Steels with bainite structure for railway wheels

Svetlana Gubenko
National Metallurgical academy of Ukraine
Dnepropetrovsk, Ukraine
sigubenko@gmail.com

Abstract. *Some wheel steels inclined for the self-quenching on bainite structure were produced and investigated after hot deformation and heat strengthening. Steels contained 0,12...0,45% of carbon, and also Si, Mn, Mo, Cr, Ni, V, Ti, Al. Steels with bainite structure after hot deformation and tempering were investigated. It was shown the possibility of the railway wheels production with bainite structure and hardness of 400HB without heat strengthening treatment. The results of investigation shown the possibility of railway wheels production with bainite structure, hardness of 400 HB and high complex of the mechanical and operating properties without heat strengthening treatment. These tasks solved owning to application of new wheel steels and up-to-date technology.*
KEYWORDS: *RAILWAY WHEELS, STEEL, BAINITE STRUCTURE, TREAD.*

1.Introduction.

The increasing of thermocyclic load on the wheel during braking is one of main problem. Heat loads promote deformation in the wheel. Tread is heating by work of friction and some surface defects are formed. Complex approach for wear mechanism of railway wheels includes not only investigation of structural and corrosive changes happening in surface layers of wheel rims [1-13], but also analysis of wear particles and establishment of mechanism of their formation [14-21]. The variety of working conditions of friction pairs suggests that the general approach may be the idea of the fatigue nature of the destruction of the surface layers [22]. The problem of production of the highstrength and reliabile railway wheels is very actual. This problem is compound and inclides some aspects which connect with production of highquality steel, optimization of the each stage of forming, development of new design of wheels and also guarantee of essential level of heat strenghtening. Modern conditions of operating of railway wheels needs the essential arrangements by the guarantee of high level of wheel rim up to 400 HB. At this time certain countries use the rails with hardness up to 450 HB and the bainite structure. At that, the ratio between hardness of wheel tread and rail should be as follows (0.8...1.0) / 1.0.

Traditional microstructure of wheel rim is dispersion perlite with small share of ferrite, that ensures sufficiently high complex of strengh, hardness and toughness of wheel steel. But such microstructure even by the using of microalloying allows to have maximum hardness of 330 HB. It lets to suppose that possibilities of perlite structure in that senses were settled and new nontraditional approach is assential.

Perspective microstructure for the guarantee of correlation of high hardness, strength, toughness and wear resistance of steel is bainite [23,24]. It is known in advanced railway countries the researches by the development of bainite rails and railway wheels are conducted. Most of works by the development of bainite wheels were connected with task of productuon of steels with high resistance to the martensite transformation for reducing and even removing of probability of surface defects of fatigue.

The goal of this work was development of bainite steels with hardness up to 400 HB and high complex of mechanical and operating properties. The investigations offer complex solution to ensure higher reliability and safety of railway wheels, in particular development and production of new railway wheels with sufficiently improved mechanical and service properties.

2. Materials and Procedures.

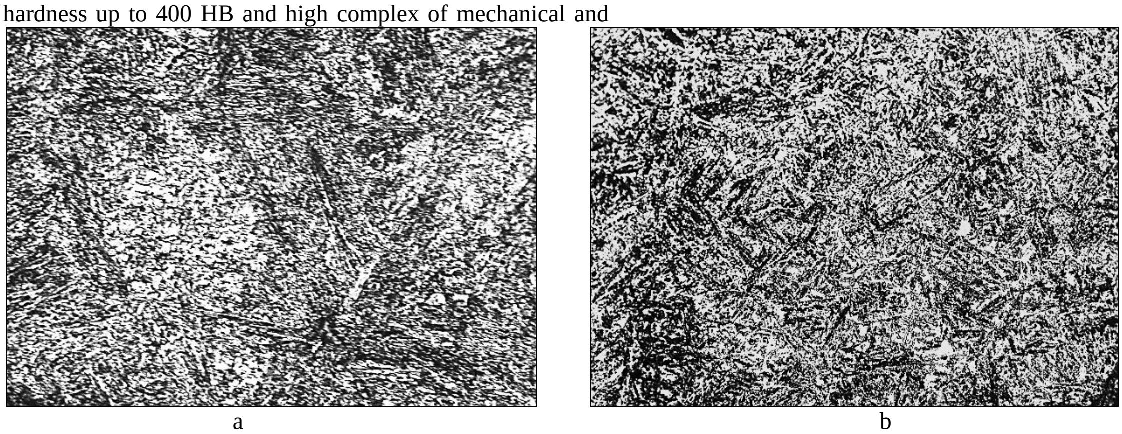
The research steels with low content of carbon (0,12…0,45%, mass) and different contents of Si, Mn, Mo, Cr, Ni, V, Ti, Al were produced. Castings were exposed to plastic deformation (1200…900 °C) with different degrees of deformation (50 and 90%) and cooled on the air. After hot deformation specimens were tempered (500…525 °C) for reduce of stresses.

