УДК 669.01-179 https://doi.org/10.34185/tpm.1.2020.01

Yershov S., Levchenko G., Wu Kaiming, Zhou Wen, Ke Rui

The development of a new deformation regime for microstructure refinement in solid railway axles by hot deformation optimization

Ершов С., Левченко Г., Ву Каімінг, Чжоу Вень, Ке Руя

Розробка нового режиму деформації для вдосконалення мікроструктури в твердих залізничних осях шляхом оптимізації гарячої деформації

Goal. *During the production of railway axles, the main target is to obtain a uniform metal structure with a grain size not larger than number 5 across the entire section of the produced axle. Moreover, in accordance with the demands of railway axle consumers, the differences in grain size numbers should not exceed 2. However, due to multi-stage processing and repeated heating of axle material, the fulfillment of aforesaid requirements is very difficult and the differences in grain size numbers are usually found as 4. Therefore, it is necessary to develop a special deformation regime for controlling the sizes and the uniformities of metal grains in the finished product.* ***Methods****. We employed experimental and theoretical investigations to reveal the microstructure refinement in the deformation zone of the produced railway axle. The experimental investigation was carried out under the production conditions, whereas the theoretical investigation was performed based on the theory of plasticity and finite element method.* ***Results.*** *Furthermore, the regularities of process parameters in the deformation zone were revealed; hence, a new deformation regime was developed, and consequently, the quality of the finished railway axle was improved.* ***Scientific novelty****. Rolling of solid railway axle required special de-formation regimes that differed from the deformation regimes for rolling of other types of products. Deformations in vertical and edging directions with edging reduction were less penetrative to the central zone of the billet as compared to surface layers, thus resulting in an increase in energy consumption and equipment load of the rolling mill. Rolling with edging reduction caused a worse de-formation at the central zone of the billet in the box caliber.Rolling without edging reduction caused large deformations in central layers of the billet and led to a significant improvement in the metal structure of the axle.*

Keywords: Rolling simulation, Deformation regime, Railway axle, Rolling mill, Grain refinement

Мета*. Під час виробництва залізничних осей основною метою є отримання однорідної металевої конструкції з розміром зерен не більше 5 на всій ділянці виготовленої осі. Більше того, відповідно до вимог споживачів залізничних осей, різниця в кількості зерна не повинна перевищувати 2. Однак через багатоступеневу обробку та багаторазове нагрівання матеріалу осі виконання вищезазначених вимог є дуже складною і різниця в числа зернових розмірів зазвичай знаходять як 4. Тому необхідно розробити спеціальний режим деформації для контролю розмірів та однорідностей зерен металу в готовому продукті.* ***Методика****. Ми провели експериментальні та теоретичні дослідження для виявлення уточнення мікроструктури в зоні деформації виробленої залізничної осі. Експериментальне дослідження проводилось у виробничих умовах, тоді як теоретичне дослідження проводилось на основі теорії пластичності та методу скінченних елементів.* ***Результати****. Крім того, виявлено закономірності параметрів процесу в зоні деформації; отже, був розроблений новий режим деформації, а отже, покращена якість готової залізничної осі.****Наукова новизна****. Прокат твердої залізничної осі вимагав особливих режимів деформування, які відрізнялися від режимів деформації для прокатки інших видів виробів. Деформації у вертикальному та кромочному напрямках із зменшенням кромок були менш проникаючими до центральної зони заготовки порівняно з поверхневими шарами, що призвело до збільшення енергоспоживання та навантаження обладнання прокатного стану.Прокат з редукцією кромок спричинив гірше деформування в центральній зоні заготовки в калібрі коробки.Кочення без зменшення кромок спричинило великі деформації в центральних шарах заготовки та призвело до значного поліпшення металевої структури осі.*

Ключові слова: імітація кочення, режим деформації, залізнична вісь, прокатний стан, розмір зерна

1. **Introduction**

Railway transport has profound impacts on all areas of human activities, and railway axle significantly affects the reliability of railway transport. Klinger et al. (Ref 1) advocated that ensuring safety to accidents should be the top priority for any locomotive industry and revealed that nonmetallic inclusion is the main reason for the failure of railway axles. Odanovic (Ref 2) found that the failure of railway axle is caused by inadequate maintenance and insufficient material properties. Gürer et al. (Ref 3) asserted that the failure of railway axle is associated with the deteriorated mechanical properties of the axle material. Náhlík et al. (Ref 4) presented a new methodology for fatigue life assessment of railway axle based on fracture mechanics. Wu et al. (Ref 5) developed a new model to describe the mechanism of fatigue crack growth in railway axle.

Cross-screw rolling is widely employed for the production of railway axles and consists of the following technological route: steel ingot casting, rolling on blooming mill, two-roll rolling on billet mill, cross-screw

Ершов Сергій – д.т.н.,проф. Уханський університет науки і технологій
Левченко Генадій д.т.н., проф. ІЧМ НАНУ
Ву Каімінг - Уханський університет науки і технологій
Ке Руя - Уханський університет науки і технологій
Чжоу Вень - Уханський університет науки і технологій

Yershov S. - Wuhan University of Science and Technologyi
Levchenko G. - Institute by name of Z.I. Nekrasov
Wu K. - Wuhan University of Science and Technology
Zhou Wen - Wuhan University of Science and Technology
Ke Rui - Wuhan University of Science and Technology

rolling on three-roll mill, and heat treatment (Fig. 1). The aforesaid production route is usually comprised of four heating phases. The first heating is carried out before the rolling in blooming mill, and the second heating phase is performed before the cross-screw rolling. The rolled billets are then slowly cooled to prevent the formation of flakes, and finally, one or two normalizations are executed depending on the required quality level of the finished product. In addition, quality control of the produced railway axle is performed by ultrasonic method.

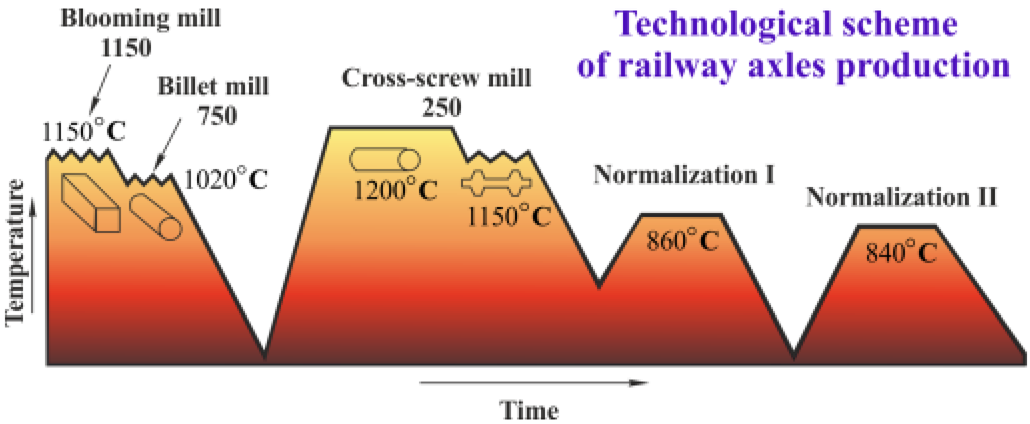


Fig. 1 The heat profile for steel axle production at a metallurgical plant

The main problem of cross-screw rolling is the dissimilarities in metal structures across the different sections of railway axle. According to the standard M101, grain size should not be less than number 5 (ASTM E112) along the cross-section of a railway axle. However, in practice, a gradient in grain size (varying from numbers 5 to 6 at the center to numbers 8 to 9 in subsurface layers) is usually noticed. Moreover, in accordance to the demands of railway axle consumers, the differences in grain size numbers should not exceed 2, thus grain refinement at the central area of railway axle is the only way to meet their expectations.

