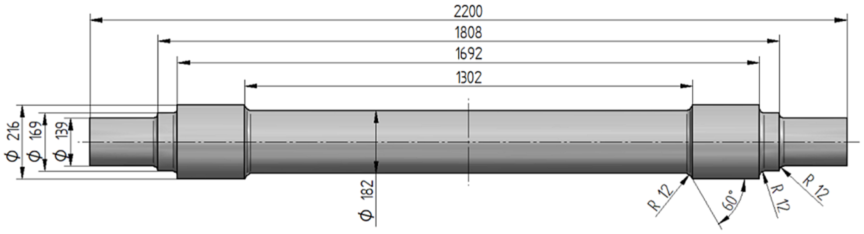

Figure 1. Railcar axle type BA3002

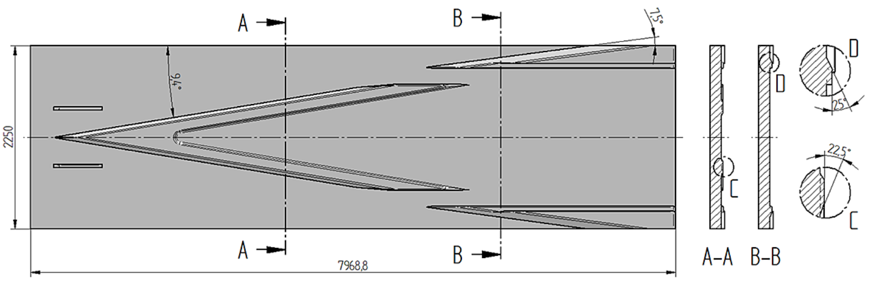

Figure 2. Wedge tool for forming a railcar axle from a cylindrical bille

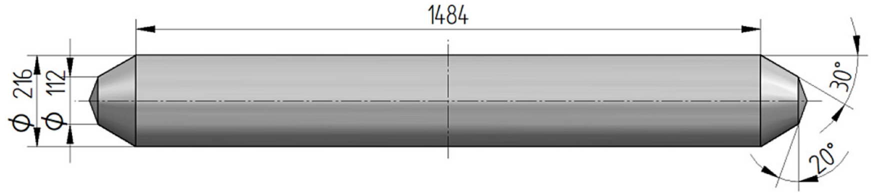

Figure 3. Cylindrical billet used for forming a railcar axle by CWR

process because it eliminates the need of cutting off waste material on the workpiece ends (Fig. 3). At the same time, however, the use of such billet increases manufacturing costs because an additional operation has to be performed to deform the conical ends. A more cost-effective solution is to use rectangular ingots as the starting material. Therefore, this study also investigates a solution in which railcar axles are formed from a rectangular billet that is shown in Figure 4. The rolling of railcar axles from such billet requires using different wedge tools than in the previous case, and these tools are shown in Figure 5. Although these tools have the same overall dimensions as those used in CWR from a cylindrical billet, their shape is different. Namely, they are made in the form of a single wedge that is described by the angles α = 22° and β = 10.4°. In this case of CWR, the workpiece is deformed along the entire length of the axis, including the largest cross-sectional reduction with a diameter of 216 mm. In addition, cutters for cutting off deformed workpiece ends are mounted in the rear of the tool.

Innovative rolling mill with segmented tools

A rolling mill equipped with wedges of almost 8 m in length (shown in Figs. 2 and 5) would have to be extremely large. In other words, a flat wedge rolling mill would have to have a length exceeding 16 m, while the diameter of the roll face with the wedges in a two-roll mill would have to be as large as 2.5 m. Not to mention the fact the production of railcar axles on these machines would be extremely power consuming. To overcome these problems, a new CWR method was designed, which allows railcar axles to be produced on a smaller machine.

Consequently, a new tool design is proposed, in which the wedge tool is divided into a series of segments that are mounted in a system resembling caterpillar drive. For the case under study, the tool is divided into 28 segments, each 284.6 mm long. These segments are attached to bases of the same width, the bases having 2 through-holes drilled at a spacing of 142.3 mm in their lower part. 90 mm diameter rods are inserted into these holes. The

