

## **Effect of Billet Strained Condition on Microstructure Homogeneity of Railway Axles**

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It is shown that deformation mode at more intensive reductions on blooming mill raises compactness of dendritic structure, promotes the formation of required homogeneous and fine grain structure of normalized railway axles and reduces number of additional heat treatments.

Keywords: RAILWAY AXLE, DEFORMATION, NORMALIZATION, MICROSTRUCTURE

### **Introduction**

The microstructure of railway axles is one of factors defining their reliability during operation. Investigation of metal quality [1] showed that dimensional difference of axle structure made from head, middle and bottom ingots is almost eliminated after normalization. But at the same time, axle microstructure after the first normalization is equigranular (pearlite grain size varies from 10 to 90 microns) and unequiaxial. Therefore one normalization does not satisfy the requirements of domestic and foreign standards. In particular, according to DSTU GOST 31334:2009 and standard of American Railways Association M 101 "Carbonaceous Heat-Treated Steel Axles" the structure of axles should be uniform with grain size not larger than 5. For this purpose axles are subjected to two normalizations. And if after such operations ultrasonic control indexes are not satisfactory, axles are additionally heat treated. This complicates the technology, raises cost price and consumption of energy resources. For example, at Dneprovsky Integrated Iron & Steel Works amount of axles subjected to additional normalizations reaches 15 %.

Earlier it was determined that metal structure becomes more fine-grained with homogeneous grain with intensification of reduction mode on blooming 1150, especially at the combination of maximum reductions with frequent manipulations [2]. However, authors did

not investigate effect of this operation on the microstructure of heat-treated metal. Positive effect of increase of reduction in thickness in separate passes on increase of density of dendritic structure is shown in [3]. This trend is saved throughout the whole cycle of railway axle manufacture [4].

It was interesting to determine how intensification of reduction mode of axle steel ingot on blooming mill would affect the formation of normalized axle structure and whether there was a relation between increase of dendritic structure density and homogeneity of ferrite-pearlite structure of axles in normalized condition.

The purpose of present research is to ensure necessary homogeneous and fine grain structure of normalized railway axles due to intensification of deformation conditions of axle steel ingot on blooming mill.

### **Methodology**

Samples of axle steel of horizon A produced by Dneprovsky Integrated Iron & Steel Works were applied in present research (**Table 1**)

Deformation of ingots obtained from a steel mold 8.4 C1:1 with geometrical sizes  $\frac{800 \times 712}{695 \times 608}$  mm was carried out on blooming

mill 1150 by two modes. Ingot of melt No. 1 was rolled on the blooming mill by commercial

**Table 1.** Chemical composition of investigated melts

No.	Content of elements, % mass.								
	C	Mn	Si	S	P	Cr	Ni	Cu	Al
1	0.49	0.85	0.21	0.021	0.019	0.01	0.02	0.03	0.02
2	0.50	0.86	0.21	0.020	0.018	0.01	0.01	0.01	-

reduction mode for 15 passes, ingot of melt No. 2 - by experimental mode with increase of reduction in thickness in the first passes where deformation was on a flat body. Further deformation and heat treatments - rolling on pipe mill in stand 900, cooling in not heated soaking pit furnaces, rolling on mill 250 and normalization - were carried out for ingots of both melts under the standard modes.

The comparative analysis of mass produced axle microstructure after the second normalization and axles fabricated by experimental deformation mode after the first normalization was accomplished in present research. Samples for metallographic analysis were selected on the whole cross-section of article according to procedure presented in [4].

Metallographic observations were conducted by using microscope "Axiovert 200 M MAT" manufactured by "Carl Zeiss", quantitative analysis was carried out with application of software "AxioVision 4.6.3". The microstructure of samples was examined according to requirements of GOST 5639 and ASTM E 112, nonmetallic inclusions - according to GOST 1778. Chemical inhomogeneity of silicon was determined by etching in hot solution of sodium picrate.

1<sup>st</sup> type samples for blow-bending test were cut out from a wheel seat Ø 230 mm on a distance of ½ radius according to DSTU GOST 31334:2009. Impact strength values were determined according to GOST 9454.