Metallographical (optical and electron microscopes) and X-ray radoigraphcal researches were made. Methods of testing: hardness, mechanical properties by tensile, fracture toughness, wear test. The resistance of steels for martensitic transformation during rapid heating and cooling by the Jomini end guenching was investigated

3. Results and discussion.

Microstructure of steel 1 after hot deformation was bainite with small part of martensite (about 5%). Degree of dispersity of structure rised with the increasing of deformation degree (Fig. 1, a, b). Needled bainite is twinned, it known else lath ferrite. Analysis of replicas shown that in regions of bainite the ultra disperse carbides Mo_2C and $(Fe, Cr)_3C$ present. Microstructure of steel 2 was ferrite-perlite. By degree of deformation 90% the ferrite banding was appeared that is admited in the structure of wheel web. In this steel the structure of bainite in the time of cooling after hot deformation was not formed.

Microstructure of steel 2 was bainite-ferrite mixture with small quantity of the martensite. Bainite has lath type. Steels 4 and 5 had bainite structures with small part of martensite (up to 5%). Morphology of bainite was lath type close to upper bainite. In the bainite laths carbides VC, Mo_2C, $(Fe, Cr)_3C$ present, although there are the lathes without carbides (they close to lower bainite). Microstructure of steel 6 is ultra dispersed perlite with slim interlayers of ferrite

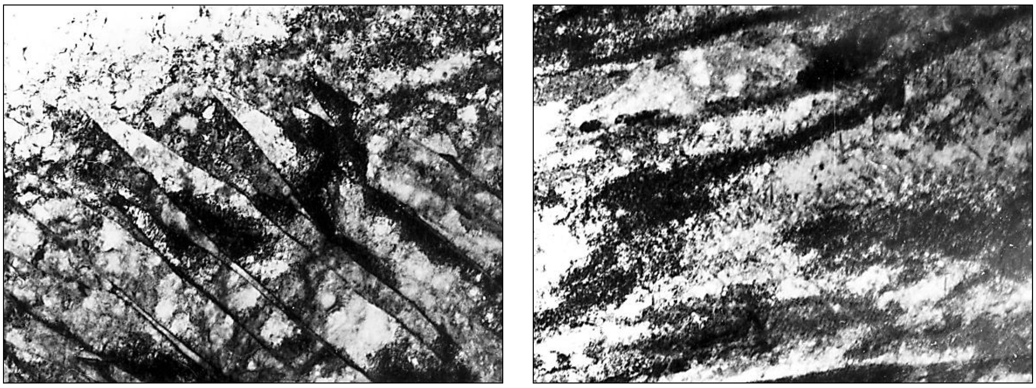


a b

Fig.1. *Microstructure of hot deformed steel 1: degree of deformation 50 (a) and 90% (b); x200*

Therefore hot deformation resulted in dispersion of microstructures of cast steels, moreover than more degree of deformation Steels 1, 3. 4, 5 after hot deformation have microstructure of bainite with small part of martensite (up to 5%). Presence of martensite is caused for nature of bainitic transformation. Obviously during formation and growth of bainitic lathes (or needles, lamelles) the local redistribution of carbon and alloying elements changes the kinetics and mechanism of austenite decomposition. Therefore there is not microstructure of steel with 100% of bainite. Except bainite and martensite, disperse carbides of molybdenum, vanadium and alloying by chromium cementite present in microstructures of steels. Steels 1, 3, 4, 5 are the self-guenching in the time of cooling after hot deformation. Bainite in these steels is different by morphology and degree of dispersity.