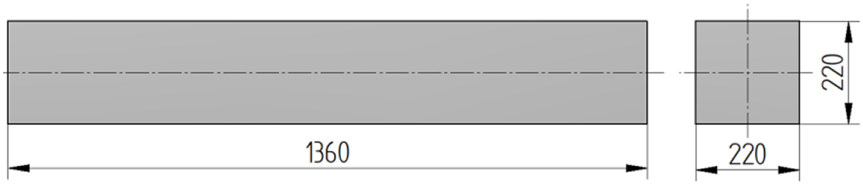

Figure 4. Rectangular billet used for rolling a railcar axle

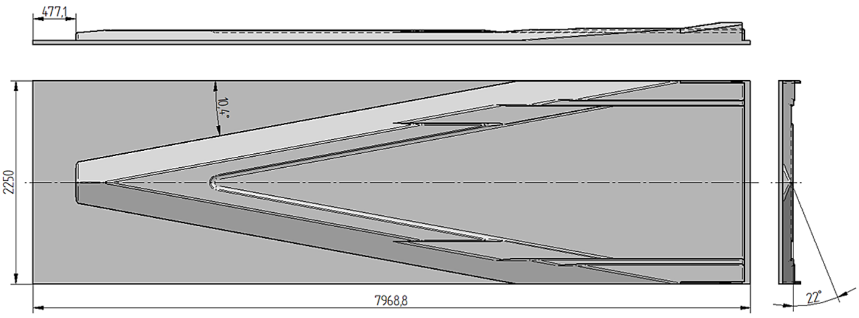

Figure 5. Wedge tools used for rolling a railcar axle from a rectangular billet

rods placed in the adjacent bases are connected by links, thus providing caterpillar drive that is shown schematically in Figure 6. The tool assembly is set in motion by toothed shafts with a nominal diameter of 1000 mm, which mesh with the rods. Three identical shafts are used: two outermost of which are powered, while the central one (which carries rotation passively) stiffens the structure of the drive unit at the point of loading resulting from the location of the workpiece. The toothed shafts are mounted by bearings to side plates, and the side plates are provided with holders for mounting the tool assembly to the columns of the rolling mill. A view of the developed segmented tool assembly and its overall dimensions are shown in Figure 7.

The segmented rolling mill is equipped with two identical segmented tool assemblies that are positioned one above the other, as shown in Fig. 8. The machine also features columns, a bottom and a top plate, as well as rotating guides for maintaining the workpiece in a stable position during rolling. The motors used for driving the tool assemblies are not shown in this figure.

Numerical simulations of CWR processes for producing railcar axles

To verify the proposed solution of manufacturing railcar axles, numerical simulations were performed for the two considered CWR processes. The simulations were performed using Simufact.Forming. This software had previously been employed to investigate processes such as cross wedge rolling [21–23], skew rolling [24–27] and ring rolling [28–30], and the numerical results showed good agreement with the results of experimental validation.

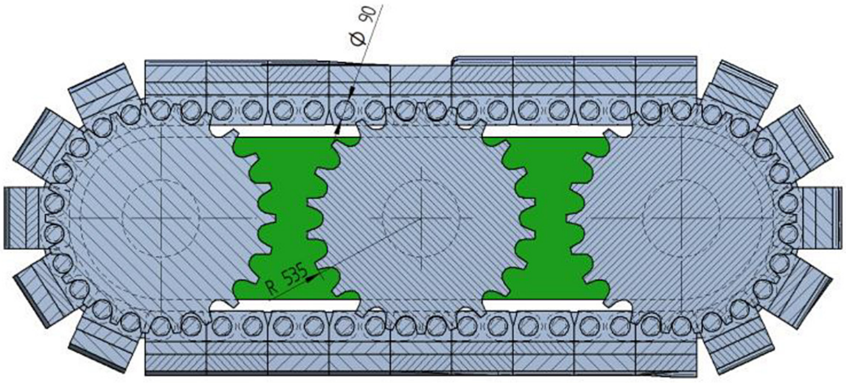

Figure 6. Schematic design showing how drive is transmitted to individual tool segments_