Microhardness was measured on PMT-3 at loading 10 grams by GOST 9450.

Mechanical characteristics were defined by the standard pulling test (GOST 1497-84).

Fractures of samples were analyzed using electron-scan microscope REM 200 in the secondary electrons mode.

## Results and Discussion

It was determined in [3] that increase of reduction in thickness in the first passes where deformation is on a flat body ensures deformation in the central area of rolled strip and its uniform

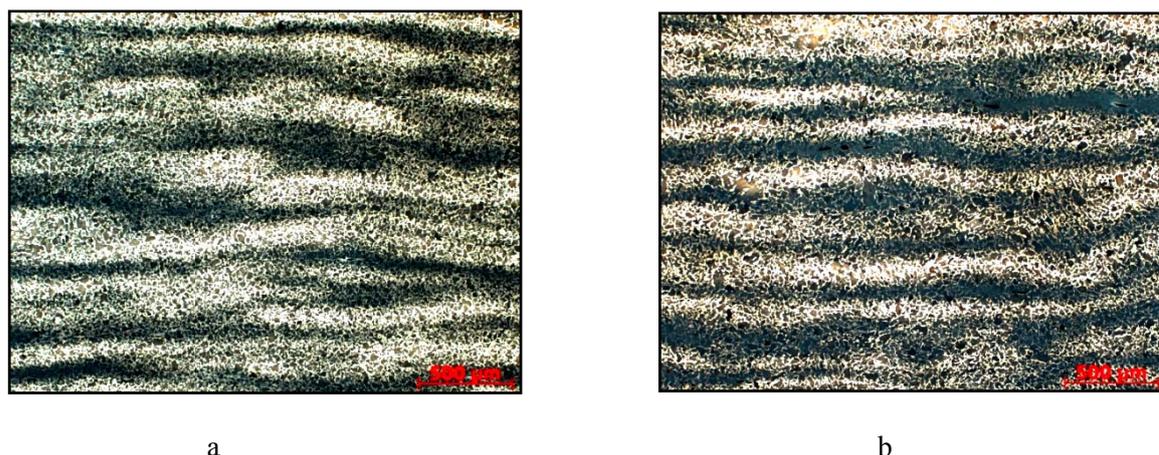
distribution throughout the height. Analysis of change of dendritic structure parameters of axle section 290×290 mm showed that after rolling under experimental mode dimensions of dendritic structure in the surface layers and on the distance of ¼ thickness decreased by 15.0 %, in the central layers - by 25.0 % as compared to commercial mode of ingot deformation. And density of dendritic structure increased by 40.0 % on average.

Investigation showed that rolling on blooming mill has a dominant effect on parameters of dendritic structure and formation of chemical microheterogeneity of silicon and manganese in the axle steel [4].

We will consider the effect of ingot deformation modes on blooming mill on the distribution of chemical microheterogeneity of Si and Mn inherited from dendritic segregation in the structure of finished axles (**Figure 1**). Dark segregation streamers are "former" interdendritic spaces in cast structure. Light strips with no visible segregation are "former" dendritic branches. Results of metallographic observation of dendritic structure elements of wheel seat Ø 230 mm samples of mass produced axles after the second normalization and by experimental mode after the first normalization are introduced in **Table 2**. It is possible to ascertain that volume ratios of segregation streamers and streamers with no segregation do not depend on deformation mode. Size reduction of dendritic branches and interdendritic spaces by 18.0 % and increase of their density by 44.0 % is characteristic for structure of axles fabricated by experimental mode of deformation.

We will analyze the effect of various distribution of chemical microheterogeneity of Si and Mn on ferrite-pearlite structure of normalized axles (**Table 3** and **Figure 2**).

