Conception of a Three Roll Cross Rolling Process of Hollow Rail Axles

Zbigniew PATER,* Janusz TOMCZAK, Tomasz BULZAK and Łukasz WÓJCIK

Lublin University of Technology, 36 Nadbystrzycka Str., 20-618 Lublin, Poland.

(Received on September 15, 2020; accepted on November 17, 2020)

The article presents an innovative method of forming hollow rail axles by cross rolling (CR) in a 3-roll mill. Assessing the correctness of the concept was conducted with numerical simulations in Forge® NxT v.3.0. In order to investigate whether the limitation in the form of material cracking would occur in the analysed cross rolling process critical values of the damage function for 42CrMo4 grade steel were determined. A new calibrating test, based on rotary compression of a disc-shaped sample in a channel was developed. Changes to wall thickness, effective strain, temperature and damage function calculated on the basis of the normalised Cockcroft-Latham criterion were determined. Distributions of force parameters were done and power of the rolling mill necessary to produce hollow rail axles were obtained.

KEY WORDS: rail axle; cross rolling; rotary compression.

1. Introduction

Rail axles are large-size elements produced in batches consisting of thousands of elements.1,2 Currently the main technologies applied in production of such elements are open die forging and forging on swaging machines.

In order to decrease the mass of rail axles whole parts are replaced with hollow ones. Due to the class of work performed by those elements (bending) their strength properties are not significantly influenced. Currently hollow rail axles are manufactured in the joint process of piercing sleeves in a skew rolling mill and forging in swaging machines.3) Many research facilities seek new, highly efficient methods of manufacturing hollow rail axles. Rolling appears to be particularly auspicious.4)

Cross-wedge rolling (CWR) technology research appears to be the most advanced. Firstly the limitations to the process of CWR of hollow elements were determined, mainly: excessive ovalisation of the cross-section, uncontrollable slip, rupture or crushing of the rolled step.5,6) Then the parameters at which the rolling process is mostly uninterrupted were determined using numerical simulations and experimental testing.7–9) It allowed one to develop new, effective methods of manufacturing sleeves10) and valves11) using CWR.

However, due to the significant length of the rail axles (over 2 m) the wedge tools need to be large as well. It was estimated that applying the classic rolling variant would require rolls with diameters exceeding 2 m. For this reason the possibility of rolling axles using several pairs of wedges simultaneously was investigated.12–14) Such solution allows the tool to be significantly shorter and used in a rolling mill with the diameter of rolls about 1 500 mm (rolling mills with such rolls are already produced in China). Unfortunately employing the multi-wedge rolling scheme magnified the problem of excessive ovalisation of the cross-section. Research by Bartnicki and Pater15) indicates that a removal of the deformation of the cross-section of a hollow element is progressing faster in the case of rolling with three tools as opposed to the traditional rolling with two tools. In the case of rail axles, however, special joint rolls have to be used, which complicates the forming process.16)

An alternative to the CWR processes may be cross rolling (CR) with three rolls, based on the method of rotary compression of hollow elements17–19) developed and researched in Lublin University of Technology. This process is presented further in this study exemplified by rolling E- and K-class American standard rail axles, shown in Fig. 1. Axles dimensions are presented in Table 1.

![Fig. 1. Shape of the analysed rail axe.](image-url)

* Corresponding author: E-mail: z.pater@pollub.pl

© 2021 The Iron and Steel Institute of Japan. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs license (https://creativecommons.org/licenses/by-nc-nd/4.0/).
2. Concept of Forming and the Numerical Model Applied

It was assumed that rail axles would be made of tubeshaped billet with the outer dimension equal to the dimension of the maximum step of the axis with an allowance for machining. It was finally assumed that the outer diameter of the billet $d_0 = 219$ mm for the axle in the E-class and 232 mm for the K-class. It was also assumed that in both cases that wall thickness was $t_0 = 40$ mm, whereas the billet length $l_0$ was 2 130 mm for the E-class axle and 2 120 mm for the K-class one.