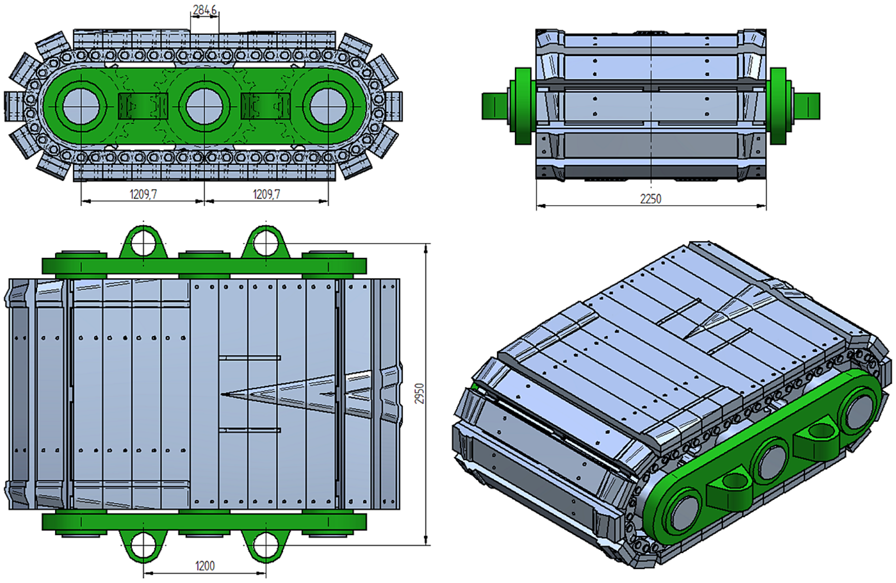

Figure 7. Innovative segmented tool assembly for CWR

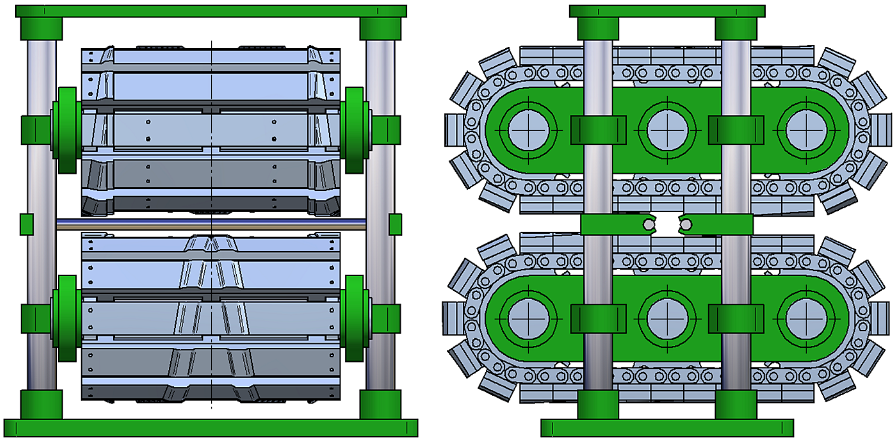

Figure 8. Schematic design of an innovative rolling mill with segmented tools for producing railcar axles

Rolling railcar axles from a cylindrical billet

Figure 9 shows the geometric model of a CWR process conducted with wedge segments in which a railcar axle is formed from a cylindrical billet shown in Figure 3. The workpiece is deformed as a result of the interaction between two identical tool assemblies and two cylindrical guides. Each tool assembly consists of 28 segments that were created by dividing the wedge tool (Fig. 2) into 28 parts with a length of 284.6 mm each. The wedge segments move with a speed of 284.6 mm/s, which corresponds to the rotational speed of a toothed shaft moving at 5 rpm. The work cycle of the drive unit is 28 s. The cylindrical guides are not driven and can only rotate as a result of action of the workpiece. It was assumed that the billet would be heated all over to a temperature of $T = 1180$ °C. It was also assumed that the temperature of all tools would be maintained constant at $T_T = 150$ °C during the rolling process. The simulations also took into account thermal phenomena occurring during the forming process, depending on the temperature of the billet, tools and environment (50 °C) as well as the workpiece/tool heat transfer coefficient (10000 W/m^{2}K) and the workpiece/environment heat transfer coefficient (200 W/m^{2}K). A model of 42CrMo4 steel was taken from the material database library of Simufact. Forming. The model is described by the following equation:

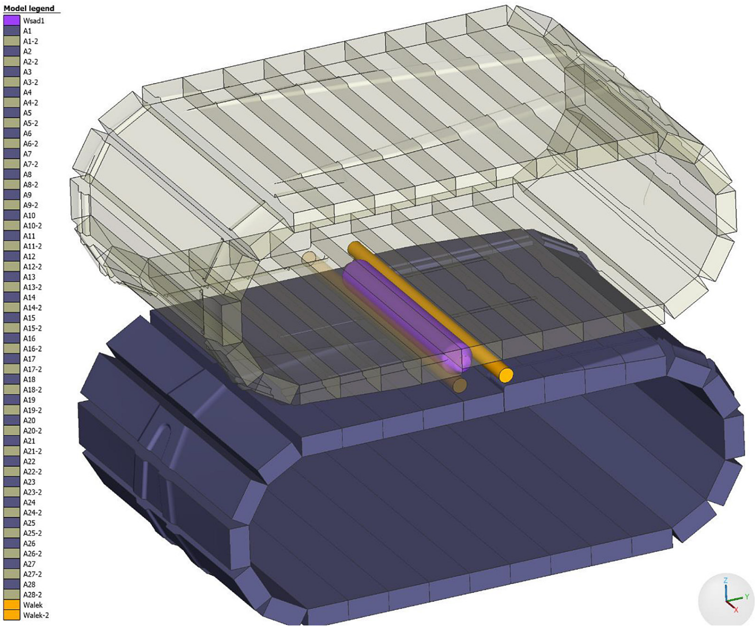

Figure 9. Geometrical model of a CWR process conducted with wedge segments, designed in Simufact.Forming 2022

$$\sigma_F = 4628.8e^{-0.00345T}\varepsilon^{(-0.00000509T-0.03638)}e^{(-0.00000461T-0.01944)/\varepsilon}\dot{\varepsilon}^{(0.0001893T-0.04627)} \quad (1)$$

where: σ_F is the flow stress, MPa; ε is the effective strain, –; $\dot{\varepsilon}$ is the strain rate, s^{-1}; T is the temperature, °C.

