Integration of automated roll pass design and simulation for the development of shape rolling technology

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Abstract. The shape rolling technology is a productive manufacturing process. Meanwhile, its efficiency is highly dependent on a proper roll pass design and accurate adjusting of a rolling mill, which is especially critical for new products and complicated profile shapes. Traditionally, the roll pass design methods have been developed relying on extensive experience and knowledge accumulation, resulting in empirical rules expressed by analytical formulae. Nowadays, some design methods are converted into computer programs to speed up calculations. Nonetheless, the approach based on empirical rules has limitations, especially when implemented to develop the rolling technology for new materials and complex shape profiles. The effectiveness of the roll pass design can be significantly enhanced with the help of finite element (FE) simulation of the material deformation that happens in the stands of the rolling mill. The material flow prediction provided by FE simulation is more accurate than empiric formulae, leading to more accurate load, torque, and energy estimations. The presented paper is focused on the integration of the FE simulation of the rolling process with the roll pass design to make it effective and automated for a wide variety of profile shapes.

Introduction

Roll pass design (RPD) methods have evolved significantly over the years, leveraging both analytical techniques and empirical knowledge [1,2]. Often integrated into software solutions, such methods were implemented for billet, bar, and rod mills [3]. For example, in the Freiberg Mining Academy was developed PyRolL, an open-source project that encapsulates the collective expertise of students, engineers, and scientists in RPD [4]. Concurrently, Finite Element Method (FEM) codes have proven effective in simulating shape rolling, though they necessitate detailed input for each stand, a task that demands substantial preparatory and analytical effort.

Several years ago, the authors developed a specialised module for shape rolling simulation within the QForm UK metal forming simulation software [5] that is now integrated with the newly developed program QKaliber for automated roll pass design. This integration enables the roll pass design software to generate and transfer detailed process parameters and groove geometries directly to the simulation program and get feedback from it. This integration, embodying Industry 4.0 ideals. It is applicable to a wide range of products in any rolling mill type. While focusing on product shapes, loads, and torques, the software also examines heat balances and is capable of simulating heat treatment processes and microstructure prediction, setting the stage for future discussions.

Materials and Methods

This study enhances our FEM simulation software for metal forming, specifically targeting the unique challenges of shape rolling simulations. Unlike forging, shape rolling involves localised, small deformation zones, with the rest of the product acting largely as a rigid body. Simultaneous rolling across multiple stands can influence adjacent stands via tension or support in continuous mills. Our solution employs a automatically densified FE mesh at contact nodes between the product and rolls for accurate deformation simulation (Fig. 1). Using Euler's method enables roll motion simulation through calculated nodal velocity vectors, keeping the FE mesh in rolls fixed in the space.

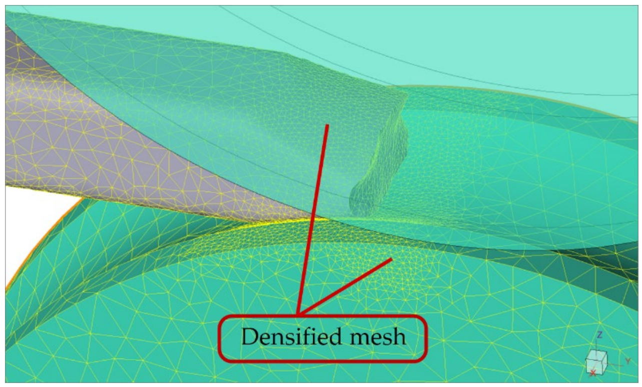
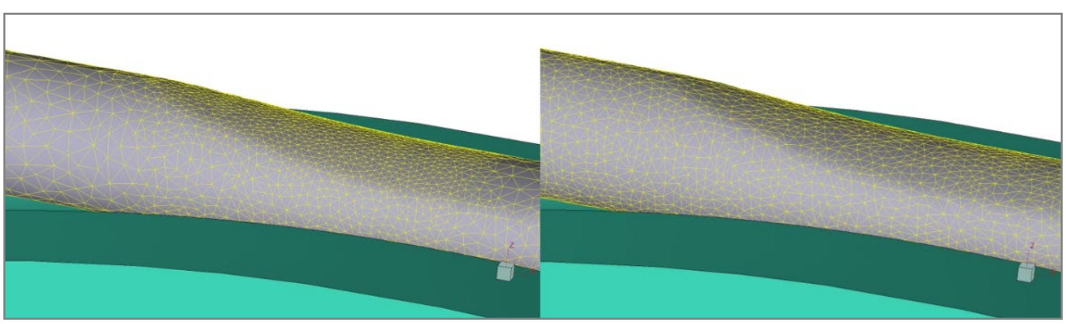