Grain refinement is usually adopted to increase the strength and the toughness of steel (Ren et al., (Ref 6)) and can be achieved by various approaches including ingot crystallization control, solid-state heat treatment, large deformation, recrystallization, cyclic heat treatment, cyclic quenching, thermal mechanical treatment, and strain-induced dynamic transformation.

Further, deformation works significantly improve the quality of the metal structure. However, Ren et al. (Ref 6) found that the effect of deformation work on ferrite grains was limited; hence, in order to overcome this limit, it is necessary to add alloying elements to steel.

In recent years, researchers have proposed multifarious theoretical approaches for the modeling of rolling processes. Wang et al. (Ref 7) developed a finite element model to simulate hot strip continuous rolling process and adopted the proposed model for the optimization of rolling schedule. Bambach et al. (Ref 8) investigated the instabilities of force and grain size predictions during the simulation of a multi-pass hot plate rolling process. It was found that the stable evolution of predicted grain size led to static recrystallization (SRX) after each deformation stage (or roll pass), and it required a large amount of deformation per pass, long inter-pass time, and slow grain growth rate.

It should be noted that the previously published works are mostly dedicated to the study of rolling in flat rolls, thus the rolling in shaped rolls for grain refinement is not well investigated. Lee et al. (Ref 9) revealed that the correct calculation of average deformation value had a great importance on the evolution of metal structure during deformation and developed a method for the calculation of average deformation during rolling in an oval-circle system. In addition, a comparative study on the effects of rolling on the smooth barrel and shaped rolls was conducted, and it was observed that the deformation scheme significantly affected the shapes of grain microstructures and the mechanical properties of steel. Lee et al. (Ref 10) improved their results by adding the deformed state calculations using finite element method (a software package 'Deform' was used in their study). It was noticed that the grain size was mainly affected by deformation rate, strain rate, and temperature, and the obtained results were in a good agreement with the findings reported by Choi et al. (Ref 11) and Choi et al. (Ref 12).

Choi, Lee, and Hodgson (Ref 13) considered the conditions of recrystallization during deformation and expounded that the differences in strain path caused by monotonic loading (plate rolling) and cross-loading (bar rolling) significantly influenced the microstructures and the mechanical properties of steel. It was found that during multi-pass rolling at higher speeds, the recrystallization behavior of steel and the evolution of austenite grains were strongly influenced by the modeling method of partial recrystallization. The modified model considered the microstructural heterogeneity (recrystallization and non-recrystallization) in steel during multi-pass rolling. It is worth noting that the afore-described studies were executed for rolling profiles with small sizes.

Nalawade et al. (Ref 14) investigated the rolling process of a bloom (initial and final cross-sections were 320 mm × 400 mm and 208 mm × 270 mm, respectively) using the 'Forge' program, and the metal flow behavior expressed that the amount of strain penetration increased with the increasing degrees of deformation. Moreover, the corners of the bloom possessed the highest strain, whereas the core section had the least strain. The macrostructure of the rolled bloom yielded a decrease in central porosity with the increasing degrees of deformation. Further, the grain size number after eight passes varied from 4–6 (large) in surface layers to 6–8 (small) at the center. It was noticed that the overall deformation degree of 0.56 (43%) after eight passes was not enough to consolidate the porosities in the rolled bar; hence, a further deformation was needed for removing these central porosities. Ginzburg (Ref 15) posited that critical strain required for the recrystallization and the modification of micro-alloyed steel was of the order of 0.1 (9.5%)–0.2 (18%).

Qingqiang et al. (Ref 16) developed a set of mechanism-based constitutive equations to analyze the effects of microstructure evolution on the elastic-plastic flow of Q235 steel, and the equations were implemented into the finite element solver ABAQUS to simulate the multi-pass H-shape rolling process.

Sen-dong Gu et al. (Ref 17) developed a multi-field (thermal, mechanical, and microstructural phenomena) coupled finite element model in MSC Marc software in order to investigate the 18-pass hot rolling process of GCr15 steel rod. It was found that the microstructure evolution during the multi-pass hot rolling process was more complicated as compared to hot compression tests which could not reflect the real evolution of microstructure during the hot rolling process of GCr15 steel rod.

It is well known that the modification of metal structure strongly depends on temperature, the degree of deformation, strain rate, and deformation scheme. Serajzadeh et al. (Ref 18) revealed that the unevenness of deformation during rolling on a flat roll caused a temperature drop at the center of the deformation zone and the temperature of strip surface dropped to 490 °C. The structural changes in steel during flat rolling were investigated based on different degrees of deformation, temperature, and friction. At the same time, friction was strongly influenced by the material from which the deforming tool was made (Efremenko et al., Ref 19).

The deformation behavior of steel during rolling depends on various conditions, such as caliber shape, geometrical sizes of the center of deformation, and rolling speed. However, the complete understanding of the processes occur in calibers during rolling is still unexposed because of the fact that more than 3000 profiles of different configurations are used for rolled steel production (Skorohodov et al. (Ref 20); Lempitskyi et al. (Ref 21); Iljukovich et al.(Ref 22)). It is practically impossible to carry out the experimental study for each type of rolling profile. The problem of optimizing the rolling parameters still exists for complex profiles (such as angular, channel, and beam) and calibers (such as box caliber, oval caliber). Although the theory of rolling in flat rolls is considered to be well developed (Wusatowski (Ref 23); Vidrin et al. (Ref 24); Tcelikov (Ref 25); Grudev (Ref 26); Nikitin (Ref 27)), the theory of rolling in shaped calibers is only partially understood (Tarnovskyi et al. (Ref 28); Vorontcov et al. (Ref 29); Iljukovich et al. (Ref 22)).

The present paper was dedicated to the development of an optimal regime for ingot rolling of steel axles on a blooming mill. In the current research, experimental methods, as well as finite element analysis, were employed to reveal the microstructure refinement in the deformation zone of the produced railway.

2. Experimental Procedures

2.1 Rolling on An Industrial Rolling Mill

Steel ingots with the geometric dimensions of 712mm × 800mm/608mm × 695mm were deformed in a blooming rolling mill for the production of billets with the geometric dimension of 290mm × 290mm. The pictorial representation of the caliber used for rolling is displayed in Fig. 2.

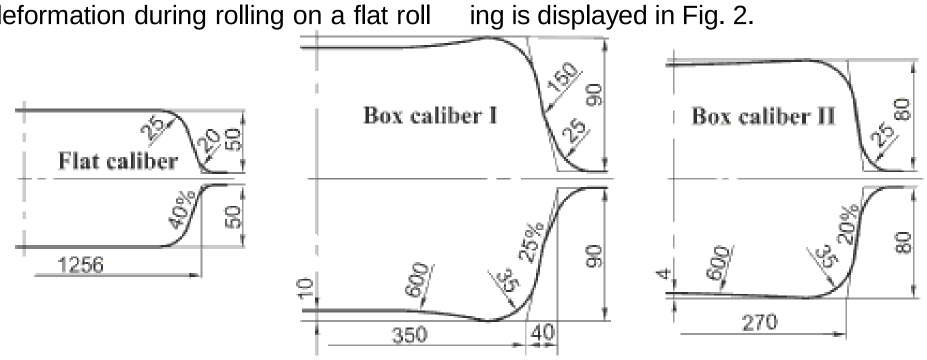


Fig. 2 The calibers used for rolling

The produced billets were further deformed and heat treated using the following route: rolling on the billet mill 900, cooling in an unheated chamber, rolling on the mill 250, and first and second normalization.

2.2. Microstructure of Steel

The metallographic studies and the quantitative analysis of steel samples were performed using the microscope "Axiovert 200 M MAT" by Carl Zeiss and the program "AxioVision 4.6.3", respectively. In addition, the microstructures of the samples were evaluated according to GOST 5639 and ASTM E 112 standards.