Friction on the workpiece/tool contact surface was described by the Tresca friction model, according to which

$$\tau = m\,k \quad (2)$$

where: τ is the shear stress on contact surface, MPa; m is the friction factor (set equal to $m = 0.9$), – ; k is the shear yield stress ($k = \sigma_F/\sqrt{3}$), MPa.

The numerical results confirmed that the proposed wedge segments could be used to form railcar axles. Figure 10 shows the changes in the shape of a workpiece during rolling. The cross–sectional reduction in the centre of the workpiece is created first, and then cross-sectional reductions are made on the ends of the workpiece. The rolling process runs in a stable way, and the use of a billet with tapered ends results in obtaining an axle with no end face cavities.

Figure 11 shows the distribution of effective strains in a produced railcar axle. As expected, an increase in the diameter reduction results in higher strains. The highest strains are located in the smallest diameter area on the workpiece end, with the highest effective strain located in the near–surface zones rather than in the axial zone

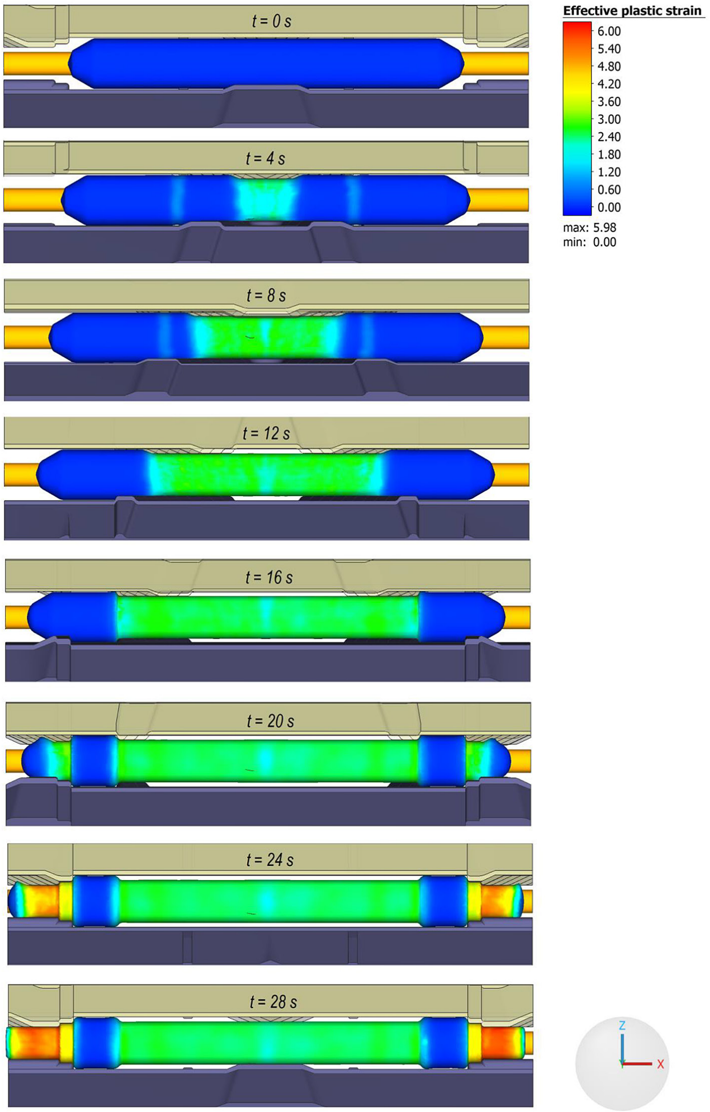

Figure 10. Changes in the shape of a workpiece in a CWR process where a railcar axle is formed from a cylindrical billet; the figure also show the distribution of effective strains in the workpiece

of the workpiece. This layered distribution of effective strains results from the action of frictional forces on the contact surface and is characteristic of CWR processes.

Although the rolling of a railcar axle takes a long time (28 s), the temperature of the workpiece does not fall below the hot forming range. As it can be seen in Figure 12, the temperature on the surface of a produced axle is 1000 °C. In the axial zone of the workpiece, on the other hand, the temperature is much higher and exceeds 1130 °C. This temperature distribution results from the fact that heat is carried away from the workpiece to the tools while at the same time large amounts of heat are generated by friction and deformation work.