Fig.1. Quasi-rotational rolls for simulation of rolling in QForm UK with densified mesh in the contact area.

Moreover, it's crucial to refine the Finite Element (FE) mesh for the product within the deformation and contact zones. In contrast, a coarser mesh can be used for the rest of the product due to the absence of deformation. However, enlarging FE elements in rigid zones can compromise the precision of the product geometry representation. To overcome this issue, a dual mesh technique has been introduced (Fig. 2). This approach consists of a "Mechanical" mesh, densified in deformation areas and used for solving the material deformation task, and a "Geometry" mesh, dedicated to storing the product's shape and solving the thermal task. Data transfer between the "Mechanical" and "Geometry" meshes allows for the exchange of temperature and strain data to solve the general coupled thermo-mechanical task of the shape rolling process. Advanced algorithms have been developed to enhance the calculation of node trajectories across the roll's curved surface, ensuring continuous contact between the material being rolled and the rolls.



(a) (b)

Fig. 2. Dual mesh method for shape rolling simulation in QForm UK: the Mechanical mesh (a) and the Geometry mesh (b).

Contemporary shape rolling technology facilitates the manufacture of diverse profiles, necessitating the capability of software to simulate processes across various rolling mill types and configurations. These include reverse stands with multiple grooves, continuous rolling mills, and

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rolling lines that combine a sequence of duo stands and universal rolling stands. The influence of a pusher, the automatic positioning of the workpiece before rolling, and the influence of entry and exit guides are integral to the rolling simulation. To provide the input of roll geometry, several alternative methods have been developed, i.e. importing 3D solid models directly from CAD systems, importing 2D roll contours and then revolving these into 3D models, and direct transfer of roll pass designs from CAD system QKaliber.

Additional parameters essential for accurate rolling simulations encompass the material properties of both the billet and rolls, rolling speed, friction, initial temperature of the billet, and more. Once all necessary process parameters are established, the simulation software can automatically execute the entire sequence of passes in reverse or continuous mills to predict outcomes with high precision.

Industrial verification of the numerical model

The simulation results for shape rolling were compared with laboratory and industrial experiments, displaying a notable correlation. The industrial experiments served not only as a means for validation but also as an opportunity to refine the simulation's boundary conditions. During these industrial tests, technological parameters were measured in the continuous mill "450" during the production runs of the I-Beam IPE 160. This mill consists of 16 stands divided into roughing and finishing groups. The pass sequence utilised in the technology under the test is detailed in Fig. 3. The technological information used for simulation is presented in Table 1.

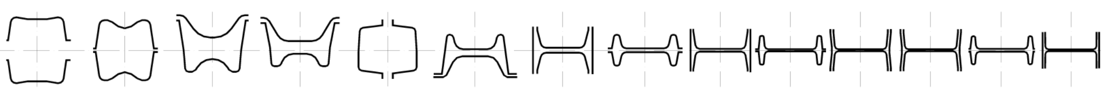


Fig. 3. The sequence of the passes in the mill “450” that is used for rolling the I-Beam IPE 160.

Table 1. Technological parameters of the I-Beam IPE 160 hot rolling in the continuous mill “450”.

