

FINITE ELEMENT SIMULATION OF PIPE STRAIGHTENING IN A 3-PAIR CROSS ROLL MACHINE WITH SYMMETRICAL AND ASYMMETRICAL PROFILING OF THE OUTER ROLLS

Eduard GRIBKOV¹, Yuriy DOBRONOSOV², Volodymyr KUKHAR³, Khrystyna MALII⁴ and Natalia HRUDKINA⁵

¹Technical University Metinvest Polytechnic, LLC, Zaporizhzhia, Ukraine,
Email: gribkov.eduard@gmail.com

²Technical University Metinvest Polytechnic, LLC, Zaporizhzhia, Ukraine,
Email: Yuriy.Dobronosov@mipolytech.education

³Technical University Metinvest Polytechnic, LLC, Zaporizhzhia, Ukraine,
Email: kvv.mariupol@gmail.com

⁴Technical University Metinvest Polytechnic, LLC, Zaporizhzhia, Ukraine,
Email: kristina.maliy@mipolytech.education

⁵Technical University Metinvest Polytechnic, LLC, Zaporizhzhia, Ukraine,
Email: vm.grudkina@ukr.net

ABSTRACT: To enhance competitiveness of domestic metal products, in particular, pipes, it is necessary to ensure their compliance with international standards on basic quality indicators. The pipe straightening process provides such quality indicators as straightness and cross-sectional shape. Cross roll pipe straighteners are the most common and most effective machines for straightening pipes of small and medium diameters. Six-roll (3-pair) pipe straighteners with special roll profiling are the most modern machines, they provide two types of straightening: in the groove of profiled rolls and at the pitch between the roll cages. However, the lack of knowledge about the forming process regularity is holding back the widespread introduction of such machines. The finite element model has been developed in the work, and with its application it has been studied how straightening process parameters in profiled rolls with symmetrical and asymmetrical profiling of the outer rolls pairs affect the indicators of pipe straightening and straightening force. Based on the results of their implementation, it is found that straightening in the groove and at the pitch makes it possible to reduce almost three times the residual curvature of the pipe, with the overlap of the middle rolls relative to the outer ones being 2.5 times smaller. At the same time, the force on the most loaded middle rolls has increased almost twofold, which should be taken into account considering the potential out-of-roundness of the thin wall pipe section. The use of additional asymmetric profiling of the outer rolls with pitch adjustment has virtually no effect on the quality of straightening in the groove, increases the quality of straightening at the pitch by up to 15% with a 5-7% decrease of the maximum straightening force. The developed finite element model allows determining the rational values of the roll overlaps to ensure the minimum residual curvature of the pipes.

KEYWORDS: roll forming process, straightening, pipe, cross roll pipe straightening machine, stress-strain behaviour, profiling roll, process settings, power parameters

1 INTRODUCTION

Pipe production has been an important part of the metallurgical industry and plays a leading role in the economy of developed countries, which is noted by the authors (Shepel et al., 2010; Gulyayev et al., 2010). As a lot of papers (Ogorodnikova et al., 2018; Orlov, G. & Orlov, A., 2018; Kukhar et al., 2021) demonstrate, one of the ways to ensure the competitiveness of pipe products in world markets is their compliance with the requirements of international standards, while achieving the

proper level of pipe quality indicators is a priority. The process of pipe straightening, which ensures straightness (Wang et al., 2022; Wang et al., 2012; Yu et al., 2022; Xiaobo et al., 2011) and compliance with the cross section shape (Yu et al., 2022; Xiaobo et al., 2011; Kukhar & Vasylevskyi, 2014; Markov et al., 2019) plays the key role in addressing it.

It is noted in papers (Wang et al., 2022; Wang et al., 2012; Zdanevich et al., 2018; Zhang & Zhong, 2021; Zhang, 2019; Huang et al., 2011) that cross roll pipe straighteners are the most common