The chemical composition of steel sample is presented in Table 1.

Table 1 Chemical composition of the samples used in the study

Content of elements,%								
C	Mn	Si	S	P	Cr	Ni	Cu	Al
0,48	0,86	0,21	0,020	0,018	0,01	0,01	0,01	-

The samples for metallographic analysis were taken after the completion of the each stage of technologikal process. Further, the samples were cut from the head part of the ingot. After processing through the blooming mill, the samples were cut from the center, the surface layer and ¼ of thickness and at the next stages of the production chain, it was cut from ½ of the radius.

It is well known that dendritic structure is characterized by two main parameters: chemical heterogeneity (the index of it defines the coefficient of dendritic liquation) and the average size of dendritic arms; hence, a smaller value of the latter parameter yields a highly-dense dendritic structure with less chemical heterogeneity (Golikov et al. (Ref 30)). Moreover, the thermal treatment of billets cannot eliminate the traces of dendritic structure. Therefore, the assessment of the structural deformation of billets on blooming mill was conducted based on the changes in the parameters of the dendritic structure.

The thicknesses of linear elements in the volume of the metal can be considered as the indicator of structural deformation. In our experiment, the "former" dendritic arms (light bands without segregation) and interdendritic spaces (dark liquation bands) were considered as the linear elements. It is worth to note that these two elements represent a system of lines parallel to each other (Saltikov (Ref 31)). Thus the density of a system of lines having a full linear orientation in space is equal to the average number of tracks of these lines per unit area of secant plane, which lies perpendicular to the axis of orientation.

The traces of dendritic structure were detected by etching in sodium picrate in a hot solution, and the reagent revealed the chemical micro-heterogeneity of silicon (dendritic segregation and solid-phase segregation). The optimal etching times of the samples were about 1~2 h.

2.3. Mechanical Properties of Steel

The determination of mechanical properties of steel samples was carried out according to the standard procedure of tensile test (GOST 1497).

The samples for the impact bending test were cut out from the axle part with a diameter of 230 mm at a distance ½ of the radius according to DSTU GOST 31334:2009, and the values of impact strength were determined according to GOST 9454.

2.4. Mathematical Model

The basic principles of the theory of plasticity were adopted for mathematical modeling of the rolling process, and the properties of the incompressible material were formulated according to the basic rules of flow theory (Milenin and et al. (Ref 32)).

The differential form of equilibrium:

$$\sigma_{ij,i} = 0, \qquad (1)$$

Saint-Venant's compatibility equations:

$$\xi_{ij} = \frac{1}{2}\left(\upsilon_{i,j} + \upsilon_{j,i}\right), \qquad (2)$$

Constitutive law:

$$\sigma'_{ij} = \frac{2\bar{\sigma}}{3\bar{\xi}}\xi_{ij}, \qquad (3)$$

The differential form of incompressibility condition:

$$\upsilon_{i,j} = 0, \qquad (4)$$

The analytical equation of the flow stress model:

$$\bar{\sigma} = \bar{\sigma}\left(\bar{\varepsilon}, \bar{\xi}, t\right), \qquad (5)$$

where σ_{ij} and ξ_{ij} signify stress and strain rate tensors, respectively, υ_i is the velocity component, σ'_{ij} is the deviator of the stress tensor, t is temperature, and $\bar{\sigma}$, $\bar{\varepsilon}$, $\bar{\xi}$ signify effective stress, effective strain, and effective strain rate, respectively. Further, Equations (1)–(4) were transformed into their discrete forms using virtual work principle and finite element method. The nodal values of velocity were considered as independent variables and 8–node isoparametric finite elements were used for the solution. The incompressibility of finite elements was solved by the method of penalty functions. The mechanical properties of steel were determined using the dependence (5) constructed on the basis of experimental data reported by Xenzel et al. (Ref 33). In addition, the simulation parameters were considered as follows: temperature = 1150 $^\circ C$, rolling speed = 4.8 mps, and coefficient of friction = 0.3.

3. Theoretical Study of The Deformed State

The main concern during any rolling process is the issue of changing deformation modes in different passes, thus sometimes it is difficult to understand how much degrees of deformation should be assigned in different passes, which deformation mode needs to be employed, and which caliber shape should be adopted. Hence, in metallurgical industries, it is often noticed that while a caliber yields excellent material quality in a certain rolling process, the same caliber causes poor material quality in other rolling processes (Yershov et al. (Ref 34)).

In order to produce high-quality railway axles, both experimental and theoretical studies were carried out in our research. The results reveal that in order to achieve a proper deformation at the central zone of a billet, a special deformation regime along with a special deformation mode should be adopted. It was found that rolling on flat rolls and rolling in box calibers manifested different efficiencies, and rolling in box calibers with edging reduction was less effective in comparison to rolling in flat rolls (Fig. 3). In the first case, rolling of a billet with 480 mm × 390 mm size and 100 mm reduction was carried out in a box caliber, whereas, in the second case, the size of the billet was 530 mm × 345 mm and the value of reduction was 105 mm. It is worth to note that the aforesaid reduction values were calculated at the middle of the width of the box caliber No. I. Moreover, the value of edging reduction of the caliber was 80 mm in the first case, whereas it was 85 mm for the second case.

In the first case, the value of edging reduction of the strip was 40 mm, whereas in the second case, rolling was performed without edging reduction. It was observed that rolling with edging reduction caused 7% higher deformation in the surface layers as compared to rolling without edging reduction. However, at the central zone of the billet, rolling with edging reduction yielded lower deformation (1.1%) as compared to rolling without edging reduction.

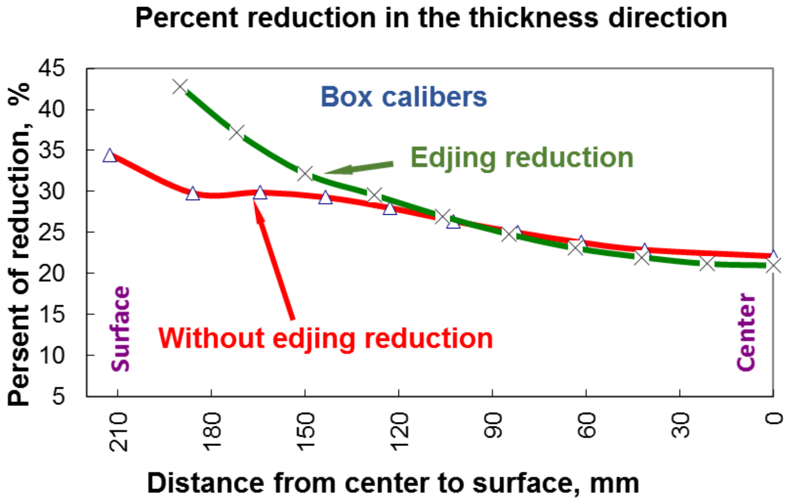


Fig. 3. The distribution of the degree of deformation

It is evident that deformation in the vertical direction was less penetrative to the central zone of the billet as compared to surface layers, thus resulting in an increase in energy consumption and equipment load of the rolling mill.

4. Development of New Deformation Modes

Two different types of regimes of reduction were developed for the proposed rolling process without changing the shape of the calibers. The first regime was soft and the second regime was rigid in terms of the operating conditions of rolling mill.

Increase in the reduction in the first passes where rolling is carried out on flat rolls were used. However, an increase in reduction during pass Nos. 1 and 2 is not advisable because it may degrade the surface quality of the finished products (Baimov (Ref 35) and Getmanetc et al. (Ref 36)). In our experiment, the quality of the metal casting process was controlled very well; therefore, the change in reduction regime did not significantly affect the surface quality of the produced steel axles. Further, it is also recommended to leave the turning after pass No. 2 because this technique can produce rolling billets with a minimum number of surface defects.