Stand №	Roll horizontal gap, [mm]	Roll vertical gap, [mm]	Roll diameter, [mm]	RPM drives	Distance to next stand, [m]	Gear ratio
1	36	-	620	156,0	4,2	9,68
2	6	-	620	152,0	4,2	8,19
3	12,0	-	605	207,0	15,0	8,25
4	14,0	-	685	205,0	5,0	6,69
5	29,6	-	603	255,0	5,0	5,55
6	10,0	-	680	209,0	25,0	4,85
7	16,0	166,4	1070	224,0	10,0	5,55
9	11,9	-	650	286,0	62,0	3,64
12	9,3	170,0	865	328,0	6,0	4,36
13	7,1	172,5	885	354,0	6,0	3,32
14	6,5	-	559	271,0	6,0	1,56
15	5,6	165,3	865	360,0	6,0	2,75
16	6,5	-	477	314,0	6,0	1,11

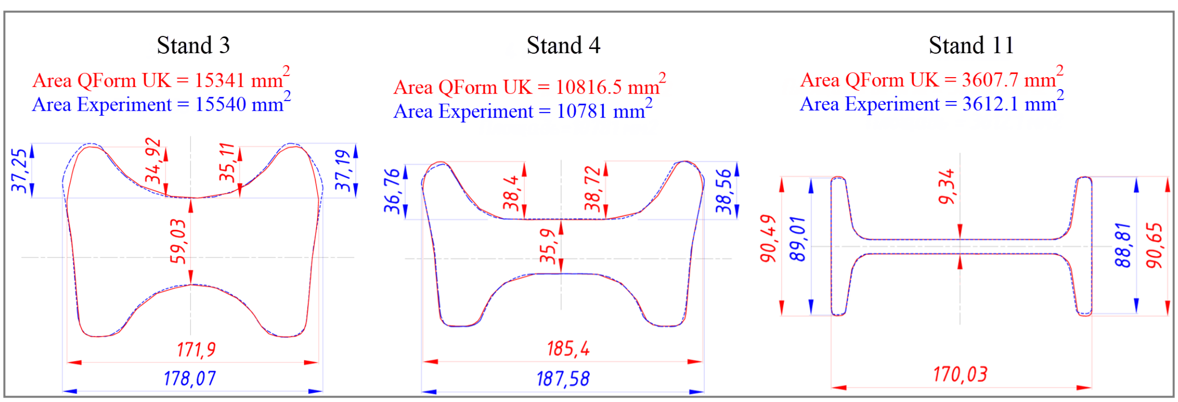
During the experiment with the I-Beam IPE 160, the procedure involved optimising the mill settings to minimise support and tension between the stands, achieving the profile shape within the standards, documenting the rolls' diameters, their rotational speeds, the real-time loads on the drives, and the temperature across passes. Extracted cross-cut templates from the product's end after every pass for geometric assessment are shown in Figure 4 and analysed in Figure 5.

(a) (b)

Fig. 4. Photos of the templates of the I-Beam IPE 160 cut from the end of the product while rolling in the mill 450: (a) templates from 3rd to 5th stand; (b) templates from 6th to 9th and 11th stands.

The simulation of the continuous rolling process was executed using the preliminary data furnished by the manufacturing facility. The simulation segmented the rolling sequence into stand groups, mirroring actual mill operations. Given the notable impact of the inter-stand group distance on metal temperature, the cooling was simulated after each group. This approach enabled the analysis of how the workpiece's cooling duration between stand groups affects the overall process.

This paper presents only a subset of the findings from these analyses. A comparison of the pass templates' geometry is depicted in Fig. 5, showcasing an impressive accuracy of the shape prediction exceeding 96.3%.



(a) (b) (c)

Fig. 5. The experimental templets and simulated shapes superposed over each other: (a) after the 3rd stand, (b) after the 4th stand, (c) after the 11th stand.

The largest discrepancy between simulation and actual measurements was observed after the 11th pass as 9.1%, while the smallest was after the 4th pass as 1%. Temperature comparisons between stationary pyrometer readings and simulations after the 3rd, 9th, and 16th stands are detailed in Table 2, with an average temperature prediction error about 4%.

Table 2. Comparison of the temperature during the rolling of I-Beam IPE 160.

Stand	Simulation	Experiment	Error
3	1096°C	1114°C	2%
9	1024°C	1012°C	1%
16	1045°C	958°C	9.1%
Mean error	4%		

A comparison of power consumption between actual experiments and simulations for the mill drives was conducted by converting real and simulated data into the drive power. Experimental rolling power was derived from average current and voltage readings and the rotational speed of main drives (RPM). Simulation power values were calculated using forces, torques, and roll RPMs, factoring in gearbox efficiency and gear ratios and compared in Fig. 6.