It was determined earlier that deformation-heat treatments cannot eliminate chemical heterogeneity of Si and Mn that appeared as a result of crystallization. And values of dendritic segregation factors of Mn and Si for axle steel are  $k_d^{Mn} = 0.75$  and  $k_d^{Si} = 0.65$  [4]. Elevated content of these elements in segregation streamers



**Figure 1.** Chemical heterogeneity of silicon and manganese in the structure of railway axles (wheel seat  $\varnothing$  230 mm,  $\frac{1}{2}$  radius): *a* - mass production, *b* - experimental production

**Table 2.** Results of metallographic analysis of railway axle dendritic structure (wheel seat,  $\frac{1}{2}$  radius)

Production conditions	Volume ratio of areas, %		Average size of areas, mkm		Density of areas in the melt volume, 1/mm <sup>2</sup>	
	Without segregation	Segregation	Without segregation	Segregation	Without segregation	Segregation
Mass	64.2	35.2	91.0	78.0	197.5	149.8
Experimental	62.8	37.2	74.5	66.8	288.4	212.3

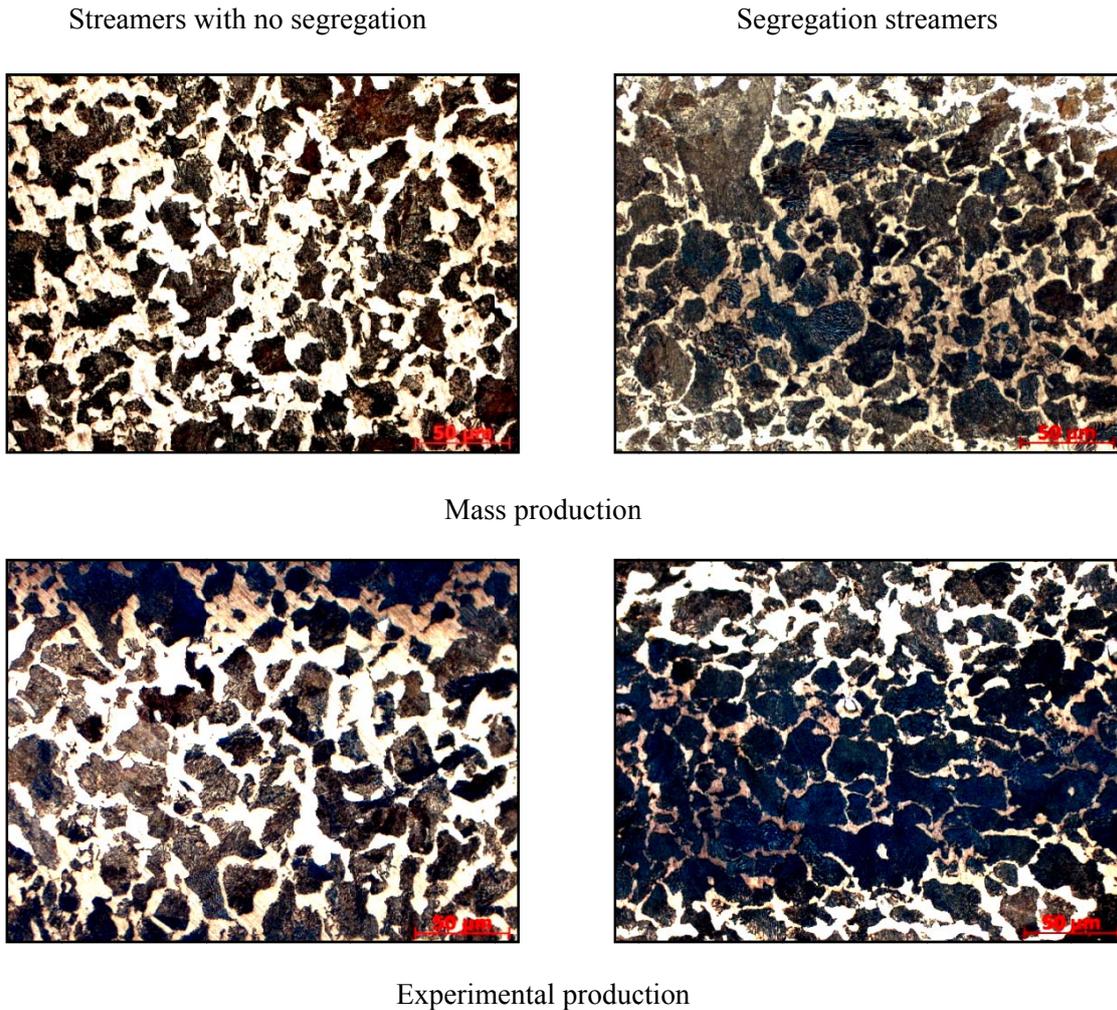
**Table 3.** Results of metallographic analysis of ferrite-pearlite structure of railway axles (wheel seat,  $\frac{1}{2}$  radius)