It was found that rolling on the blooming mill 1150 caused a reduction of up to 130 mm in the first two passes and resulted in an entering angle of 28°; however, this value is close to the maximum allowable angle for rolls with a coarse surface (32°). Therefore, a reduction of 110 mm was recommended to pass No.3. In the remaining passes including pass No.6, it is recommended to increase reduction value on 10~15 mm, and the angle of entrance for pass No.3 was 25°. Furthermore, rolling in pass Nos. 3–8 was performed without a turning and caused an increase in the degree of deformation of the central zone of the produced billet, thus after pass No.8, the thickness and the height of the strip was found as 260 mm and 630 mm, respectively. Therefore, it can be inferred that this type of rolling is impossible on flat rolls because of the high probability of loss of stability. Further rolling with an increased degree of deformation (105~120 mm) was carried out during passes 9 and 10 using box caliber No. II. In this case, a secure entrance in the caliber was guaranteed by the presence of edging reduction in the caliber. Further, in order to achieve the correct geometric shape of the billet, rolling in passes 11 and 12 was carried out in flat rolls with 10 mm and 15 mm reductions, respectively. Finally, rolling in pass No.13 was executed with a reduction of 125 mm.

The first mode A was considered as the basis for the second deformation regime B. During passes 3-8, deformations were distributed accurately in order to allow a reduction of 170 mm in the 9th pass. Thus the degree of deformation at the central zone of the billet was found to be 35% (Severdenko et al. (Ref 37); Zhadan (Ref 38); Florov et al. (Ref 39); Lezinskaja (Ref 40); Akimova et al. (Ref 41); Romantcev et al. (Ref 42)); however, the main disadvantage of this technique was the large entrance angle 33°. It is well known that large entrance angle is critical for rolling without edging reduction, thus the edging reduction of the billet did not achieve the maximum effect of the increase in height reduction.

The schedules of the deformation regimes A and B are depicted in Table 2. Moreover, rolling is carried out in metallurgical industries according to the reduction regime C.

5. Results and Discussion

The heating parameters for steel ingots are presented in Fig. 1. The first 11 ingots were rolled according to mode A, whereas the rest was processed according to regime C. It was found that regime A did not manifest effective results for structural refinement of the central part of the produced axle; therefore, the results obtained from regime B were used in our analysis.

Fig.4 displays the change in dendritic structure along the cross-section of the billet (rolled according to regimes B and C) with 290 mm × 290 mm size. The microstructures of the samples are exhibited in Figs.5 and 6, and the results of the metallographic analysis are depicted in Table 3.

It was observed that the thickness of the dendritic structure was minimal for the most deformed surface layers, thus the dendritic bands close to the central layer manifested lower thickness values. However, the liquation zones of higher densities were evenly distributed in the billets obtained from regime B, thus indicating a better deformation of the structure (Fig. 7).

Table 2 Schedules of used deformation regimes

No. of pass	Schedule for regimes of deformations					
	A		B		C	
	Type of calibers	Reduction, mm	Type of calibers	Reduction, mm	Type of calibers	Reduction, mm
1		110		110		110
2		110 turning		110 turning		65 turning
3		110		95	Flat rolls	100
4		100		95		90
5	Flat rolls	100	Flat rolls	100		95
6		100		105		85 turning
7		25		35		45
8		25 turning		30 turning		65
9	Box caliber No. II	120	Box caliber No. II	170	Box caliber No. I	70
10		105 turning		85 turning		70 turning
11		10		15		55
12	Flat rolls	15 turning	Flat rolls	15 turning		50 turning
13	Box caliber No. II	125	Box caliber No. II	125	Box caliber No. II	110

Further, it was found that rolling on blooming mill, slow cooling rate, rolling on mill 250, and first and second normalization had no profound effect on the volume fractions of dendritic bands with and without segregation; however, their average dimensions decreased due to deformations (Table 2).

Therefore, it was observed that the best deformation for the dendritic structure was achieved after the rolling on blooming mill in accordance with regime B (Fig. 8).

The samples obtained after rolling on blooming mill (regime B) were characterized by a fine-grain structure (1474 μm, grain number 3.9), whereas the samples found in regime C manifested an average grain size of 2140 μm (grain number 5.1) (Fig. 9).

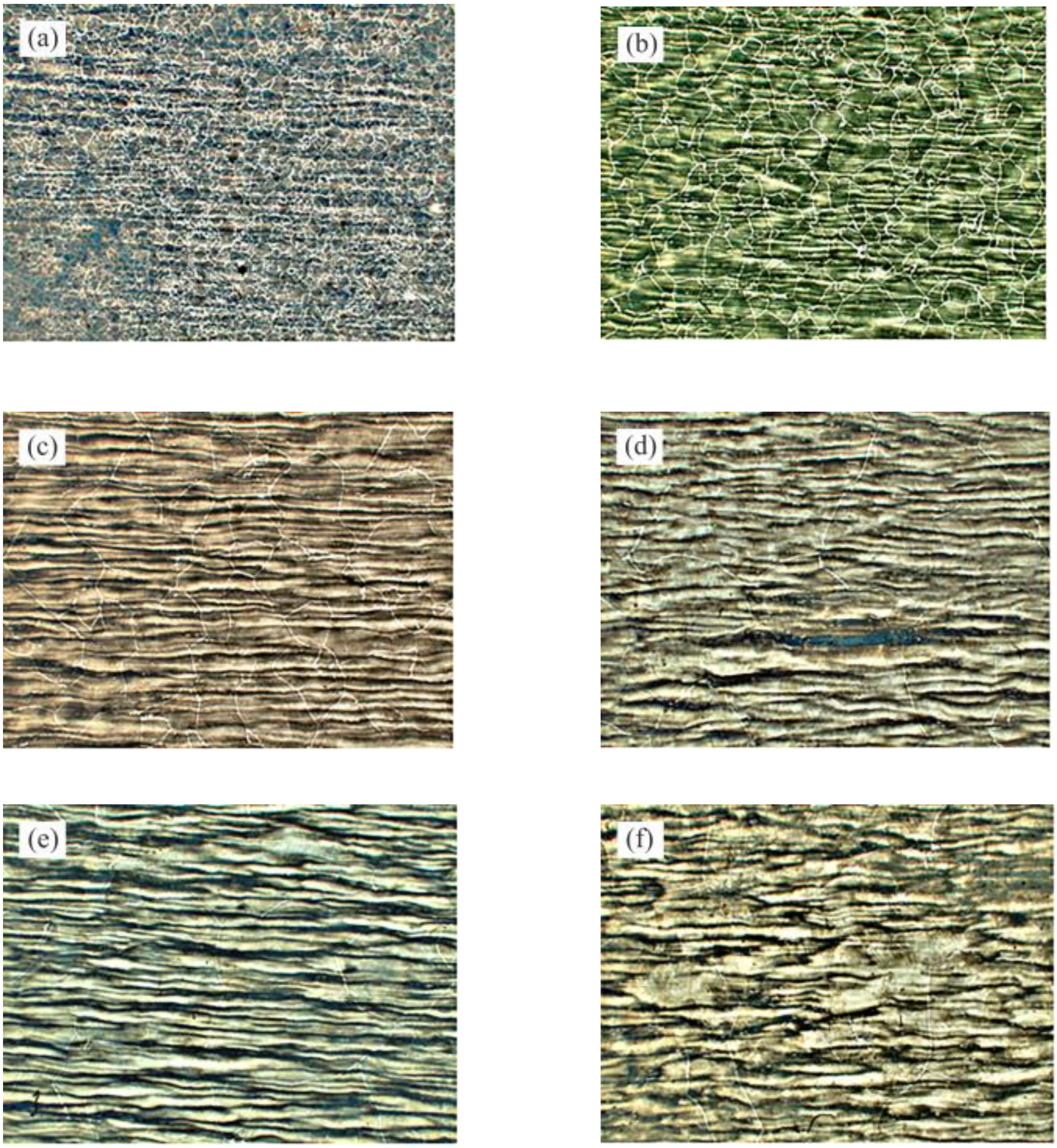
In the hot-rolled state, steel samples obtained from regime C yielded a more coarse-grained and uneven structure in comparison to the samples found in regime B (Fig. 10).