As previously mentioned, the formation of internal crack poses a significant problem in the CWR of railcar axles. This is mainly due to the use of very high forming angles α and tool angles β. In this study, the angles α and β were assigned standard values, which resulted in low values of the damage function. According to Figure 13, for the case under study, the maximum damage function does not exceed a value of 1. In contrast, the critical damage value for 42CrMo4 steel at 1138.7 °C is much higher and equal to 3.56 [31]. Thus, it can be concluded that the proposed CWR method should not cause internal crack formation in the workpiece.

A major challenge in the CWR process for producing railway axles is to ensure that sufficient power is supplied to the tool assemblies. This is due to very high loads in the forming process. Figure 14 shows the distributions of two forming loads, i.e. tangential (along the tool travel direction) and radial (perpendicular to the segment base surface). The tangential load reaches its maximum value of 891 kN when the cross–sectional reductions are created on the workpiece ends. On the other hand, the radial load reaches two peaks (2270 kN) at the beginning of creating the cross-sectional

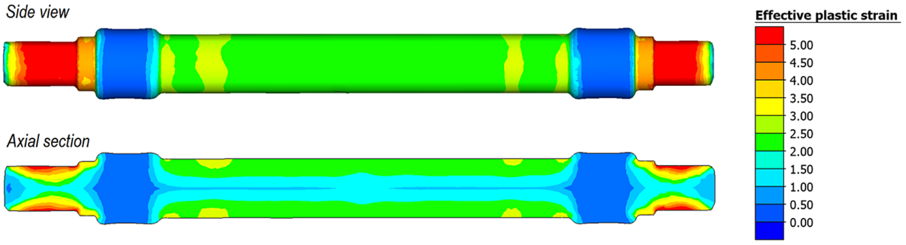

Figure 11. Distribution of effective strains in a railcar axle formed from a cylindrical billet by CWR

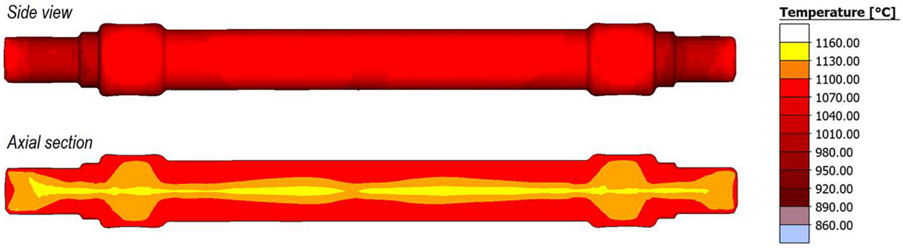

Figure 12. Distribution of the temperature in a railcar axle formed from a cylindrical billet by CWR

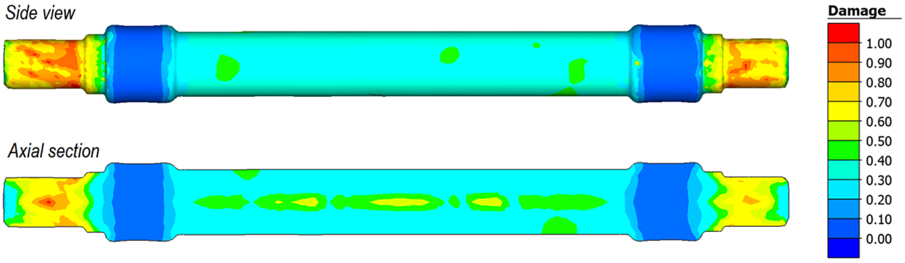

Figure 13. Distribution of the damage function calculated in accordance with the Cockcroft–Latham criterion in a railcar axle formed from a cylindrical billet by CWR

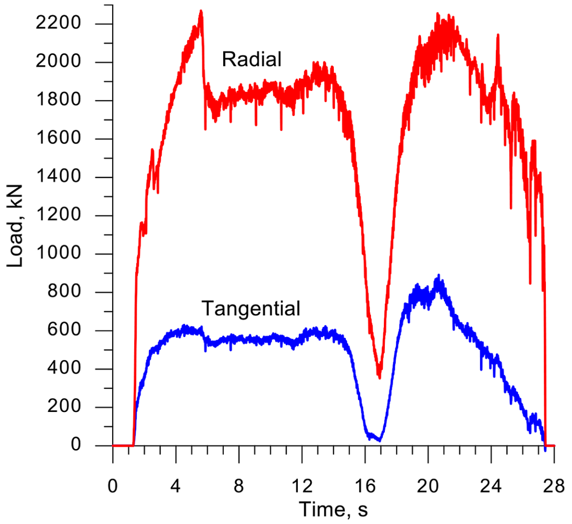

Figure 14. Distributions of the radial and tangential loads in a CWR process when a railcar axle is formed from a cylindrical billet

reductions in the centre of the workpiece and on its ends. Given the maximum tangential load and the tool travel speed, the minimum power of the tool assembly can be estimated to be 254 kW. Allowing for a certain safety factor, it can therefore be assumed that 4 motors of 180 kW each (2 motors per tool assembly) are sufficient to drive the proposed rolling mill, a value which is not too high in relation to the overall dimensions of the workpiece.