Electron microscopic investigations was shown that and upper, and low bainites have favourable lath structure with characteristic cellular dislocation substructure. Density of dislocation is about $10^{11} – 10^{12}$ cm, which close to substructure of deformed metal (Fig. 2). This allows the possibility to admit that bainite in definite measure heredites the deformation substructure. Degree of hot deformation influence on the degree of dispersity of bainite and cellular dislocation substructure. Analysis of fine structure of martensitic regions was shown that in martensite at the temperature of bainitic transformation self-tempering pased and because martensite will not call the brittleness of steel.



a b

Fig.2. *Fine structure of bainite in hot deformed steels 1 (a) and 4 (b); degree of deformation 50%; x22000*

System of alloying of steel influence on the position of crytical points on diagram equilibrium Fe-C and therefore influence on the morphology of α-phase and carbides in bainitic structure. In upper bainite (without carbide) the considerable part of carbon, which did not diffuse to surrounded austenite during growth of laths of bainite, forms Cottrell atmospheres on the dislocations. Remnant of carbon is spended on the carbides and martensite formation. Upper bainite does not need tempering, therefore it is the favourable structure from point of view of strength, plastic and tough properties correlation.

In table 1 the parameters of fine structure of steels after hot deformation are shown.

Table 1. *Parameters of fine structure of bainite after hot deformation*
(D_{hkl} – size of blocks, Δ a/a – microstresses, ρ⊥ - density of dislocations)

Treatment	steel 1			steel 3			steel 4		
	$D_{HKL} \cdot 10^{-4}$ cm	Δ a/a $\cdot 10^{-3}$	ρ⊥, cm^{-2}	$D_{HKL} \cdot 10^{-4}$ cm	Δ a/a $\cdot 10^{-3}$	ρ⊥, cm^{-2}	$D_{HKL} \cdot 10^{-4}$ cm	Δ a/a $\cdot 10^{-3}$	ρ⊥, cm^{-2}
Hot deformation (ε = 50 %)	4,4	2,32	$7 \cdot 10^{12}$	3,9	-	$4,5 \cdot 10^{11}$	3,0	0,45	$2,6 \cdot 10^{12}$
Hot deformation (ε = 50 %) + tempering	4,5	2,24	$6,5 \cdot 10^{11}$	4,8	-	$6,9 \cdot 10^{10}$	2,7	0,21	$5,0 \cdot 10^{11}$

After tempering the level of microstresses in all steels is reduced. Meanings of dislocation density confirm the results of electron microscopic investigations. After tempering the density of dislocations reduces on the order. The quantity of retained austenite was 5…10 %.

After hot deformation the hardness of steels was defined (table 2).

Tabl. 2. *Hardness of steels (HB) after hot deformation and tempering*

steel	Condition of steel			
	Hot deformation ε 50 %	Hot deformation ε 90 %	Hot deformation ε 50 % + tempering	Hot deformation ε 90 % + tempering
1	405	420	432	455
2	190	264	195	250
3	408	410	402	409
4	420	424	437	451
5	400	401	409	432
6	338	475	363	434

Steels 1,3,4,5 with bainite microstructure have hardness 400…455 HB after hot deformation or deformation and tempering. It is important that bainitic structure in hot deformed steels was formed without special heat treatment. That allows to affirm that essential level of hardness of railway wheel rims may be provided after hot deformation without heat strengthening quenching. But it is essentially also to define the level of the mechanical properties and resistance of steels to the martensitic transformation during heat of tread of railway wheel.

The complex of the new wheel steels characteristics was as follows (Table 3)

.