and most effective machines for straightening pipes of small and medium diameters. Individual studies (Yin et al., 2014; Mutrux et al., 2011; Roy & Pal, 2022) have been carried out, which show that an important task in improving the process of straightening pipes and pipe workpieces on cross roll pipe straightening machines is to improve the quality of end sections straightening. One of the ways to improve the straightening quality by increasing the number of reverse bends is to increase the number of pairs of straightening rolls from three (six-roll machines) to four or five (eight-roll and ten-roll machines) and more (Zdanevich et al., 2018; Zhang & Zhong, 2021; Zhang, 2019; Huang et al., 2011; Yin et al., 2014; Mutrux et al., 2011; Roy & Pal, 2022; Ma et al., 2021). However, this way does not solve the problem of achieving an effective straightening of the curvature of pipe ends. The process deflection for achieving elastic-plastic bending for these layouts is set only by changing the pitch of the rolls, i.e., by shifting the rolls of one (or more) mill(s) relative to the rolls of adjacent cages, as a result of it the end section of pipes is not subjected to elastic-plastic deformations sufficient for high-quality straightening. The metal consumption also increases and the equipment of the straightening machines becomes more complicated, the beds of machines are subject to greater deflections (Wang et al., 2011), which negatively affects the accuracy indicators of the rolled pipe.

To solve this problem, six-roll machines have been developed for straightening round products with elastic-plastic bending directly in profiled straightening rolls, which are called roll groove (Fig. 1) (Ma et al., 2020; Das Talukder et al., 1990; Roy et al., 2021; Maskileison et al., 1989).

When straightening on a machine with such a layout is performed, the pipe is subjected to deformations of two types: bending along the length between sequentially located rolls and bending within the boundaries of elongated rolls of the middle cage due to specially made profiling of these rolls. Considering the elastic-plastic deformation, calculations of residual stresses and deformations, curvature indicators should take into account the change of steels properties under cyclic loads (Karnaukh et al., 2022; Tkaczyk et al., 2011; Barabash et al., 2014).

The roll of the middle pair, on which the pipe rests during bending between the cages, is called the backup roll, and the opposite is the pressure one. The barrel of the backup roll of the middle pair is elongated with a lower profile than the theoretical hyperboloid, wherein the lowering decreases

smoothly from the maximum value in the middle of the roll body to zero at its ends.

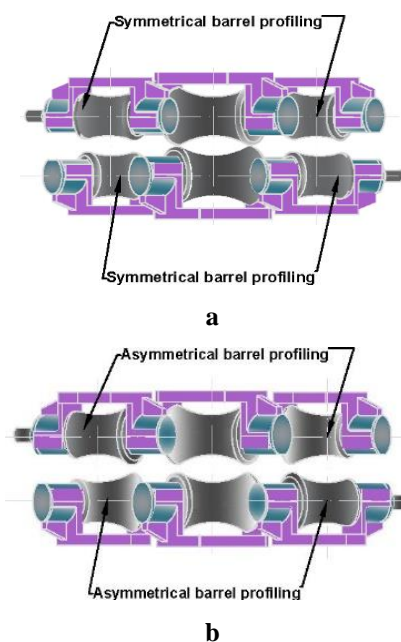


Fig. 1 Cross roll machines for pipe straightening at the pitch and in the groove with an elongated barrel of middle rolls and a symmetrical (a) and asymmetrical (b) barrel of outer rolls (Ma et al., 2020; Das Talukder et al., 1990; Roy et al., 2021; Maskileison et al., 1989)

The pressure roll body of this pair is elongated with a profile the greatest lowering of which from the theoretical hyperboloid at the edges is equal to the lowering in the middle of the body of the backup roll and gradually decreases to zero in the middle of the body (neck). The straightening quality will be defined by the following structural and adjusting characteristics (Roy et al., 2021; Ma et al., 2019): distance between rolls in each cage; shift (overlap) of the middle cage relative to the outer stands to ensure deflection at the machine roll pitch; angle of installed rolls of the outer stands corresponding to the diameter of straightening pipe; angle of installed elongated rolls of the middle cage to create the required deflection value on the length of these rolls in accordance with the diameter of the pipe subjected to straightening.

Currently due to insufficient knowledge of these technologies, there is no quantitative assessment of how parameters of the straightening process for machines with straightening inside the groove affect the quality of the finished product, which limits the effectiveness of their application. To study the processes of elastic-plastic deformation, the stress-strain behaviour and residual stresses, the method of finite elements is effectively used, as shown in papers (Markov et al., 2019; Kukhar et al., 2019; Li et al., 2023; Ji et al., 2023). To form operational

properties of pipes, depending on the nature of residual stresses and deformations, heat treatment modes of pipe steels are developed by experimental and simulation methods (Chabak et al., 2022; Zurnadzhy et al., 2020).

The purpose of this work is to increase the efficiency of pipe straightening by refining knowledge about the regularities of how process parameters affect the quality of pipe straightening in cross roll machines with special roll profiling.