Production conditions	Streamers with no segregation			Segregation streamers		
	Volume ratio, %		Pearlite grain size	Volume ratio, %		Pearlite grain size
	ferrite	pearlite		ferrite	pearlite	
Mass	69.5	30.5	6.8	44.30	55.70	8.0
Experimental	53.0	47.0	7.5	39.00	61.00	8.1

(Mn  $\sim$ 1.0 %, Si  $\sim$  0.5 %) leads to increase of volume ratio of pearlite and to reduction of its grain size (Figure 2) as compared to these characteristics in strips with no visible segregation. And grain size is almost identical in segregation areas for both mass produced axles after the second normalization and for experimental axles after the first normalization (Table 3).

Based on computation of thermodynamic activity of carbon, manganese and silicon in [5], it is shown that the optimum ratio of manganese

content to silicon content at which thermodynamic activity of carbon flattens -  $a_C^0 = a_C^{(Mn)} = a_C^{(Si)}$  is 1.5-2.0 times. The ratio of given elements content is optimum in segregation areas of investigated steel owing to dendritic segregation and low diffusive mobility of manganese and silicon. Manganese reduces carbon activity factor and promotes its concentration increase. At the same time, silicon raises carbon activity factor and leads to that the latter having concentrated in segregation streamers will try to reach areas with no



**Figure 2.** Microstructure of railway axles (wheel seat  $\varnothing$  230 mm,  $\frac{1}{2}$  radius)

visible segregation. As a result, growth of pearlite grains is retarded in sections enriched in manganese and silicon. Therefore there are the finest pearlite grains in these microvolumes, they are arranged uniformly and separately from each other surrounded by ferrite.

With the knowledge of pearlite volume fraction (**Table 3**) it is possible to describe qualitatively the carbon distribution between segregation areas and those with no visible segregation. Areas enriched in manganese and silicon correspond to steel containing 0.44 % C (for mass production) and 0.48 % C (for experimental production). Density of analyzed streamers in the microstructure of experimental axles is higher, and microvolumes with no visible segregation will be enriched in carbon to a greater degree than similar areas in mass produced axle microstructure at the equal length of diffusive mean free path of carbon. As a result, areas without segregation differ by smaller amount of pearlite which corresponds to steel with 0.24 % C

(for mass production) and 0.38 % C (for experimental mode), i.e. carbon distribution in the microstructure of axles after experimental rolling is more uniform in comparison with microstructure of axles fabricated under current conditions.

Investigations showed that there was a homogeneous structure of austenite with average grain size 7-7.5 (ASTM E 112) at heating up to 870 °C as a result of phase transformation  $\alpha + K \rightarrow \gamma$ . Degree of austenite supercooling from normalization temperatures to temperatures of polymorphic transformation  $\gamma \rightarrow \alpha$  and austenite decomposition on ferrite-carbide mixture  $\gamma \rightarrow \alpha + K$  (pearlite) will change for layers with a different carbon content. According to [6], critical nucleus size decreases and their amount grows at the initial stage of increase of supercooling degree. Obviously, that is why there are most often the finest pearlite grains in segregation streamers of axial steel structure irrespective of number of normalizations. Insignificant increase in their sizes is observed in strips without visible segregation of

experimental axle structure (**Figure 2**). The largest grains are featured for the same microvolumes of mass produced axle structure.