The samples obtained from the first normalization process manifested a uniform fine-grained structure. According to the standard M101, the grain numbers of the samples found in regimes B and C were 8 and 7.5, respectively. In addition, the average grain size in the axle found in regime C was 72 μm (grain number 4.5) (Fig. 11).

The second normalization process did not change the structure of the axle obtained from regime B, thus the structure became more equiaxial and the average grain size number was found to be 8. However, the second normalization process improved the structure of the axle found in regime C, consequently, larger pearlite grains disappeared and the structure became more uniform (average grain size number was 8.4) (Fig. 11).

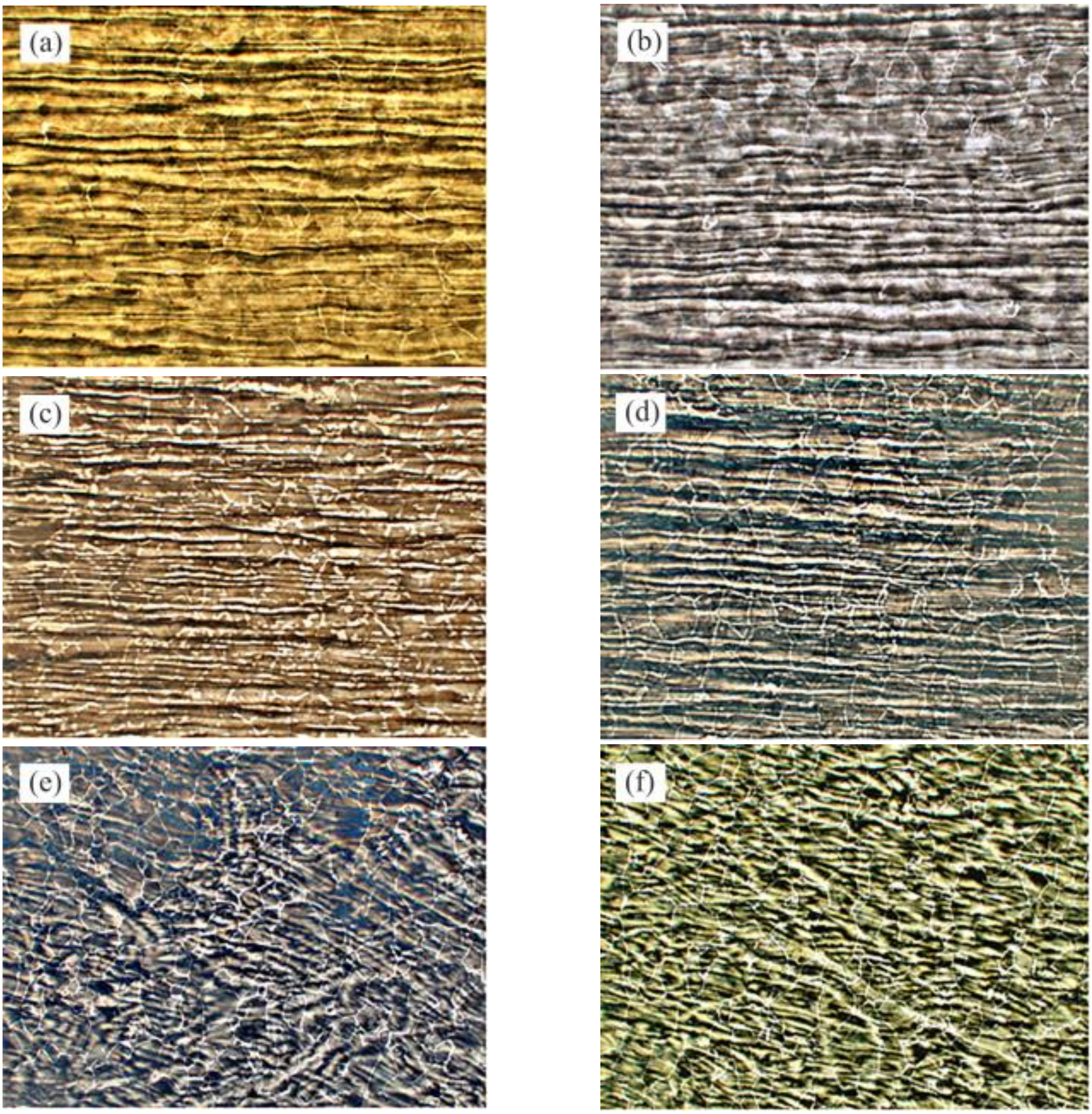
Moreover, it was found that mechanical properties of the specimens obtained in both regimes were not affected by second normalization (Table 4).

Further, the results reveal that the desired structural and mechanical properties of the axles (for both regimes) were achieved after the first normalization process.



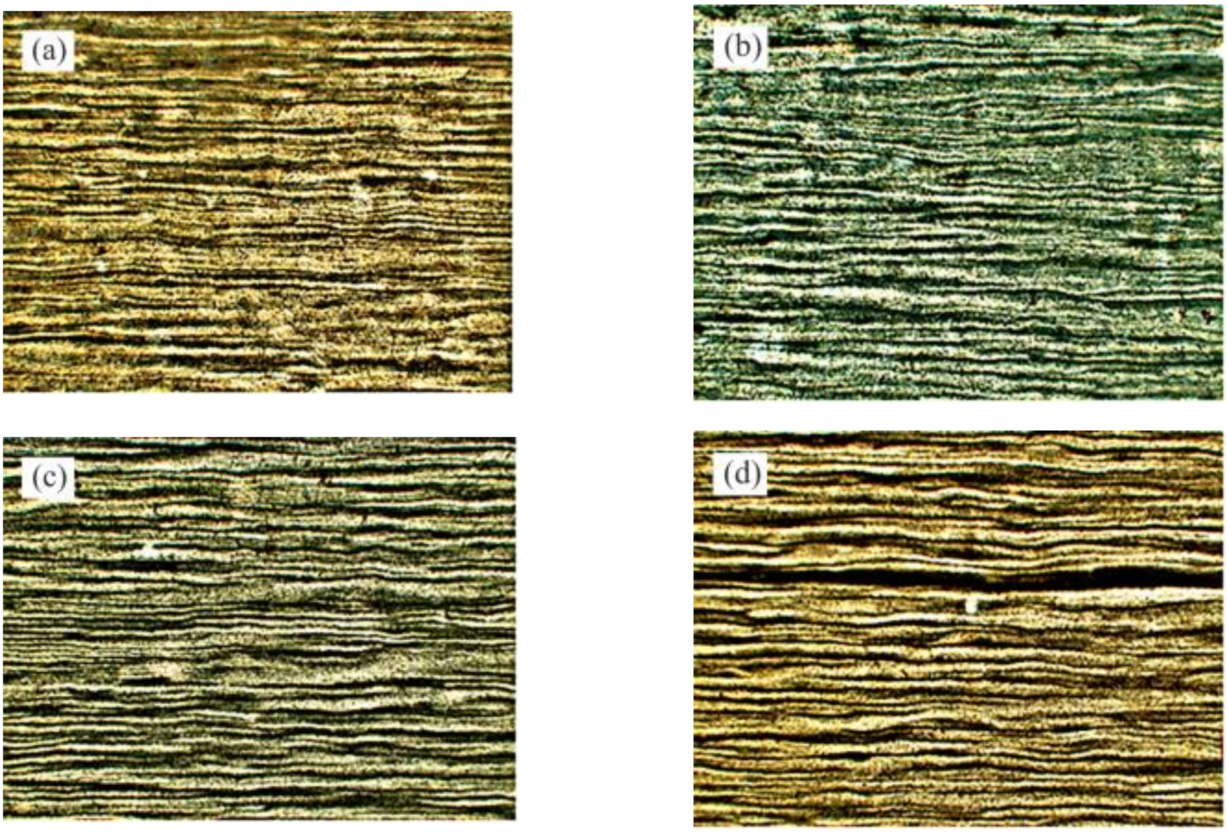
Regime B *Regime C*

Fig. 4 Changes in the dendritic structure along the section of the billet 290 × 290 mm after rolling at the blooming rolling mill: (a), (b) surface; (c), (d) ¼ of height; (e, f) center. × 7