Tabl. 3. *Mechanical and operation properties of bainitic steels and standard wheel steel[*]*

	Hardness, HB	Ultimate strength, MPa	Yield point, MPa	Percent elongation, %	Percent reduction, %	KCU, J/sm^2
after hot deformation	400…435	1309…1610	1044…1318	7,8…13,2	8,2///28,5	15,61… 41,8
Standard wheel steel after heat strengthening	248 255	900…1100 930…1130	- -	12 8	21 14	3,0 2,0
Improvement the resistance against wear and tear to 1.2-1.4 times						
In a situation of sharp brake in the operation period this structure can guaranty the high resistance against the thermo impact						

[*]Tested in Institute of Ferrous Metallurgy NAS of Ukraine

Properties of bainite steels are better than properties of standard wheel steel with perlite structure.

During operation of railway wheel the tread is exposed to heat and mechanical loads, which promote the accumulation of heat and mechanical fatigue, wear of tread and flange, plastic shears in the slim surface layer, appearance of some defects which are caused by formation of martensite near tread (Fig. 3). These defects are formed in conditions of abrupt braking, when thin surface layer of tread is heated up to temperature of austenite area (upper 800^{0}C) by friction from abrupt action of the brake block. Deformation of this thin layer in the plastic austenite condition takes place, but it can not endure a big operating load, then tread abruptly cooling in the time of disengagement of brakes and this leads to formation of the "white layer". It is known "white layer" represents ultra dispersed martensite (gardenite), which has high brittleness, especially by the blows of wheel against the butts of rails (that is by dynamic load). Moreover, it promotes formation of some defects in the areas of heat action and this lead to increase of quantity of metal which is removed by the turning in the process of tread profile restoring.

For comparison the specimens of standard wheel steel and experimental steels 1, 3, 4, 5, 6 were exposed to heating in the austenite area by the Jomini end guenching.

The results of microhardness measuring are shown in table 4.

a b c

Fig.3. *Structure of railway wheel tread after operating, x200*

Tabl. 4. *Microhardness (HV) along length of specimens*

Steel	Place of measuring from the end of specimen, mm						
	0	2	4	6	8	10	12
Standard wheel steel	640	640	625	500	320	250	250
1	400	400	400	400	390	380	380
3	420	445	430	420	420	370	380
4	450	460	470	440	460	430	430
5	460	470	450	440	450	435	430
6	600	600	590	590	580	575	570

Standard wheel steel and steel 6 have inclining to the martensitic transformation. Steels 1, 3, 4, 5 showed stable values of microhardness with the level of bainite microstructure, and this was confirmed also by the metallographical research of these specimens. Of course, it is not possible to expel the possibility of formation of sliders and dynamic loads connected with sliders in the wheels from bainite steel. But advantages of the bainite wheels are evidently in this problem by the comparison with wheels from standard steel.

4. Conclusions.

The results of investigation shown the possibility of railway wheels production with bainite structure, hardness of 400 HB and high complex of the mechanical and operating properties without heat strengthening treatment. These tasks solved owning to application of new wheel steels and up-to-date technology.

5. Literature.

1. Gubenko S.I. Some structural aspects of wheel steel that determine the quality of railway wheels. Modern technologies for the production of transport metal. - Russia, Nizhny Tagil: NMTK, 2008, 394 p. (pp. 88-113). 2. Taran Yu., Esaulov V., Gubenko S., Kozlovsky A., Staroseletsky M.Peculiarities of plastic deformation and microdestruction in wheel steel. Proceedings of XIII International Wheelset Congress, Italy, Rome, sept.17-21, 2001, pp. 236-241.

3. Sladkowski A., Gubenko S., Pogorelov D., Iwnicki S., Licciardello R.V. Rail vehicle dynamics and associated problems: monograph. – Gliwice: Silesian University of Technology, 2005, 187 p.

4. Gubenko S.I. Physics of steel fracture near non-metallic inclusions. – Dnepropetrovsk: NMetAU, Information Technology Systems Technologies, 2014, 301 p

5. Gubenko S.I. Non-metallic inclusions and ductility of steels. The physical basis of the ductility of steels. - Saarbrücken: LAP LAMBERT. Palmarium academic publishing, 2016, 549 p.

6. Kushner V.S., Kutko A.A., Vorobev A.A., Gubenko S.I., Ivanov I.A. The effect of the structure and mechanical characteristics of

wheel steels on wear and restoration modes of the wheelset profile. - Omsk: OmSTU, 2015, 221 p.