In the presented rolling scheme (Fig. 2) it was assumed that forming axles is realised with three rolls, with one of them shown in Fig. 3. The rolls are located on the circumference of the billet by each 120° and their axes are located at 570 mm from the axis of the workpiece. The hollow rail axle is formed simultaneously on its entire length as a result of the working surfaces of the roll gradually growing (eccentrically) on the arch of the roll at the angle 216°, which is the working zone. Tools in this zone were separated into 3 equal parts, differing in the intensity of growth of the radius of the working surfaces. This growth is the most significant in the first zone, where it reaches 50% of the total growth and the least significant in the third zone where it reaches only 20% of the total growth.

Such a solution causes the load of rolls in the forming zone to be more even. Behind the forming zone a sizing zone, located on a 72° angle arch can be found. A characteristic trait of this tool zone is the fact that the distance between the working surfaces and the axis of the roll is constant, which is necessary for the steps to acquire a desired axial-symmetric shape. Behind the sizing zone an output zone is located, done on a 22° angle arch. In this area of the tool radiuses of the working surfaces of the rolls decrease (by 5 mm), which facilitates a smooth output of the workpiece from the working zone of the rolling mill. In the remaining part of the circuit of the rolls their surfaces are lowered to enable free input of the workpiece. Moreover, a dent is made in one of the rolls. The rolled axle falls into the dent and during the next rotation of the rolls it is ejected from the rolling mill.

In order to assess the correctness of the concept of forming hollow rail axles numerical simulation were performed in Forge® NxT v.3.0. Figure 4 presents one of the geometrical models of axle rolling. To quicken the calculations the symmetry of the process was used. It was assumed in the analysis that the rolls act as perfectly rigid bodies, whereas the workpiece acts as a deformable body.

Material model of the formed 42CrMo4 grade steel is described by the Hansel and Spittel equation in the following form:

$$\sigma_p = 1 827.07e^{-0.00289T} \cdot e^{-0.1123} \cdot e^{-0.04879/c} \cdot e^{-0.14368} \ldots (1)$$

where: $\sigma_p$ – flow stress, MPa; $T$ – temperature, °C; $e$ – effective strain, $-1$; $e$ – a strain rate, s$^{-1}$.

In the calculations it was assumed that prior to rolling the billet is evenly heated to 1 200°C throughout its entire volume. The tool temperature is constant and equal 300°C. Heat transfer between the formed material and the tools is determined by heat transfer coefficient equal 10 000 W/
m²K. Remaining parameters assumed in the simulation referred to the rotational speed of the rolls (equal 3 rpm) and to the friction model. On the basis of the study it was assumed that the most favourable friction model is constant shear friction model, where the friction factor is equal 0.8.

3. Determining the Critical Damage Value of 42CrMo4 Grade Steel

A frequent limitation to the CR process is material fracture/cracking. In the case of hollow elements these cracks are located mostly on their inner surfaces. The occurrence of ductile fractures can be modelled by calculating the damage function, which ought to be smaller than the critical damage value obtained in the calibrating test.

In this analysis normalised Cockcroft-Latham criterion was used for modelling damage. The damage function is described from the dependency:

\[ f_{\text{CL}} = \int_0^\varepsilon \frac{\sigma_1}{\sigma_i} \, d\varepsilon, \]

where: \( f_{\text{CL}} \) – damage function according to the normalised Cockcroft-Latham criterion, \( \sigma_1 \) – maximum principal stress, MPa; \( \sigma_i \) – effective stress, MPa; \( \varepsilon \) – effective strain, -.

In order to determine the critical damage value rotary compression in a channel was performed. During this test the stress state is very similar to the stress state occurring in the process of CR. The rotary compression test, shown schematically in Fig. 5, comprises of experimentally determining the length of the path at which cracks occur in the axial area of the samples. Due to an insignificant width of the samples a crack is initiated throughout the sample and it can be observed on the side surface of the sample. Upon determining the length of the critical path the rotary compression test on this path is modelled numerically. On the basis of the calculations value of the damage function in the axis of the sample is determined and equal to the sought critical value of \( C_{\text{CL}} \).