2 RESEARCH METHODOLOGY

The study was conducted using the finite elements method, which in our time is considered as the most rational method of solving applied problems of the metal forming theory and which allows bringing the process simulation as close as possible to the real conditions of its implementation and to take into account the maximum number of factors (Tanner et al., 1998; Zhang et al., 2016; Zhang, 2016). Abaqus CAE software has been applied for implementing this method as a general-purpose universal program for conducting multi-purpose engineering analysis of physical processes (ABAQUS/CAE, 2000; Lin et al., 2022).

Cross roll machine has been used as an object of study with a 600 mm roll diameter along the neck and a barrel length varying from a nominal 800 mm depending on the type of process being simulated. The nominal pitch of the machine cages was 1500 mm and could vary within 40 mm when simulating rolls with asymmetric profiling, depending on the type of process being simulated, due to the axial movement of the outer rolls. Roll angles were initially selected equal for all models, taking into account the recommendations of papers (Peng et al., 2023; Zhang, 2019) and varied during the simulation process in the range of 28°-320°.

Straightening of pipes with diameter $D = 273$ mm and wall thickness $S = 8$ mm, 15 mm, 20 mm of 1.1121 steel was simulated, the deformation resistance of which considering strain hardening was $YS = 400$ MPa (Dogui & Sidoroff, 1987; Wulfinghoff, 2014; Kleemola, & Nieminen, 1974). The initial deflection of the pipe was taken as 10 mm/lm (millimetre per linear meter). Process simulation was performed including the selection of finite elements, the construction of a finite element grid, the simulation of bodies of rolls and a pipe and the type of contact between them, the movement of rolls in the global coordinate system. Rolls were modelled as surfaces of revolution with no deformation created by rotating the curve of the calculated profile around the axis of the roll using three-dimensional four-knot undeformed elements

of R3D4 type (ABAQUS/CAE, 2000; Lin et al., 2022). The material of the pipe was simulated as an isotropic elastic-plastic body, and for its discretisation four-knot rectangular shell elements are used with monitoring of destruction of S4R type (ABAQUS/CAE, 2000; Lin et al., 2022). The contact between the rolls and the workpiece was determined by the surface-to-surface contact simulation with friction factor $f = 0.25$ (Khodadadi et al., 2023; Leu, 2011; Kukhar et al., 2020).

The finite element model corresponding to the layout in Fig. 1, a is shown in Fig. 2.

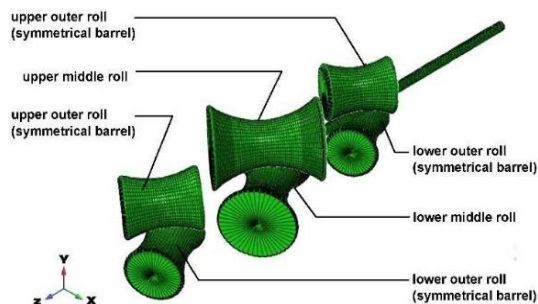


Fig. 2 Finite element model and numbering of rolls of six-roll machine with symmetrical profiling of outer rolls according to Fig. 1,a

The length of the outer rolls barrel in this case corresponded to the nominal value, and the length of the average rolls barrel was 1,225 mm. Profiling is performed in accordance with known methods, the bases of which are described in papers (Wang et al., 2022; Yu et al., 2022; Xiaobo et al., 2011; Peng et al., 2023; Huang et al., 2022).

Finite element model of the straightening process in a cross roll machine with asymmetric profiling of the outer rolls (see Figure 1,b) is shown in Fig. 3.

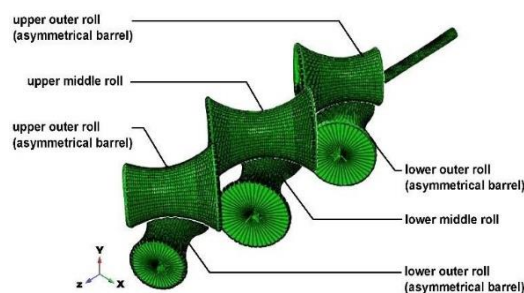


Fig. 3 Finite element model and numbering of six-roll machine with asymmetric profiling of the outer rolls as per Fig. 1,b