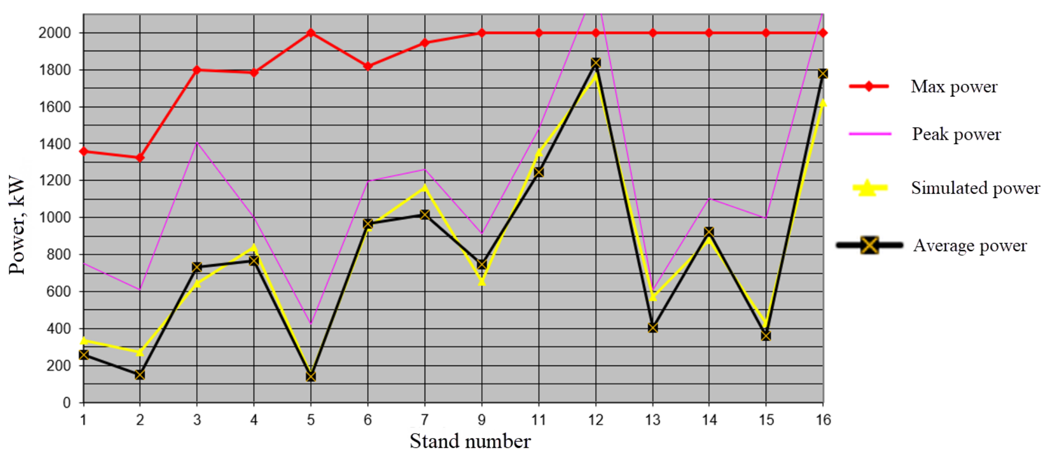


Fig. 6. Power of the stand drives of the mill "450" during rolling I-Beam IPE 160 profile.

The simulated power (yellow graph) and measured power (black coloured) have shown a total correspondence of 94.43%.

Automated roll pass design system QKaliber

QKaliber is our innovative software for automated roll pass design, offering a comprehensive selection of functionalities such as creating groove configurations for shape rolling, preparation of technical documentation, and initial data generation for simulation in QForm UK. It incorporates databases for rolling mill specifications and roll inventories, groove shapes design with rolling process parameters like temperature, speed, loads, and torques. It also conducts rolling process analysis within mill limitations. The software enhances understanding of metal deformation and bite conditions through visualizations, maintains an archive of groove variations, and conducts roll stress analysis. Additionally, it automates the generation of essential technical documentation and data preparation for simulations, streamlining the roll pass design process. The program's adaptability allows for the design of shaped profiles in two directions, i.e. from the workpiece to the finished profile and in the opposite direction. The typical breakdown passes are shown in Fig. 7.

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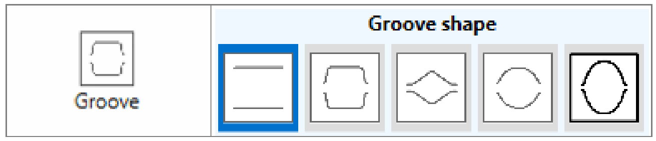


Fig. 7. The breakdown passes of the CAD QKaliber.

In QKaliber, breakdown grooves such as round, diamond, square and oval are defined in parametric form. The system enables the design of grooves from billet to final shape by specifying groove dimensions and calculating the spread and elongation of metal cross-cut sections along with rolling parameters for all the passes. An alternative design approach from the final section to the workpiece allows to work with complex shapes like I-beams, T-bars, rails, channels and others. Here, profiles undergo segmentation into parametric components, and their sizes are automatically determined through a built-in algorithm that considers the dimensional aspects of adjacent roll passes. The user can easily adjust this algorithm to achieve a well-balanced reduction pattern. Elements of the profile are quadrilateral with straight, rounded, or inclined sides. The example of the I-Beam profile divided into elements is shown in Fig. 8.