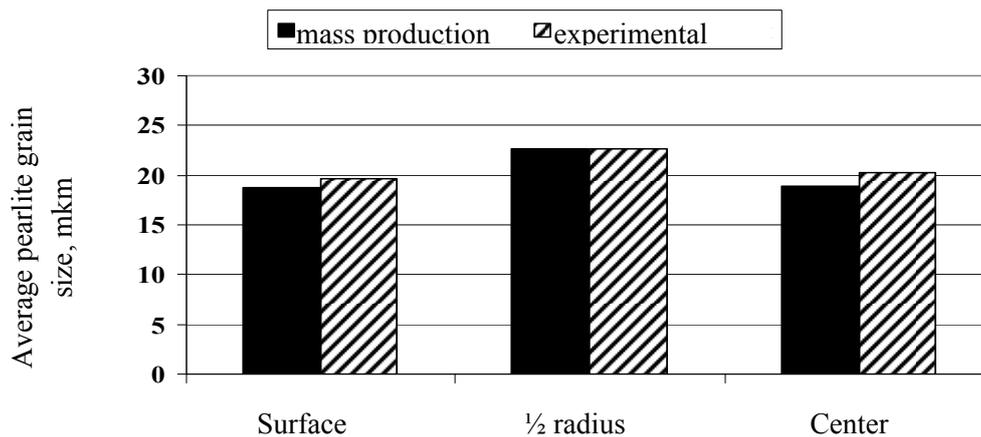
Change of real grain size in the cross-section of wheel seat Ø 230 mm is shown in **Figure 3** depending on deformation and heat treatment modes. It is necessary to mention that railway axle produced by experimental technology already after the first normalization is characterized by fine grain structure on all cross-section of rolled metal similar to mass produced axle structure with two costly treatments (average pearlite grain size is ≈ 20 microns). The structure of axles completely meets the requirements of standard M 101 and DSTU GOST 31334:2009.

As shown in [1], second normalization often leads to both decrease of average grain size and elimination of nonuniform grain pearlite structure. Application of experimental production conditions with only one normalization allowed not only

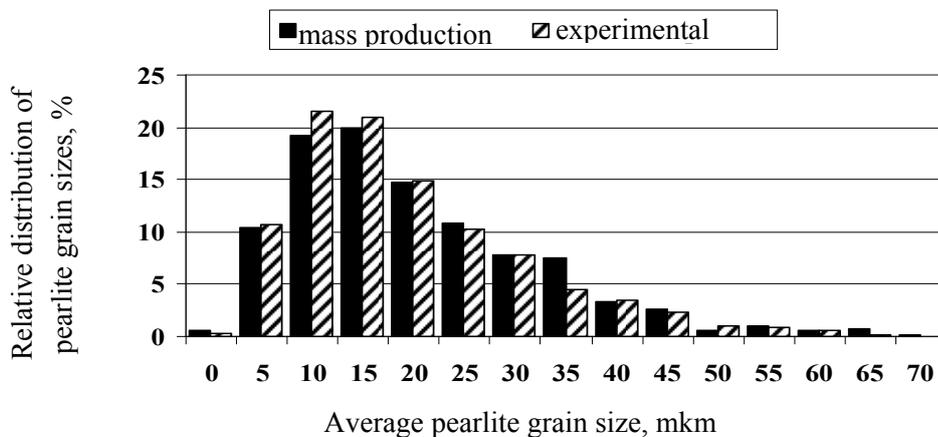
necessary uniform and fine grain structure similar to structure of double-normalized axle (**Figure 4**) but also reducing expenditures connected with additional heat treatment.

Thus, dendritic structure elements attained close-packed distribution. Favorable chemical microinhomogeneity of silicon, manganese and carbon was formed as a result of more intensive drafting schedule on blooming mill which finally allowed homogeneous and fine-grained ferrite-pearlite structure of railway axles already after the first normalization.

We will consider the effect of increase of dendritic structure compactness on microhardness distribution in the structure of axial steel after the first and second normalizations. Microhardness values of investigated samples are presented in **Table 4**. First, we defined how microhardness values of ferrite and pearlite change in segregation streamers and areas without segregation.