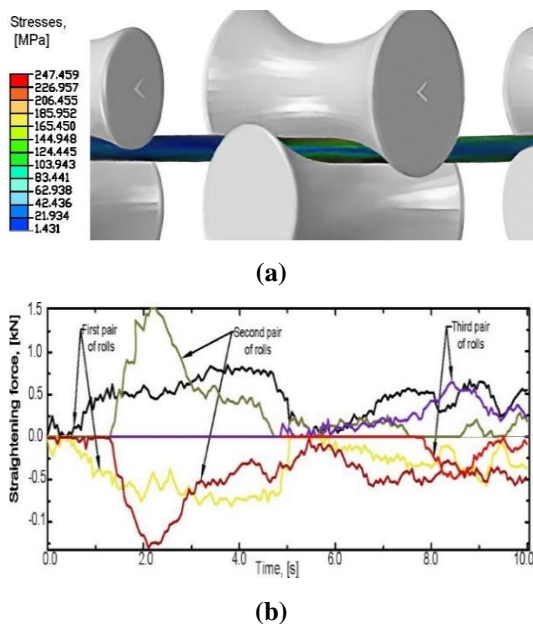
In this case, the middle rolls also have a barrel length of 1,225 mm and symmetrical profiling, and the outer rolls are asymmetrical and have a barrel length of 1,015 mm.

Simulation was performed for the same pipe size as in the previous case. The initial curvature of the

pipe was taken as 10 mm/lm. Pitch adjustment for the simulated range of products in accordance with the recommendations of the paper (Peng et al., 2023; Zhang, 2019) is performed by axial shift of the outer rolls relative to the axis of straightening, for our case by 65 mm, which corresponded to the pitch value of 1,535 mm.

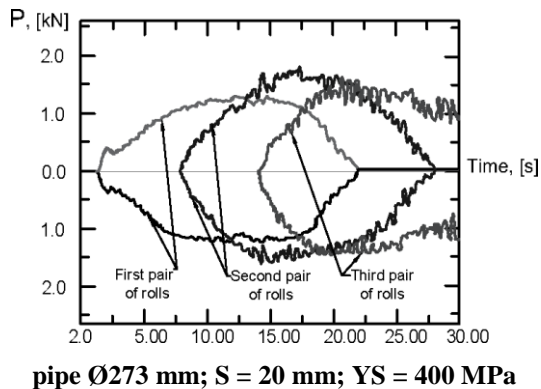
3 RESULTS AND DISCUSSION

Results obtained during simulation of the profiling process in a groove with an elongated barrel of the middle rolls and a symmetrical barrel of the outer rolls (see Fig. 1,a) are presented as corresponding graphical dependencies (Fig. 4-6).



pipe Ø273 mm; S = 8 mm; YS = 400 MPa

Fig. 4 Example of the calculation results of the pipe stress state in the middle rolls (a) and the change in the straightening force from the time of the calculation step (b) when straightening is fulfilled as per layout in Fig. 1,a



pipe Ø273 mm; S = 20 mm; YS = 400 MPa

Fig. 5 Calculated dependencies of the straightening force change for each roll from time of calculation step according to the layout in Fig. 1,a

The analysis of the obtained results shows that if the straightening layout in the cross roll machine with special profiling of rolls with straightening at the pitch and in the middle of the groove is applied, it is possible to achieve more qualitative indicators of the resulting curvature of the $\Delta_{residual}$ with smaller deflection values of the middle pair of rolls than on machines with straightening only at the pitch (see. Figure 6,a). So, for simulated standard sizes, the final curvature when straightening in the groove was 0.5 mm/lm at 1.5 mm/lm for straightening at a pitch with a much smaller, 2.5 times, deflection of the middle cage relative to the outer ones.