Rolling a railcar axle from a rectangular billet

The CWR process in which a railcar axle was formed from a rectangular billet (Fig. 4) was conducted using the tools shown in Figure 5, which were also divided into 28 parts. For this case, the operation of cutting off deformed ends was taken into account, which, consequently, entailed changing the design of the guides for maintaining the workpiece in a stable position during rolling. Figure 15 shows the geometrical model of a CWR process in which a railcar axle is formed from a rectangular billet. Apart from the tool segments, the model features two guides that move along the axis of the workpiece so as to avoid collision with the wedge segments. This motion can be achieved by using independently-driven guides or by mounting special inserts on the wedge segments. The kinematics of the tool assemblies was identical to that in the previously analysed case of CWR. The numerical simulation of rolling a railcar axle from a rectangular billet was performed using the same material model, friction model and thermal parameters as in the previous case. As previously, the full forming cycle was 28 seconds. However, the simulation was terminated earlier (at t = 26.2 s) when the operation of cutting off waste material on the workpiece ends took place (Simufact.Forming can only proceed with calculations as long as the workpiece is a single body).

The simulations demonstrated that the CWR process in which a railcar axle was formed from a rectangular billet proceeded without any interruptions (Fig. 16). This information is particularly interesting given the very large cross–sectional reduction made in the process, it value amounting to 68.6% for the case of creating the cross–sectional reduction with a diameter of 139 mm on the workpiece end. The employed method of guiding the workpiece during the rolling process was found to be effective, and the waste material on the workpiece ends was removed effectively.

The use of a rectangular billet results in higher effective strains in the rolled railcar axle (Fig. 17). This observation is important when an ingot is used as the starting material, as it ensures adequate grain size reduction. Obviously, a greater cross–sectional reduction results in higher strains, with the strain values being the highest in the smallest diameter area, i.e. on the ends of the workpiece.

In the CWR process where a railcar axle is formed from a rectangular billet, the contact area between the workpiece and the tools is significantly larger than in the previously considered process where an axle was rolled from a cylindrical billet. This leads to increased heat transfer from the workpiece to the tools and thus to a lower temperature of the workpiece (Fig. 18). Despite this decrease, however, the temperature remains within the hot forming range (mainly between 960 and 1060 °C). Higher temperatures are located in the axial zone of the product.

The cross-sectional reduction increase led to an increase in the damage function that was calculated according to the normalized Cockcroft–Latham criterion. An analysis of the distribution of the damage function shown in Figure 19 demonstrates that the highest values (~1.3) are located in the axial zone with the cross-sectional reductions on the workpiece ends. These values are higher than those obtained for a cylindrical billet, but at the same time they are much lower than the critical values. This means that material cracking should not occur in the axial zone of the workpiece for this case of CWR either. The use of a rectangular billet leads to a marked increase in