Rotary compression of a disc sample in a channel was performed in a rolling mill located in Lublin University of Technology. Four forming cases were subjected to tests in which the disc samples were heated to 900°C, 1000°C, 1100°C and 1200°C. On the basis of the research conducted it was stated that the length of the critical path at which cracking occurs depends highly on temperature. This phenomenon is noticeable in Fig. 6, where samples heated to different temperatures and deformed on the same path length were presented. It was established that the length of the critical path equals 225 mm for \( T = 900°C \), 275 mm for \( T = 1000°C \), 350 mm for \( T = 1100°C \) and 500 mm for \( T = 1200°C \).

The rotary compression test was also modelled in ForgeNxT v.3.0. In the simulation the same material model as previously was used – expressed by the dependency (1) as well as friction model. Tool temperature was assumed to be 50°C, heat transfer coefficient 10 000 W/m²K and travelling velocity of the movable upper tool \( v = 300 \text{ mm/s} \) (similarly...
Four tests differing in sample temperature and the length of the forming path were simulated. Progression of one of those tests was shown in Fig. 7 with changes to the damage function illustrated. It can be observed that the maximum value of $f_{CL}$ is reached in the axis of the sample, which is the area of material cracking.

In order to determine the critical damage value in the axis of the sample 11 virtual sensors were applied to record the values of this parameter. Changes to the $f_{CL}$ recorded in the sensors during one of rotary test are presented in Fig. 8. It can be observed that the function $f_{CL}$ grows monotonically along with the sample travelling along the nether tool, which increases proportionally to the forming time. The presented chart indicates that in all sensors located in the axis of the sample the damage criterion increased almost similarly, which is confirmed by the lines of growth of the damage criterion $f_{CL}$. Only in the case of side sensors, located in the front areas of the sample values of the $f_{CL}$ criterion are slightly smaller. The final critical damage value $C_{CL}$ was calculated by averaging the end values $f_{CL}$ registered in 11 sensors. The obtained $C_{CL}$ values, dependent on forming temperature are shown in Fig. 9. Upon analysing the data presented in the figure it can be stated that forming temperature has a significant role in the occurrence of cracks in CR. Its increase significantly decreases the risk of cracking.

### 4. Results

Numerical simulations conducted confirmed the validity of the concept of forming hollow rail axles. Figure 10 shows progression of one of the analysed cases. Firstly the tube-shaped billet is placed between the stopped rolls. Then the drive is activated and all of the rolls (rotating at the same speed in the same direction) perform one rotation during which the axle is formed. The product falls into the dent in one of the nether rolls and is ejected from the rolling mill. After the movement of the rolls ceases, another billet is placed in the working area and the process is repeated.

Figure 11 presents progression of shape of a hollow E-class rail axle during rolling. It can be observed that all steps are formed simultaneously. Material travels in the radial direction and in the case of the end steps also in the axial direction, which leads to the workpiece being elongated and reaching the desired dimensions in the final stages of the process. Numerical simulations showed that in both analysed cases the process progressed in a stable manner and at no limitations caused by uncontrolled slipping.
occurred at any stage of the process.

**Figure 12** presents cross-sections of the obtained rail axles. Additionally, in the cross-sections control circles were made using the three-point method. The points defining the control circle were placed on the circumference of the obtained cross-sections. Deviations of the roundness, which can be described as the greatest distance between the circle on the cross section and the control circle were measured. The cross-sections in the A-A surface for both axes overlap perfectly. In B-B and C-C cross-sections a greater roundness deviation occurs for the E class. The greatest roundness deviations in both cases occur in D-D cross-section, that is in the central part of the axis. In the case of E-class axle the greatest value of roundness deviation was 2.71 mm, whereas for K-class it equalled 1.6 mm.

**Figure 13** presents distributions of effective strain in the formed rail axles. These distributions are typical for CR processes, since the strains are distributed in the form of annular layers with the maximum values located in the outer layers, where the material is acted upon by friction forces. Generally, it was stated that increase of the diameter reduction of the axle results in an increase of effective strain.