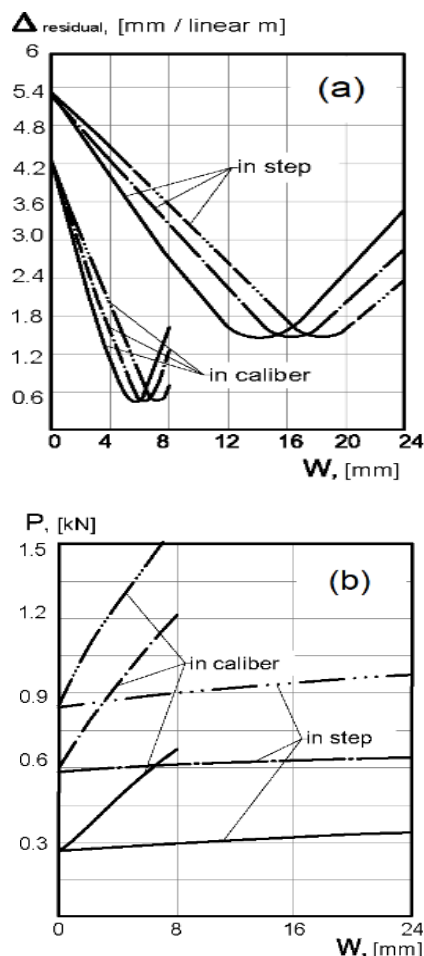
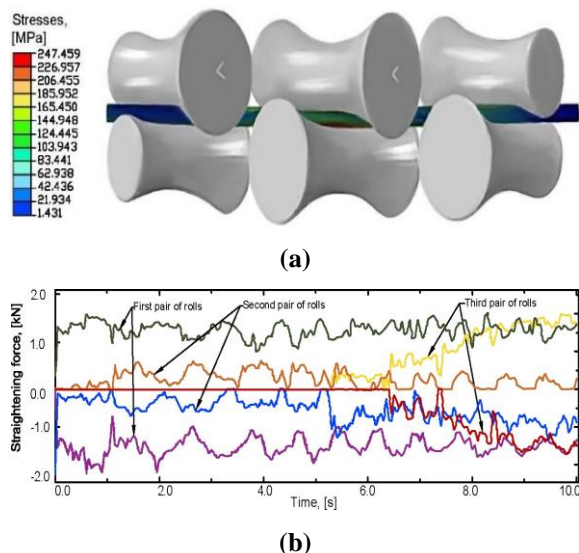


Fig. 6 Calculated dependencies of the resulting curvature of the pipe $\Delta_{residual}$ and the force of straightening P from the deflection of the middle pair of rolls W, obtained by simulating the process of straightening on the cross roll straightening machine according to Fig. 1, and in groove and at a pitch with different wall thicknesses S (pipe Ø273 mm; YS = 400 MPa, initial pipe deflection 10 mm/lm)

Straightening of the end sections of the pipe is confirmed in simulation, inter alia, in a part of visualisation of the process in time. However, straightening force created by rolls sharply

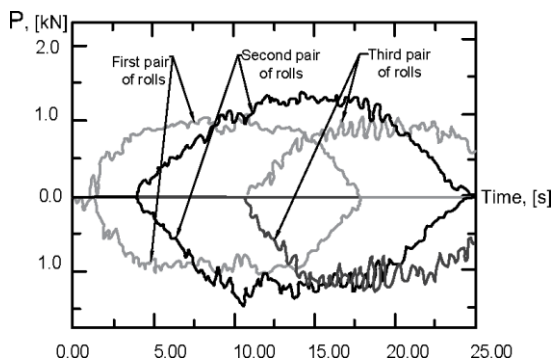
increases and more than doubles similar indicators at straightening only on a pitch of roll cages (see Fig. 6,b). The greatest straightening force appears for the upper roll of the middle pair (backup roll). The noted aspects shall be taken into account in connection with the potential out-of-roundness of the pipe section under the action of the force scheme (considered in the papers (Wang et al. 2012; Yu et al., 2022; Kukhar et al., 2019; Zhang, 2019; Kukhar et al., 2022; Kukhar et al., 2016)). This factor imposes an additional restriction on the choice of process parameters when straightening thin wall pipes.

The results of mathematical simulation of the straightening process in the cross roll machine with asymmetric profiling of the outer rolls are shown in Fig. 7-9.



pipe Ø273 mm; S = 8 mm; YS = 400 MPa,
pipe deflection 10 mm/lm

Fig. 7 Example of the calculation results of the stress state of the pipe (a) and the change in force over time (b) when straightening is under layout in Fig. 1,b



pipe Ø273 mm; S = 20 mm; YS = 400 MPa

Fig. 8 Calculated dependences of change of straightening force for machine with asymmetric roll profiling for each roll from time of calculation step when straightening as per layout in Fig. 1,b

Comparison of the simulation results of pipe straightening in the cross roll straightening machine with symmetrical and asymmetrical roll profiling shows that when straightening in the groove of the middle rolls and at the pitch between the middle and outer rolls, the quality of straightening in the groove changes slightly, and the quality indicators of straightening at the pitch improve more significantly (see Fig. 9, a), up to 15% on the minimum residual curvature due to the ability to change the pitch of the rolls. The straightening force both in the groove and at the pitch is 5-7% less for the option with asymmetric profiling of the outer rolls. Maximum values of stress intensity in the straightening pipe for both layouts appear in the place of pipe contact with the rolls of the middle cage during the straightening in the groove.