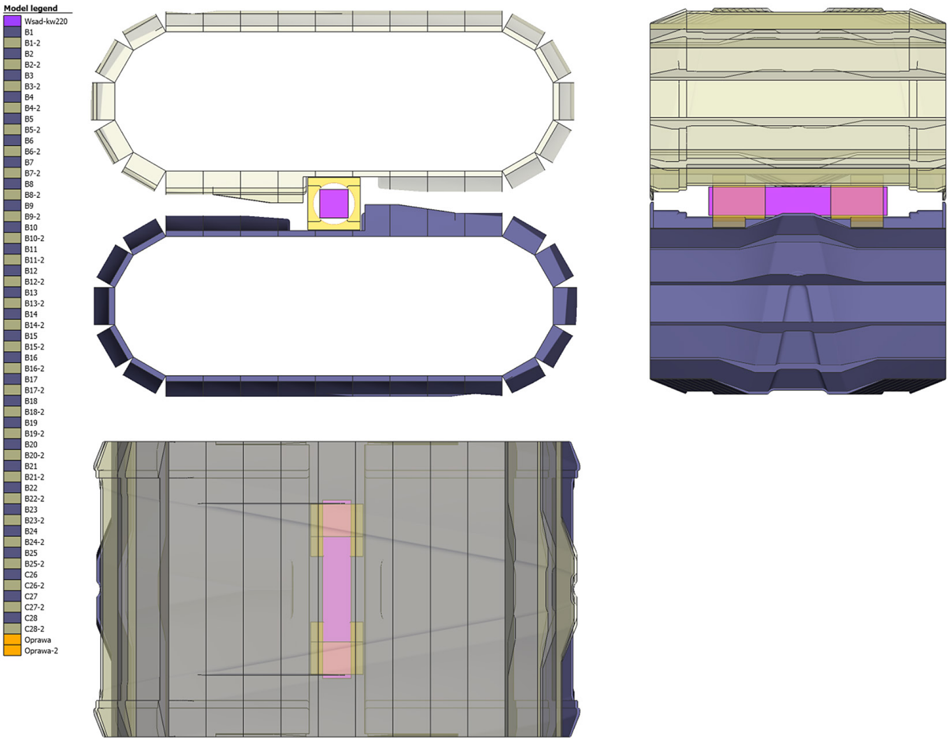

Figure 15. Geometrical model of a CWR process in which a railcar axle is formed from a rectangular billet

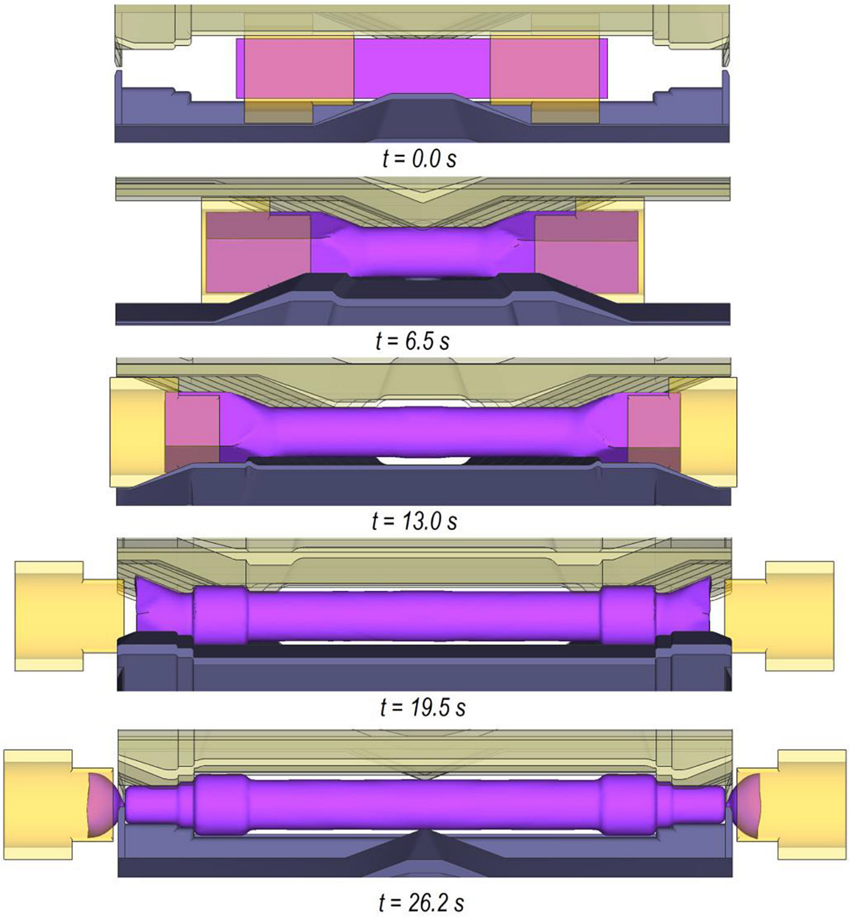

Figure 16. Changes in the shape of a workpiece in a CWR process where a railcar axle is formed from a rectangular billet

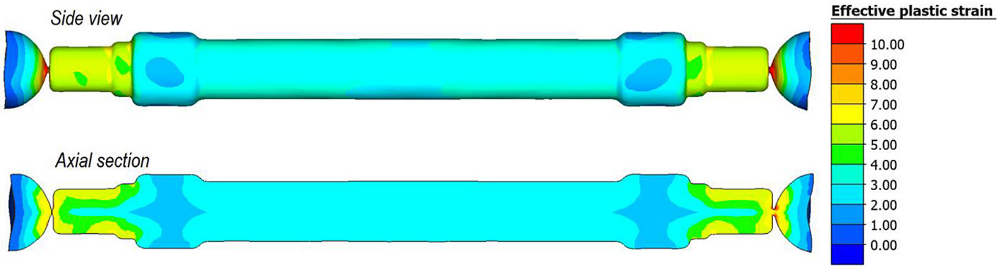

Figure 17. Distribution of the effective strain in a railcar axle formed from a rectangular billet by CWR