Regime B Regime C

Fig. 5 The structure of the billet after treatment according to schedule B and C: (a), (b) after billet rolling mill, before slow cooling; (c, d) after slow cooling chamber; (e, f) samples from axle neck Ø 180 mm after rolling on rolling mill 250. × 7

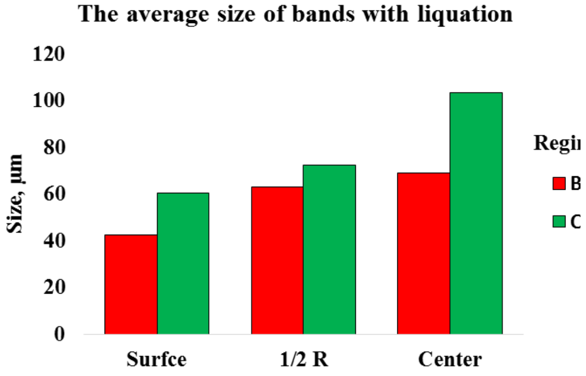


Regime B Regime C

Fig. 6 Traces of the dendritic structure in the neck of axle Ø 180 mm after the first and second normalizations: (a, b) after I normalization: (c, d) after II normalization. × 7.

Table 3 The results of the metallographic analysis

The stage of production	Regime	Place in cross section	The average size of bands, μm	
			Without liquation	With liquation
After rolling at blooming rolling mill	B	Surface	54,2	42,4
		½ R	72,9	63,0
		Center	79,7	69,0
	C	Surface	72,5	60,3
		½ R	109,5	72,4
		Center	131,5	103,3
After billet mill, before slow cooling	B	½ R	72,1	61,4
	C		101,3	71,8
After slow cooling	B		71.9	55,0
	C		92,5	70,4
After rolling at rolling mill 250	B		67,5	55,6
	C		96,4	67,7
After I normalization	B		66,8	66,4
	C		89,8	71,3
After II normalization	B		68,7	70,5
	C		88,3	73,2



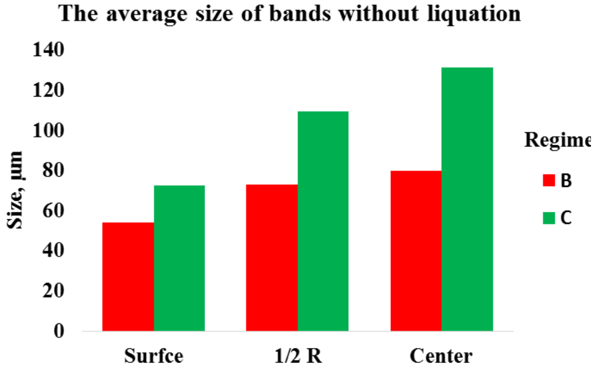
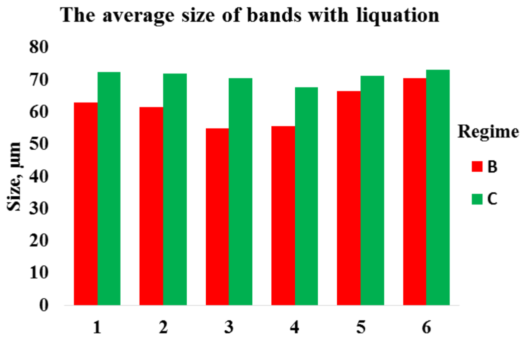


Fig. 7 The alteration in the average size of bands with liquation and bands without liquation along the cross-section of the billet after rolling on the blooming mill. B – proposed regime, C – used in the enterprise regime



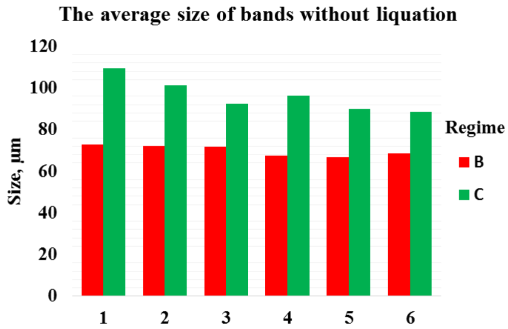
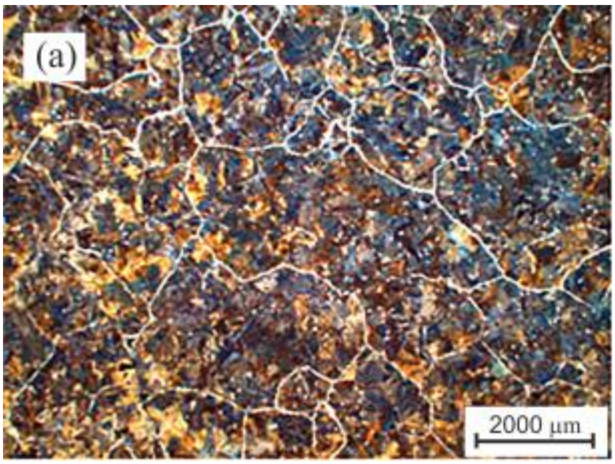
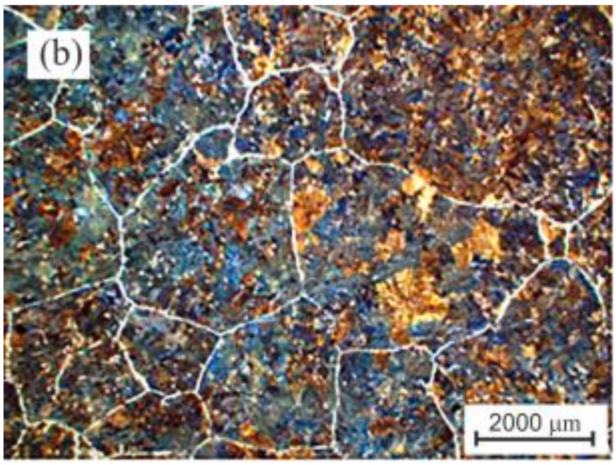


Fig. 8 The changes in the average size of bands with liquation and bands without liquation after the following stages of the axle production: 1 – rolling at the blooming mill; 2 – rolling at the billet mill, before the slow cooling; 3 – after the slow cooling; 4 – after rolling at the mill 250; 5 – after the I normalization; 6 – after the II normalization. B – proposed regime, C – used in the enterprise regime