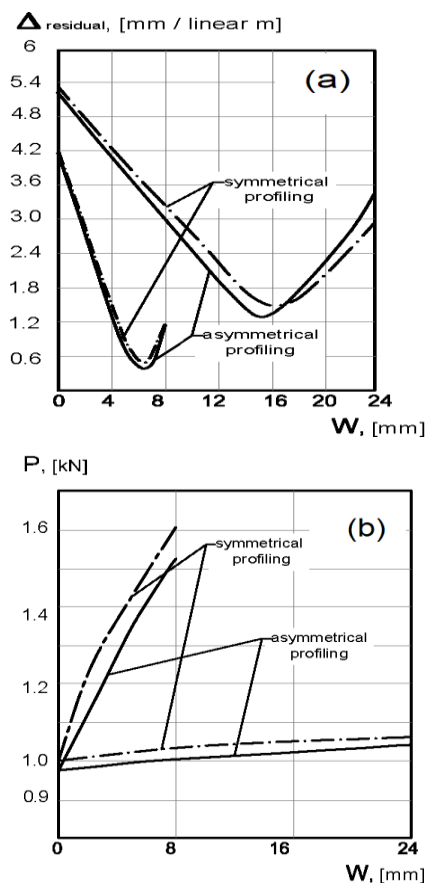


Fig. 9 Comparison of calculated dependences of the resulting curvature of the pipe $\Delta_{residual}$ (a) and the straightening force P (b) from the deflection of the middle pair of rolls W obtained during the simulation of the straightening process on the cross roll straightening machine according to Fig. 1,b in the groove and at the pitch with symmetrical and asymmetrical profiling of the outer rolls (pipe Ø273 mm; S = 20 mm; YS = 400 MPa, pipe deflection 10 mm/lm)

In general, the results of the simulation confirmed the greater efficiency of straightening with asymmetric profiling of the outer rolls.

The practical focus of the work lies in the fact that the developed finite element model can be used to determine the power parameters, in particular, the straightening force in the roll cages and the indicators of the resulting curvature of the pipes when designing the process modes of straightening in cross roll machines with special roll profiling. In particular, as can be seen from Fig. 6,a and Fig. 9,a, it is possible to establish rational values of roll overlap, which ensure the minimum residual curvature of the pipes, as well as determine the maximum straightening forces in time, which shall not exceed the values leading to deformation and out-of-roundness of the thin wall pipe section. For the conditions studied, the rational overlap of the rolls ranges 5 to 7 mm when straightening in the groove and in the range of 14 to 18 mm when straightening at the pitch for pipes with a diameter of 273 mm and a wall thickness of 8 to 20 mm (Fig. 6,a). The use of symmetric or asymmetric profiling does not make a fundamental difference in terms of both the straightening quality and the straightening force (Fig. 9). However, the use of straightening in the groove improves the quality of straightening significantly, up to 0.4 mm/m at maximum quality when straightening at a pitch of 1.2 mm/m.

4 CONCLUSIONS

Analysis of literary sources indicates a lack of data on the regularities of the straightening process in cross roll pipe straightening machines with special roll profiling, which limits the possibility of their use. The urgency of the problem and the practical focus of the work derive from the need to increase the efficiency of pipe straightening machines based on the development of knowledge about the regularities of the straightening process. Finite element models of pipe straightening on cross roll machines with straightening in the groove of rolls with special profiling and at the pitch between the roll cages have been developed. Based on the results of their implementation, it is found that straightening in the groove and at the pitch makes it possible to reduce almost three times the residual curvature of the pipe, with the overlap of the middle rolls relative to the edge ones being 2.5 times smaller. At the same time, the force on the most loaded middle rolls has increased almost twofold, which should be taken into account considering the potential out-of-roundness of the thin wall pipe section. The use of additional asymmetric profiling of the edge rolls with pitch

adjustment has virtually no effect on the quality of straightening in the groove, increases the quality of straightening at the pitch by up to 15% with a 5-7% decrease of the maximum straightening force. The developed finite element model allows determining the rational values of the roll overlaps to ensure the minimum residual curvature of the pipes.

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