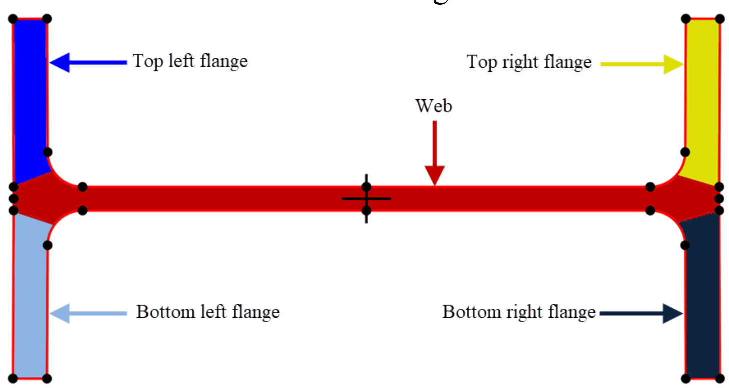
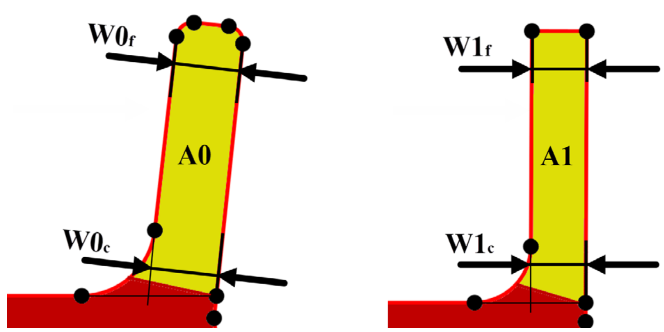


Fig. 8. The I-beam profile consists of five elements: four flanges and a web.

The strain in the passes is calculated automatically according to the total elongation between the final and leader profiles. It can be controlled separately to achieve the needed dimensions on the preliminary passes based on the chosen strategy. QKaliber helps the roll pass designer calculate all deformation coefficients in each pass in alignment with element dimensions. Fig. 9, using the example of a flange element, illustrates the labelling of element parameters that the software employs to calculate deformation coefficients.



(a) (b)

Fig. 9. Flange dimensions and areas of pre-finish (a) and finish (b) passes.

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The reduction coefficients (Eq. 1), relative reductions (Eq. 2) and elongation factor (Eq. 3) are calculated as follows:

$$\mu_f = \frac{W0_f}{W1_f},\ \mu_c = \frac{W0_c}{W1_c}, \tag{1}$$

$$\mu_f, \% = \frac{W0_f - W1_f}{W0_f} \times 100\%,\ \ \mu_c, \% = \frac{W0_f - W1_f}{W0_f} \times 100\%, \tag{2}$$

$$E = \frac{A0}{A1}, \tag{3}$$

All the dimensions of elements are gathered into one table of passes, where the ratio of heights (coefficient *kH*) along with the absolute reduction (*dL*) are presented (Fig. 10). The obtained coefficients can be displayed as a graph along passes.

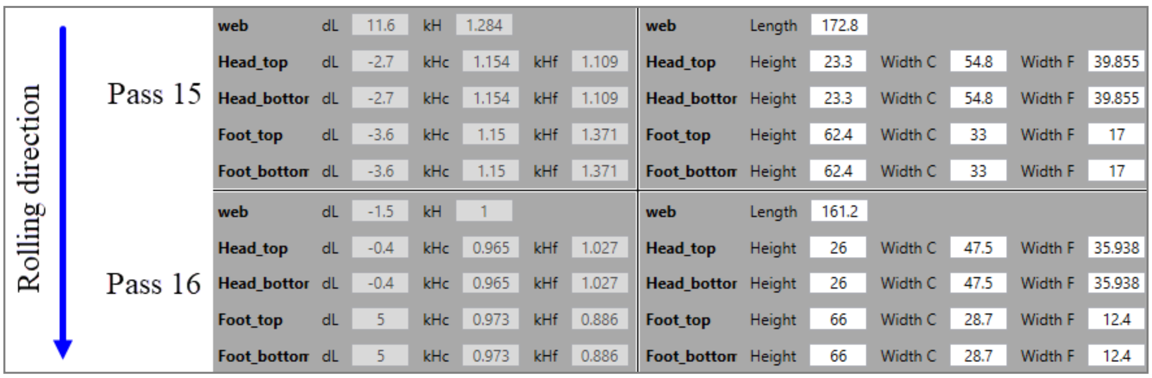

Fig.10. Dimensions of profile elements are calculated according to the previous pass opposite to the rolling direction.