7. Belchenko G.I., Gubenko S.I. Deformation of non-metallic inclusions during steel rolling. News of the USSR Academy of Sciences. Metals, 1983, № 4, pp. 80-84.

8. Gubenko S.I., Ivanov I.A., Sobolev A.A. Proceedings of St. Petersburg University of Railway Transport. - St. Petersburg: Publishing House of State University of Railway Transport, 2013, pp. 73-84.

9. Gubenko S.I., Pinchuk S.I., Belaya E.V. The influence of the structural state of wheel steel on the development of corrosion. Metallurgical and mining industry, 2009, № 2, pp. 69-73.

10. Gubenko S.I., Pinchuk S.I., Belaya E.V. Study of the influence of non-metallic inclusions on the corrosion behavior of wheel steel, 2011, №7, pp.70-74.

11.Gubenko S.I., Pinchuk S.I., Belaya E.V. Investigation of non-metallic inclusion effect on corrosion behavior of wheel steel. Metallurgical and Mining Industry, 2011, № 3 (2), pp. 63-66.

12. Pinchuk S., Gubenko S., Belaya E. Correlation between electrochemical corrosion and structural state of steel by simulation of operation conditions of railway wheels. Chemistry & Chemical Technology, 2010, № 4 (2), pp. 151-158.

13. Gubenko S.I., Ivanov I.A., Kononov D.P. The effect of steel quality on the fatigue strength of seamless-rolled wheels. Factory Laboratory. Diagnostics of materials, 2018, v. 84, №3, pp. 51-60.

14. Gubenko S., Proidak Yu. Investigation of wear mechanism of tread during operation of railway wheels. Transport problems, 2012, № 7, pp. 119-125.

15. Taran Y.N., Esaulov V.P., Gubenko S.I. Increase of wear-resistance of railway wheels with different profile of tread. Metallurgical and Minning Industry, 2000, N 2, pp. 42-44.

16. Gubenko S.I., Pinchuk S.I., Belaya E.V. System study of wear mechanism of railway wheel tread surface. Metallurgical and Mining Industry, 2010, № 2 (1), pp. 51-56.

17. Taran Y., Yessaulov V., Sladkovsky A., Gubenko S., Kozlovsky A. Wear Reduction on Working Surface of Railway Wheels. Boundary Element Technology – XIII. Computational Methods and Testing for Engineering Integrity. Southampton-Boston: WIT-press, 1999, pp.693-701.

18. Gubenko S., Proidak Yu., Kozlovsky A., Shramko A., Iskov M. Influence of Nonmetallic Inclusions on Microbreaks Formation in Wheel Steel and Railway Wheels. Transport Problems, 2008, v. 3, N 3, pp. 77-81.

19. Gubenko S. I. Influence of Nonmetallic Inclusions and Corrosion Products on the Wear Resistance of Railroad Wheels. Steel in Translation, 2019, v. 49, No. 6, pp. 427–431.

20. Gubenko S. Proidak Y., Kozlovsky A., Shramko A., Iskov M. Influence of Nonmetallic Inclusions on Microbreaks Formation in Wheel Steel and Railway Wheels. Materials of VIII Scientific Conference “Telematics, Logistics and Transport Safety” TLTS’08, Poland, Katowice-Cieszyn, 2008. - oct 16-18.

21. Gubenko S.I., Pinchuk S.I., Belaya E.V. The influence of plastic deformation in the surface layer of the rim on the mechanism of wear of railway wheels during operation. Metallurgical and mining industry, 2009, № 6, pp. 72-74.

22. Sladkovsky A., Yessaulov V., Gubenko S., Shmurygin N., Taran Y. An Analysis of Stress and Strain in Freight Car Wheels. Computational Methods And Experimental Measurements VIII. Materials of International Conference. Oxford-Rodos, 1997, pp. 15-24.

23.Bhadeshia H.K.D.H. Bainite in Steels. London: Institute of Materials. 1992, 468 p.

24.Cassidy P.D. A new wheel material for the new century. Proceedings of XIII International Wheelset Congress, Italy, Rome, sept.17-21, 2001.