**Figure 3.** Change of average pearlite grain size on the cross-section of wheel seat



**Figure 4.** Pearlite grain size distribution bar chart in wheel seat Ø 230 mm of axles on the distance of 1/2 radius

Microhardness level of ferrite and pearlite in the areas enriched in silicon and manganese increased by 50.0 and 35.0 % respectively and did not depend on number of heat treatments. Now, with the knowledge of volume fraction of these phases in segregation streamers and in the areas with no visible segregation we will calculate an additive microhardness for each area [7].

$$H_{\mu} f-p = H_{\mu} p \cdot V_p + H_{\mu} f \cdot V_f \quad (\text{Eq. 1})$$

where  $H_p$ ,  $H_f$  – microhardness of ferrite and pearlite,  $N/mm^2$ ;  $V_p$ ,  $V_f$  – fraction volume of ferrite and pearlite in segregation streamers and areas without segregation, %. Additive microhardness of axial steel samples taking into account segregation (**Table 2**) was calculated by following formula:

$$H_{\mu} a-b = H_{\mu} a \cdot V_a + H_{\mu} b \cdot V_b \quad (\text{Eq. 2})$$

where  $H_{\mu} a$ ,  $H_{\mu} b$  – microhardness of segregation streamer and streamers without segregation,  $N/mm^2$ ;  $V_a$ ,  $V_b$  – volume fractions of streamers in

axial steel. Calculations showed that microhardness of segregation streamers raised by 50.0 % at 1.0 % Mn and 0.5 % Si. As a whole, additive microhardness level of axial steel remains constant- 2465.0  $N/mm^2$ .

However frequency of alternation of harder and stronger segregation layers and layers without visible segregation increases with decrease of dendritic structure dimensions at the experimental deformation conditions. It was determined in [8] that level of specific elongation, assurance coefficient ( $\sigma_{TS}/\sigma_{YS}$ ) and energy of fracture raise simultaneously at frequent alternation of layers with various microhardness level.

Railway axles work under conditions of long cyclical loads, therefore alternation of hard and soft layers in their structure, apparently, will ensure high endurance strength of an article.

Results of mechanical tests of experimental axle samples after the first normalization and mass produced axles after the second normalization are introduced in **Table 5**. It is shown that increase of dendritic structure density did not

**Table 4.** Microhardness of normalized axle samples (wheel seat, 1/2 radius)

Production conditions	H $\mu$ ferrite, N/mm <sup>2</sup>				H $\mu$ pearlite, N/mm <sup>2</sup>			
	without segregation	segregation	$\Delta H_{\mu}$	$\Delta H_{\mu}$ , %	without segregation	segregation	$\Delta H_{\mu}$	$\Delta H_{\mu}$ , %
Mass	1597.6	2367.7	770.1	48.2	2324.5	3147.5	823.0	35.4
Experimental	1605.6	2419.8	814.2	50.7	2301.6	3106.0	804.4	34.9
Additive microhardness taking into account phase composition:								
Production conditions	Additive microhardness taking into account segregation (%), N/mm <sup>2</sup>							
	Streamers without segregation	Segregation streamers	$\Delta H_{\mu}$	$\Delta H_{\mu}$ , %				
Mass	1819.8	2792.9	973.1	53.5				
Experimental	1932.7	2838.4	905.7	46.9				
Production conditions	Additive microhardness taking into account segregation (%), N/mm <sup>2</sup>							
Mass	2429.6							
Experimental	2501.5							

affect neither total microhardness level nor mechanical properties. However, experimental axle samples after the first normalization are featured by increase of impact strength by 20.0 % at actually equal level of strength and ductility of samples of experimental and mass produced axles.

Macrostructure of impact sample fractures has granulitic appearance (**Figure 5**). Flat faces of broken crystalline grains make brittle fracture luster.