Let us consider the following case study. The roll pass design of the Rail 54E1 profile according to EN 13674-1 standard is created based on the modern rail rolling mill and verified by the simulation. The roll pass design for the Rail was made using both approaches, i.e. from the final shape to the preliminary profile (leader profile) and from the rectangular billet to the leader. This article provides a detailed analysis of the creation of RPD in the direction opposite to the rolling, utilising new features in the QKaliber program. The results are presented partly for the first half of the RPD, which was prepared following the rolling direction.

The first step is to select the pass sequence and determine the number of passes according to the rail type and size. We selected the typical rolling scheme, where the leader rail section is produced in two roughing stands by ten passes and then fed into the group of universal and edger stands with seven passes. Then, the rail shape is obtained in the semi-universal stand, which has only one vertical roll.

The next step was to create the Rail 54E1 profile according to EN 13674-1 standard in its hot state, excluding radii and inclines. The profile is constructed from five parametric elements, i.e. Top and Bottom Tips of the Rail, Top and Bottom Roots of the Rail, and the Web. Based on the selected mill layout, we proceeded with the getting of the leader profile in the roughing group and roughly estimated its dimensions. Subsequently, we employed automatic calculation of reduction coefficients opposite to the rolling direction from the finished profile to the leader profile (Fig. 11). During the calculation, all intermediate shapes are composed of the same elements but with varying dimensions, except for shapes that are rolled on edger stands and which were not considered.

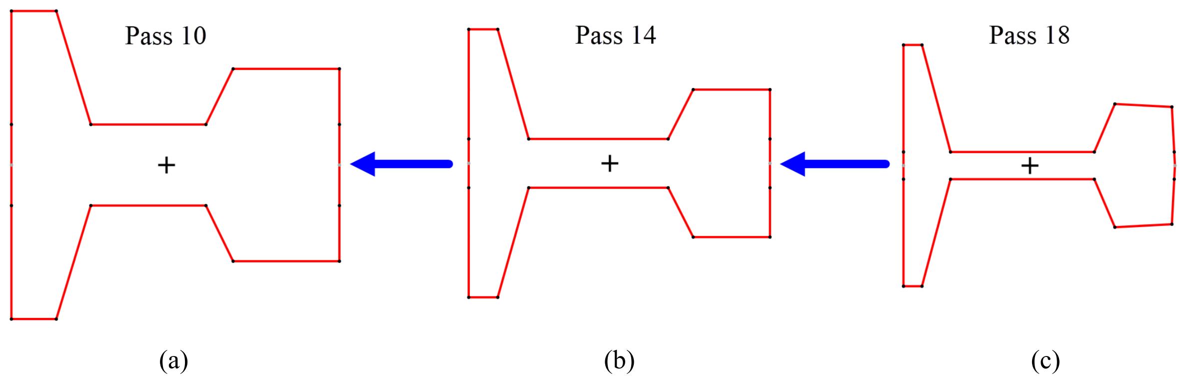

Fig. 11. The sequence of the roll passes created in the inverse direction from the 18th to the 10th pass: (a) leader shape, (b) one of the intermediate shapes, (c) final shape of the rail.

The analysis of reduction coefficients across passes (Fig. 12) indicates that the thickness on the Rail's Tip free side (F) exceeds that on the contact side (C) with Tip (F) being higher than Tip (C), which is also true for the Rail's Root. This distribution is consistent with the fundamental guidelines for rail RPD [7]. However, the reduction of the rail's Root is greater than of the Tip, which is incorrect. The next step in the RPD process should be to adjust the distribution ensuring the Tip experiences greater reduction than the Root.