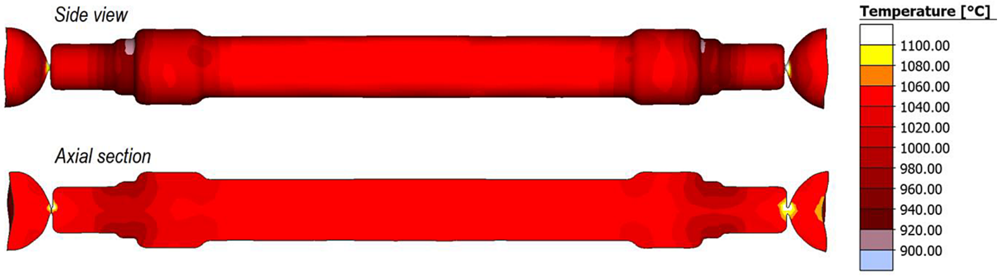

Figure 18. Distribution of the temperature in a railcar axle that was formed from a rectangular billet by CWR

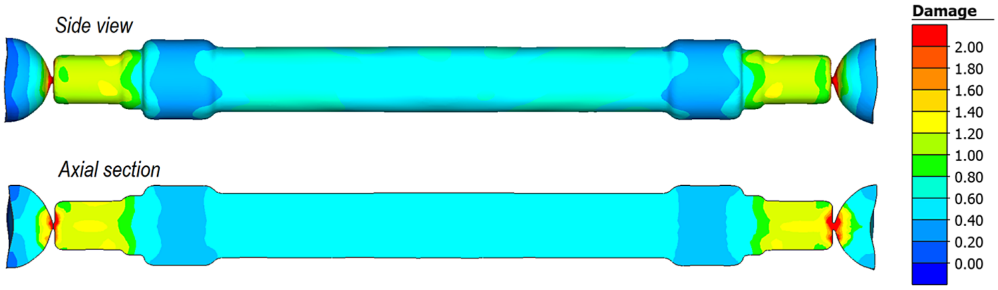

Figure 19. Distribution of the damage function (calculated based on the normalized Cockcroft–Latham criterion) in a railcar axle that was formed from a rectangular billet by CWR

the forming loads (Fig. 20) compared to the CWR process conducted from a cylindrical billet. The maximum tangential and radial loads are 1828 kN and 4402 kN, respectively. They are therefore more than twice as high as those observed in the previous CWR process. Furthermore, these loads decrease in an oscillatory manner, which results from variations in the radial dimension reductions (the greatest reduction occurs on the diagonal of the cross section, while the smallest is parallel to the side of the workpiece). The increase in the forming loads entails an increase in the rolling mill drive power, which – for this case – is estimated to be at least 520 kW for a single drive unit. Considering an adequate power reserve, it can be assumed that 4 motors of 360 kW each would have to be used to power the rolling mill when railway axles are rolled from rectangular billets.

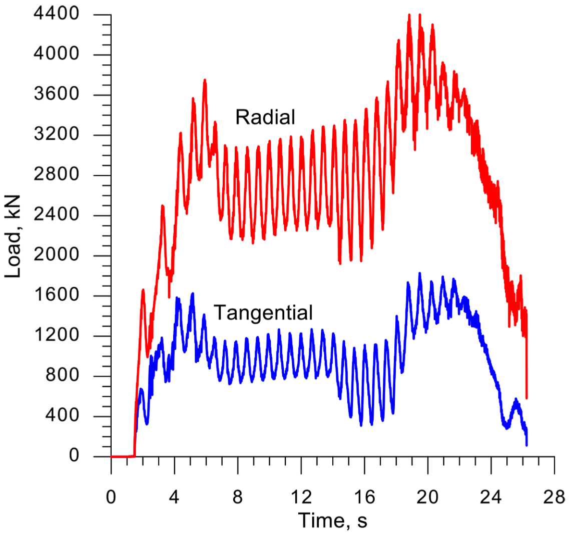

Figure 20. Radial and tangential loads in a CWR process when a railcar axle is formed from a rectangular billet

CONCLUSIONS

The results of this study lead to the following conclusions:

- A new variant of the cross wedge rolling process has been developed in which the workpiece is formed by segmented tool assemblies;
- Considering the tool kinematics from the workpiece point of view, the proposed CWR process boils down to forming railcar axles with two counter-rotating flat wedge tools;
- A characteristic of the new CWR process is the absence of tool idling and the presence of relatively low forming loads;
- An example of a design of a rolling mill for implementing the proposed CWR process is presented;
- The results of the numerical simulations of the new CWR process confirmed that the proposed solution can be used to produce BA3002 type railcar axles;
- The power of the rolling mill drives was estimated for the CWR process in which railway axles were formed from both cylindrical and rectangular billets.

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