Longitudinal sections of the axles shown in Fig. 13 enable one to determine the changes to the wall thickness. In the case of the K-class rail axle a significant thickening of the wall of a central conical step, this increased to 56 mm in the centre. Thickening depended on the diameter reduction and decreased as it neared the step with the biggest diameter. Wall thickening was also observed in side steps, where the maximum wall thickness neared 58 mm. The last step of the axle in which axial material flow occurred and the axis elongated up to about 200 mm is of a relatively constant thickness equal about 47 mm, which then decreases and at 1 118 mm from the centre (end of the axle) equals 30 mm. This problem can be solved as elongating the end steps of the axle and removing the allowance in which wall thickness decreased. In the case of K-class axle changes to the wall thickness are similar. Due to using smaller diameter reductions wall thickening is not so significant in this case.
Fig. 16. Distributions of radial loads acting on the rolls in the process of CR of the analysed hollow rail axles. (Online version in color.)

Fig. 17. Distributions of torque on the roll in the process of CR of a hollow rail axle depending on its class. (Online version in color.)

Figure 14 presents distributions of temperature on the surface and in the axial section of the cross rolled rail axles. It can be observed that the lowest temperature (about 1 000°C) occurs in the outer layers where it came in contact with much cooler tools. As the distance from the outer surface increases, the temperature of the material increases. The calculations showed that the maximum temperature differences between the outer and inner surfaces of hollow rail axles are up to 150°C. Such temperature distribution results, on one hand, from the heat being transferred to the rolls and on the other hand from generating significant amounts of heat as the result of plastic work.

Distributions of damage function $f_{CL}$ calculated using the normalised Cockcroft-Latham criterion are presented in Fig. 15. As expected, the greatest value of the function is obtained on the inner surface of the conical central step. The absolute values of this function are significantly greater in the case of E-class rail (formed at higher diameter reductions) and equal about 1.2. In order for cracking to occur the value of the function must exceed the critical value, which equals about 2.7 for 42CrMo4 grade steel formed at 1 150°C (see Fig. 9). It can therefore be stated that cracking should not occur during CR of hollow rail axles.

The simulation performer allowed one to determine force parameters of the presented method of forming rail axles. Figure 16 presents distributions of radial force acting on the roll in both discussed cases. The obtained distributions are similar. Forces increase in the forming zone and then decrease in the sizing zone. Maximum force values equalled 598.5 kN and 504.5 kN, respectively in the process of forming E- and K-class axles. The greater force occurring in the case of the E-class part is indubitably caused by the greater reduction of diameters.

Figure 17 presents distributions of torque, which is relatively constant due to the assumed solution. It is slightly higher in the process of rolling E-class axles, for which the maximum value of the parameter equals 660.5 kNm. The maximum value of torque in the case of K-class axles was 486.2 kNm. Based on the obtained maximum value of torque and upon determining the rotational speed of the roll the minimum engine power used to drive a single roll can be calculated and would equal 207.4 kW. Upon considering power allowance one can estimate the power of the rolling mill securing the rolling process of hollow rail axles to be 3 × 250 kW.

5. Conclusions

On the basis of the research conducted, the following conclusions were drawn:
- The presented method of CR ought to facilitate manufacturing hollow rail axles;
- As a result of CR the walls of the formed steps thicken;
- The maximum value of the damage function calculated on the basis of the normalised Cockcroft-Latham criterion is over two times lower than the critical value determined by rotational compression in a channel; therefore it can be
stated that the conditions occurring during the CR process do not facilitate inner cracking;
- Despite a relatively long forming time the temperature of the workpiece remains in the range typical for hot working processes; the temperature difference between the outer and inner surfaces of the formed rail axle is about 150°C;
- In order to realise the proposed method of forming hollow rail axles a three-roll mill the body of which can transfer the load of 6 MN is required; the power of the rolling mill is estimated to be 3 x 250 kW.

Acknowledgment
The research has been conducted under the project No. 2017/25/B/ST8/00294 financed by the National Science Centre, Poland.

REFERENCES

2) C. Xu and X. Shu: Metalurgija, 57 (2018), 153. https://break.scree.hr/199231