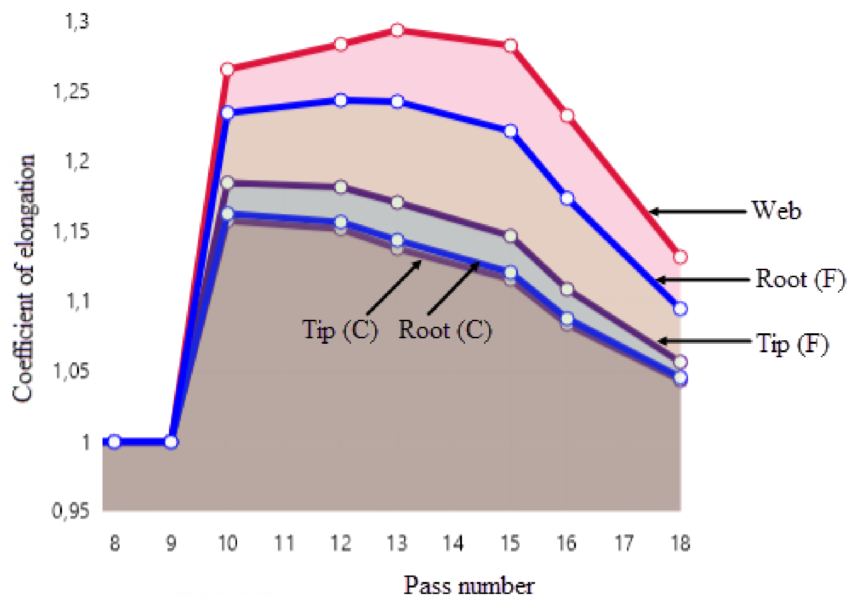

Fig. 12. The coefficients of reduction as a graph along passes after the automatic calculation.

In the next phase, we adjusted the width of the profile according to the configuration of the tandem group, refined the leader shape and adjusted the Tip and Root inclines in line with the roll configuration. By modifying the dimensions of the elements, we achieved the desired distribution of reduction coefficients across all the passes (Fig. 13). Fig. 14 shows the intermediate shapes of the rail after adjusting the reduction coefficients.

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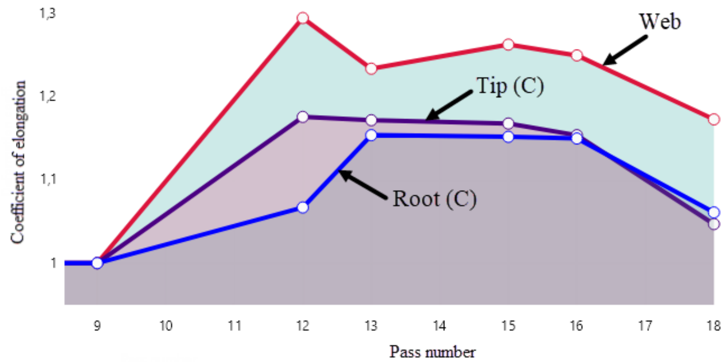
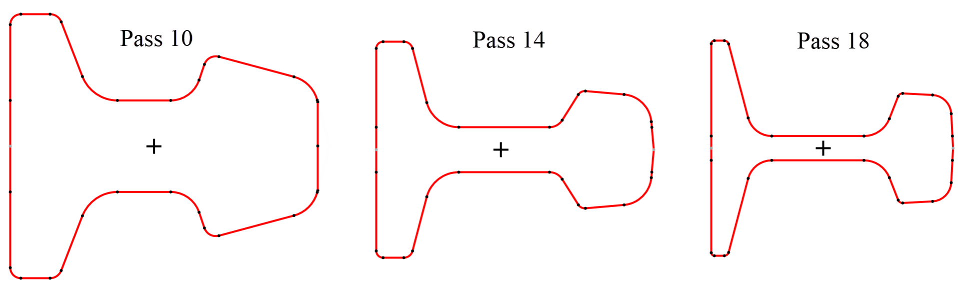