Electron microscope investigation reveals a curly structure of fractures of samples under examination (**Figure 5**), which is a result of interaction of moving fracture with crystal defects

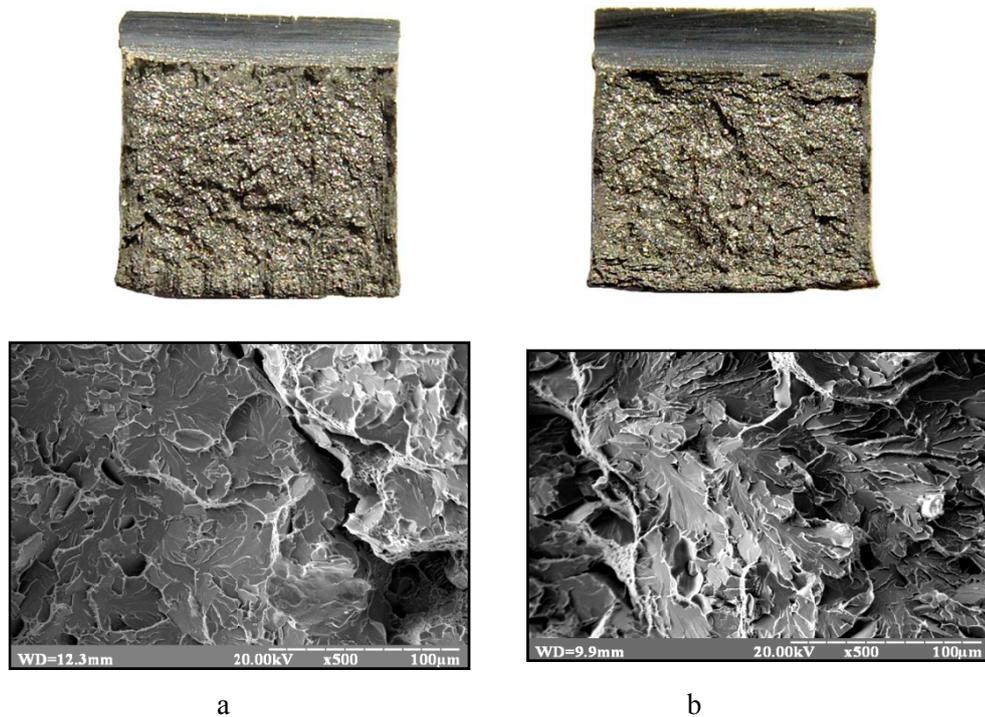
as well as the presence of preferable crystallographic orientations of cleavage facets. It was determined that fraction of viscous component in both fractures of impact samples of mass produced axles after the second normalization and fractures of experimental normalized axle samples was 15.0 % at brittle transgranular fracture.

Thus, increase of impact strength as structurally-sensitive characteristic of axle experimental samples subjected to only one normalization is directly related to decrease of real grain size and growth of homogeneity of dendritic and grain structures.

**Table 5.** Mechanical properties of normalized axle samples (wheel seat)

Production conditions	Tensile strength $\sigma_{TS}$ , N/mm <sup>2</sup>	Yield stress $\sigma_{YS}$ , N/mm <sup>2</sup>	Specific elongation $\delta_5$ , %	Impact hardness at 20 °C KCU, J/cm <sup>2</sup>	
				Arithmetical average for 4 samples	Minimum for individual samples
Mass	674	387	27	34.5	30.5
Experimental	692	387	24	41.5	32.0
Requirements DSTU GOST 31334:2009	650 and above	325	18	Not less than 34.0	29.0

\* Yield stress norms are for optional use



**Figure 5.** Macrostructure ( $\times 4$ ) and fracture patterns of impact samples of railway axles (wheel seat  $\varnothing$  230 mm,  $\frac{1}{2}$  radius): *a* - mass production, *b* - experimental production

## Conclusions

It was determined that intensification of drafting schedules of axial steel ingot on blooming mill raises compactness of dendritic structure, promotes the formation of required homogeneous and fine grain structure of normalized railway axles and reduces number of additional heat treatments.

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## Влияние деформированного состояния заготовок на однородность микроструктуры железнодорожных осей

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Показано, что режим деформации с более интенсивными обжатиями слитка на блюминге повышает плотность дендритной структуры, способствует образованию требуемой однородной и мелкозернистой структуры нормализованных железнодорожных осей и сокращению количества дополнительных термообработок.