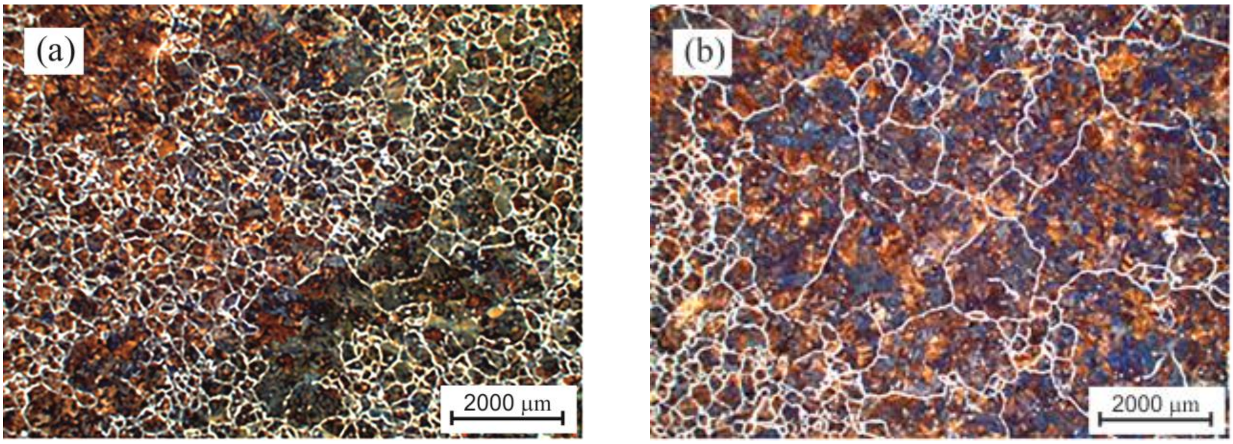


Regime B



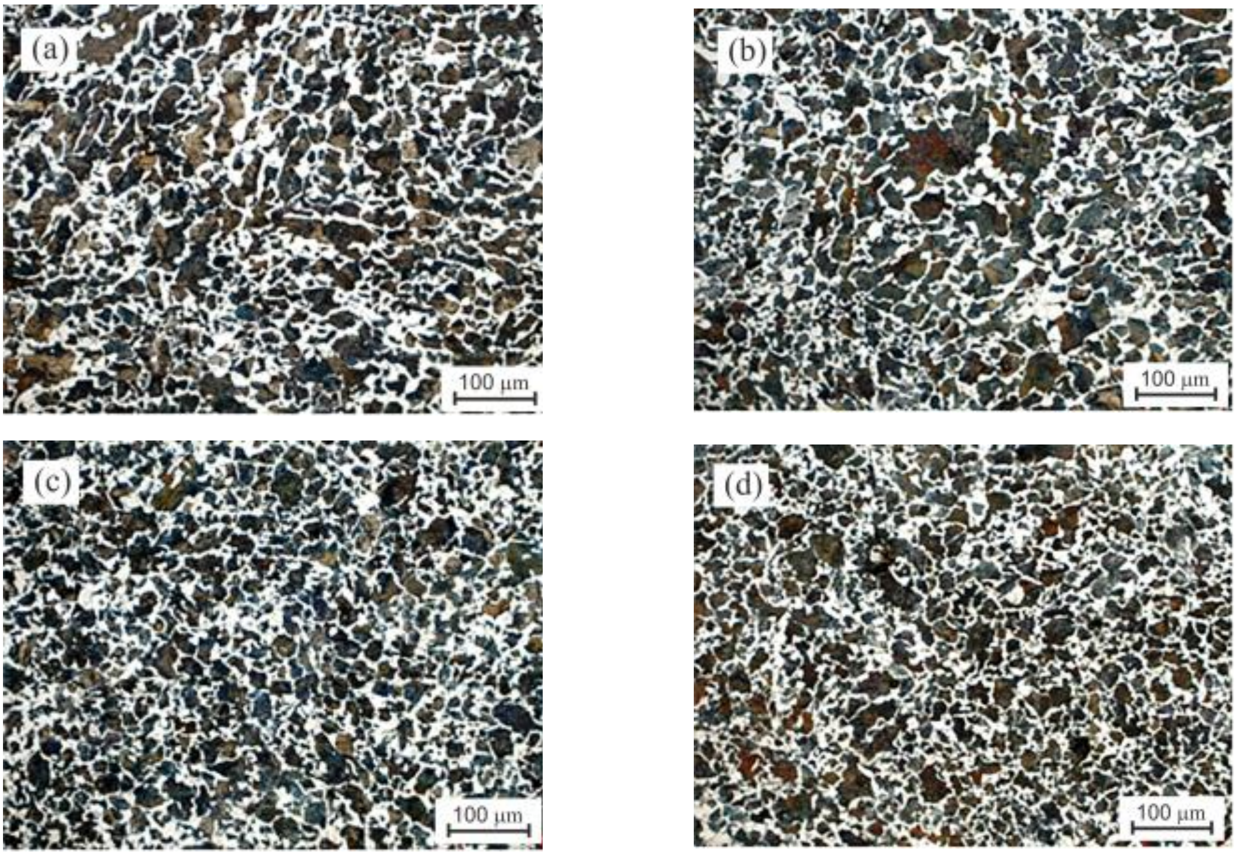
Regime C

Fig. 9 Structure of samples of the axle billet (1/4 thickness) after rolling at the blooming mill according to the proposed regime B (a) and the existing regime C (b). ×10



Regime B Regime C

Fig. 10 The structure of the samples of the axle after rolling on mill 250 (hot rolled state) that was rolled in the blooming mill according to the proposed regime B (a) and the existing regime C (b). ×10



Regime B Regime C

Fig. 11 The structure of the samples of the axle neck that has passed the I (a, b) and II normalizations (c, d). ×100. Proposed regime B (a, c), existing regime C (b, d)

Ultrasonic testing of billets (diameter 250 mm) found in regimes B and C as well as of the rough axle (as a reference sample) obtained after the first normalization was carried out. For each billet, tests were carried out in three sections and five points (Table 5).

No radial monitoring signal from internal defects was observed and the sound quality of the billet rolled in regime B was enhanced by 3~5 dB. However, with respect to the reference sample, the sound quality of the billets obtained in regimes B and C was degraded by 8~13 dB and 11.4~14.2 dB, respectively.

The acoustic characteristics of the rough axles obtained after the first normalization (for both regimes B and C) are presented in Table 6.

Table 4 Mechanical properties

The production condition of axle	Regime	Yield Tensile strength H/mm^2	Ultimate tensile strength, H/mm^2	Elongation,%	Reduction of area,%	Impact toughness, KU, J/cm^2
Hot deformed	B	352	704	15	27	–
	C	360	723	21	27	–
After I normalization	B	360	685	24,5	47	56
	C	360	682	24	49	58
After II normalization	B	341	671	25	50	52
	C	331	657	24	50	54
The requirements of M 101 standard (not less)		*345*	*608*	*22*	*37*	–

No significant difference was noticed between the axles obtained from regimes B and C. However, in the first case, the result of ultrasonic testing along the circumference was slightly better.

Therefore, it can be inferred that in spite of insignificant effects on mechanical properties, the experimental deformation regimes positively influenced the structure of the produced axle.

Table 5 Results of ultrasonic inspection of blanks in the mill 250

The number of cross section	Regime	The mean sound intensity (dB)
I	B	53,6
	C	53,8
	Reference sample	*59*
II	B	56,8
	C	52,6
	Reference sample	–
III	B	57,2
	C	52,4
	Reference sample	*66,4*

Table 6 Results of ultrasonic inspection of axles after I normalization

Regime	Mean sound intensity, (dB)	
	Center	Surface (along a circle)
B	26,5	37,0
C	26,5	36,7

6. Conclusions

Rolling of solid railway axle required special deformation regimes that differed from the deformation regimes for rolling of other types of products.

Deformations in vertical and edging directions with edging reduction were less penetrative to the central zone of the billet as compared to surface layers, thus resulting in an increase in energy consumption and equipment load of the rolling mill.

Rolling with edging reduction caused a worse deformation at the central zone of the billet in the box caliber.

Rolling without edging reduction caused large deformations in central layers of the billet and led to a significant improvement in the metal structure of the axle.