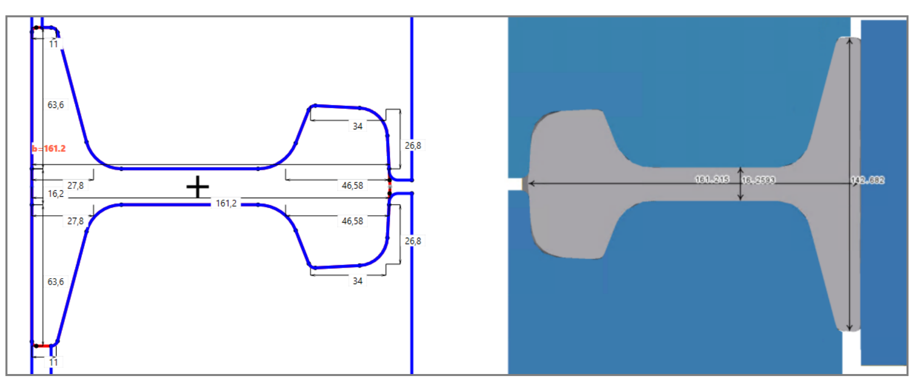
Fig.13. The coefficients of reduction as a graph along passes after the RPD correction.



(a) (b) (c)

Fig. 14. The corrected RPD shapes: (a) leader, (b) one of the intermediate shapes, (c) final shape of the rail.

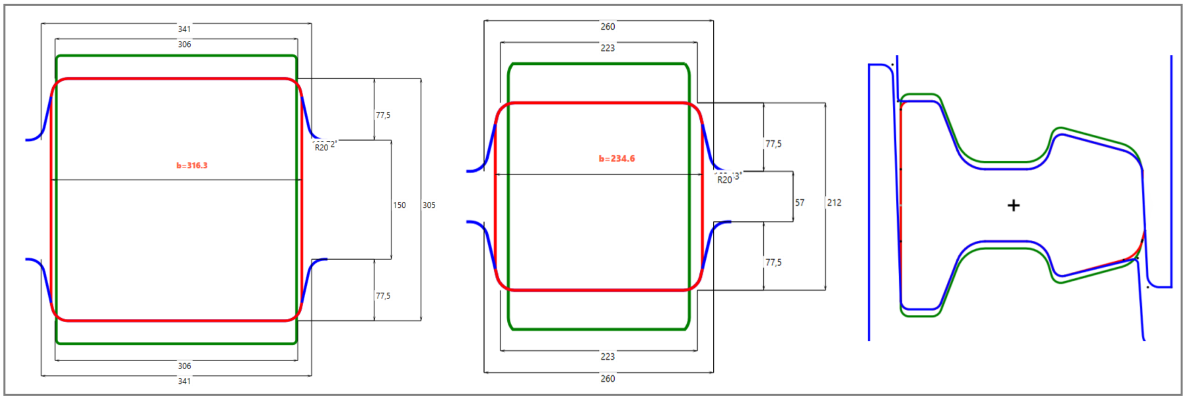
After refining the RPD, drive parameters were added from the rolling mill database, as well as all the necessary technological parameters, such as temperature, roll rotation speed, and the distance between stands. Integrating these technological parameters with the developed RPD makes it possible to simulate the rolling of a specified profile shape. Utilizing the API allows for the initiation of rolling simulation directly from the QKaliber software. The initial simulation was conducted solely to verify the rolling of the desired final rail profile from the selected leader profile shape, which served as a billet. Through finite element analysis, the simulation confirmed the effectiveness of the developed RPD (Fig. 15).



(a) (b)

Fig. 15. The finish pass design of the Rail 54E1 profile with dimensions (a) and results of its simulation (b).

A rectangular bloom with hot dimensions of 363x300 mm was selected as the workpiece, for which the first part of the RPD was prepared following the rolling direction on roughing stands to obtain the leader shape of the rail (Fig. 16). This was followed by verification using FE simulation, and finally, the entire project was simulated in full from the billet to the finished rail shape to prove the developed RPD.



(a) (b) (c)

Fig. 16. Passes from the workpiece to the leader profile: (a) box groove in the first pass, (b) box groove in pass 5, (c) leader shape in pass 10.

Summary
This article presents an innovative automated roll pass design approach, seamlessly integrated with comprehensive FEM simulations. The system enables efficient management and creation of roll inventories and sequences. It offers significant enhancements, notably the streamlined design process for new profiles, optimisation of load and torque for existing designs within the limits of equipment capabilities, and the enhancing of new and established shape rolling technologies.

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