Acknowledgements

The authors are grateful for the financial support from the Natural Science Foundation of Hubei Province (Grant Nos. 2016CFA004) and the 111 Project.

References.

1. C. Klinger, D. Bettge. Axle fracture of an ICE3 high-speed train. Engineering Failure Analysis, 2013, 35, p 66–81
2. Z. Odanovic. Analysis of the railway freight car axle fracture. Procedia Structural Integrity, 2017, 4, p 56–63
3. G. Gürer, C.H. Gür. Failure analysis of fretting fatigue initiation and growth on railway axle press-fits. Engineering Failure Analysis, 2018, 84, p 151–166
4. L. Náhlík, P. Pokorný, M. Ševčík, R. Fajkoš, P. Matušek, P. Hutař. Fatigue lifetime estimation of railway axles. Engineering Failure Analysis, 2017, 73, p 139–157
5. S. Wu, Y. Liu, C. Li, G. Kang, S. Liang. On the fatigue performance and residual life of intercity railway axles with inside axle boxes. Engineering Fracture Mechanics, 2018, 197, p 176–191
6. X. Ren, Z. Wang. Study on model of metal structure refinement during hot deformation. Journal of Materials Processing Technology, 2004, 151, p 115–118

7. W. Min-ting, Z. Xin-liang, L. Xue-tong, D. Feng-shan. Finite Element Simulation of Hot Strip Continuous Rolling Process Coupling Microstructural Evolution. Journal of Iron and Steel Research International, 2007, 14 (3), p 30–36
8. M. Bambach, S. Seuren. On instabilities of force and grain size predictions in the simulation of multi-pass hot rolling processes. Journal of Materials Processing Technology, 2015, 216, p 95–113
9. Y. Lee, S. Choi, H. Kim, W. Yong-choo. An Experimental study of the mean effective strain in rod (or bar) rolling process. Metals and Materials, 2000, Vol. 6, No. 6, p 525–531
10. Y. Lee, S. Choi, P. Hodgson. Analytical model of pass-by-pass strain in rod (or bar) rolling and its applications to prediction of austenite grain size. Materials Science and Engineering, 2002, A336, p 177–189
11. S. Choi, Y. Lee, S. Lee. A Study of the Influence of Strain Path Change on the Microstructure and Mechanical Properties of Low Carbon Steel Using Plate and Bar Rolling. Metals and Materials International, 2001, Vol. 7, No. 2, p 115–121
12. S. Choi, Y. Lee, P. Hodgson. A comparative study of microstructures and mechanical properties obtained by bar and plate rolling. Journal of Materials Processing Technology, 2002, Volume 124, Issue 3, p 329–336
13. S. Choi, Y. Lee, P. Hodgson, J. Soo-woo. Feasibility study of partial recrystallization in multi-pass hot deformat - on process and application to calculation of mean flow stress. Journal of Materials Processing Technology, 2002, 125–126, p 63–71
14. R. Nalawade, A. Puranik, G. Balachandran, K. Mahadik, V. Balasubramanian. Simulation of hot rolling deformation at intermediate passes and its industrial validity. International Journal of Mechanical Sciences, 2013, 77, p 8–16
15. B. Ginzburg. Metallurgical design of flat rolled steels. Marcel Dekker, New York, 2004
16. H. Qingqiang, S. Jia, Y. Chengxin, Z. Junyou, Z. Zongbo. Thermo-mechanical modeling and simulation of microstructure evolution in multi-pass H-shape rolling. Finite Elements in Analysis and Design, 2013, 76, p. 13–20
17. S. Gu, L. Zhang, C. Yue, J. Ruan, J. Zhang, H. Gao. Multi-field coupled numerical simulation of microstructure evolution during the hot rolling process of GCr15 steel rod. Computational Materials Science, 2011, 50, p 1951–1957
18. S. Serajzadeh, A. Taheri, M. Nejati, J. Izadi, M. Fattahi. An investigation on strain inhomogeneity in hot strip rolling process. Journal of Materials Processing Technology, 2002, 128, p 88–99
19. V. Efremenko, Yu. Chabak , A. Lekatou, A. Karantzalis, A. Efremenko. High-temperature oxidation and decarburization of 14.55 Cr-cast Iron in dry air atmosphere. Metallurgical and Materials Transactions A, 2016, 47A (2), p 1529–1543
20. N. Skorohodov, B. Iljukovich, I. Shulaev. Roll design of complex shape. Metallurgy, Moscow, 1979
21. V. Lempitskyi, I. Shulaev, I. Trishevskyi. The shaped profiles. Handbook. Metallurgy, Moscow, 1981
22. B. Iljukovich, N. Nehaev, V. Kapeljushnyj. Rolling and calibration, 6 vols., Dnipro-Val, Dnepropetrovsk, 2004
23. Z. Wusatowski. Fundamentals of rolling. Pergamon Press, London, 1969
24. V. Vidrin, A. Fedosienko, V. Krainov. The process of continuous rolling. Meatllurgy Press, Moscow, 1970
25. A. Tcelikov, G. Nikitin, S. Rokotian. The theory of longitudinal rolling. Metallurgy, Moscow, 1980
26. A. Grudev. The theory of rolling. Metallurgy, Moscow, 1988
27. G. Nikitin. The theory of continuous longitudinal rolling. MGTU of Baumana, Moscow, 2009.
28. I. Tarnovskyi, A. Skorohodov, B. Ilukovich. The elements of the theory of complex profiles rolling. Metallurgy, Moscow, 1972
29. V. Vorontcov, P. Poluxin, V. Belevitin. Experimental methods of mechanics of deformable solids. Metallurgija, Moscow, 1990
30. I. Golikov, O. Maslenkov. Dendritic liquation in steels and alloys. Metallurgy, Moscow, 1977.
31. S. Saltikov. Stereometric metallography. Metallurgy, Moscow, 1976
32. A. Milenin, P. Kustra, T. Furushima, P. Du, J. Němeček. Design of the laser dieless drawing process of tubes from magnesium alloy using FEM model. Journal of Materials Processing Technolpgy, 2018, 262, p 65–74
33. A. Xenzel, T. Spittel. Calculation of power parameters in metal forming processes. Handbook. Translation from German. Meatllurgy Press, Moscow, 1982
34. S. Yershov, G. Levchenko, S. Melnik. The role of roll design in the formation of surface cracks in the rolling production. Processing of materials by pressure. Collection of scientific papers. Kramatorsk, DGMA, 2009, 20, p 338–342
35. N. Baimov. The optimization of rolling processes in rolling on breakdown mills. Metallurgija, Moscow, 1974
36. V. Getmanetc, V. Shevchuk. Rational modes of blooming mills. Metallurgija, Moscow, 1974.
37. V. Severdenko, L. Gurskiy. Some of the features of fractional rolling. Izvestiya. Ferrous Metallurgy, 1965, 5, p 119–123
38. V. Zhadan. Influence of deformation-speed parameters of rolling at high temperature thermo-mechanical treatment on the structure and properties of steel. Steel, 1975, 10, p 904–908
39. V. Florov, S. Shubina. The influence of rolling on the formation of austenitic grain of steels for the tube billet and universal strip. Metallurgical and Mining Industry, 1977, 1, p 33–36
40. E. Lezinskaja, L. Shevchenko. Regulation of grain size in hot-deformed pipes made of stable austenitic steel. Steel, 1976, 3, p 264–265
41. E. Akimova, O. Viliams, E. Lezinskaja. Features of production of hot-deformed pipes with regulated grain size. Metallurgical and Mining Industry, 1980, 1, p 20–22
42. B. Romantcev, I. Morozova, A. Lisovskyi. To the question of formation of the structure and properties of metal materials in screw rolling. Izvestiya. Ferrous Metallurgy, 2002, 11, p 28–30

Стаття поступила:15.11.2019