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RAILROAD RAILS FROM BAINITIC STEEL

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The properties of railroad rails produced from bainitic steels are compared to those from traditional pearlitic steels. Formation and propagation of contact fatigue cracks in the rails is considered. It is shown that bainitic steels exhibit a better combination of strength and ductility characteristics than pearlitic steels.

Key words: contact fatigue cracks, rate of crack propagation, wear, contact fatigue resistance.

INTRODUCTION

Railroad rails (RR) are composite constructions (Fig. 1) produced in huge amounts and serving under heavy and complicate operating conditions [1]. The operating conditions of RR become more and more rigid due to the propagation of the railroad net to regions with low temperatures, growing loading of the rails and marked increase of the speed of motion of trains. This demands progressive advancement of the operating properties of steels used for making rails.

The aim of the present work was to review the stages of creation of rail materials and to analyze the operating properties of rails from bainitic steels.

STAGES OF PRODUCTION OF RAILROAD RAILS

We may break the development of the production of RR into four stages [2].

The first stage (1857 – 1930). The rails are produced from medium-carbon steels with up to 0.4% carbon and ultimate strength $\sigma_r \approx 650$ MPa. The main drawbacks of such steels are their brittleness, fracture at low climatic temperatures, and collapsing of the head under the load produced by the wheels of the rolling stock.

Second stage (1930 – 1980). The carbon content in the steel is raised to 0.6 – 0.7% and the ultimate strength σ_r exceeds 700 MPa. With advancement of the metallurgical processes of production of rail steels, the content of harmful impurities (sulfur, phosphorus, nitrogen and oxygen gases) in them decreases, which makes it possible to lower the susceptibility of the steels to brittle fracture independently of the growth in the carbon content. Growth in the strength raises the wear resistance and the resistance to collapsing of the head. Unfortunately, the increasing loads elevate persistently the susceptibility to the appearance of transverse contact fatigue cracks in rail heads (defects 21 and 23 in [3]).

Third stage (1980 – 1995). The carbon content in the rail steels continues to grow (hypo- and hypereutectic steels), their composition is enriched with microadditions of vanadium and modified with calcium. The use of volume quenching of rails in oil and of subsequent tempering yields high mechanical properties typical for sorbite structures (σ_r = 980 – 1420 MPa, δ = 6 – 12%, $KCU_{+20°C}$ = 0.32 –

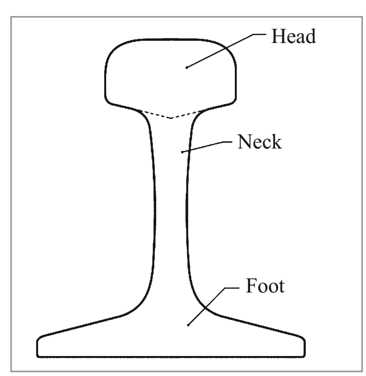

Fig. 1. Main components of a railroad rail [1].

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0.46 MJ/m^2) and elevates the hardness (347 – 354 *HB*) [4]. Unfortunately, when the rails of this type are straightened, tensile stresses arise in the head and worsen the operating properties. The resistance of the steels to nucleation and propagation of contact fatigue cracks in the head is still not high despite some refinement of the structure.

Fourth stage (from 1995). Various grades of bainitic steels are developed for the production of railroad rails. The stage has not finished and continues to develop actively. Some companies do produce RR from bainitic steels. Such rails are used in individual railroad regions, and their behavior in service is carefully controlled.

To provide high strength properties and resistance to contact fatigue and well enough hardness and toughness, the structure of the rails should be very fine, which is implementable in the case of lower bainite. Appropriate alloying (1.5 – 2.0% Si) and heat treatment gives rails without cementite in the structure (which is known as "carbide-free" bainite).

Railroad rails have a composite profile, and some parts of a rail (the surface and the internal volume) cool at different rates in the process of natural cooling from the temperature of heating for austenitization (about 1000°C). This requires careful choice of the chemical composition and of the process of heat treatment of the steel for forming the required bainitic structure in the whole of the cross section of the rail. The difficulties of the production find reflection in the cost of these high-quality bainitic rails. Solution of the problems arising in the production of RR from bainitic steels will take ten more years. Today, they have already proved to be more advantageous than pearlitic rails under the conditions of contact fatigue loading.

RESULTS AND DISCUSSION

Contact Fatigue Cracks in Rails

Contact fatigue due to the motion of wheels over the rails yields a number of fatigue flaws on the surface (surface fatigue cracks and breaks on the rolling surface, scouring, local collapsing) and inside the head of the rail. In both cases, contact fatigue flaws appear as a result of repeated overloading of the material of the rail on the functional surface or in the depth due to hundreds, thousands and millions of intense contact cycles in the zone of interaction between the rail and the wheels of the rolling stock [5].

The problem of contact fatigue of rails has come to the fore after 1990. By the data of the Federal Railroad Admiration of the USA it has become the only cause of 120 cases of derailing during 1995 – 2002; in 160 cases it intensified the action of other causes. In Europe, the cost of the measures used to prevent and eliminate the consequences of contact fatigue is approaching 300 million Euro. In the USA, the figure is even higher [5].

Contact fatigue due to the motion of rolling stock on rails develops in two processes, i.e., nucleation and propagation

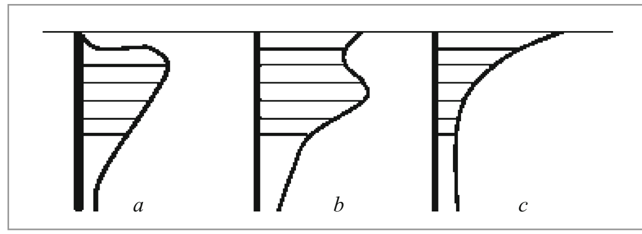

Fig. 2. Variation of tangential stresses over the thickness of rails at different coefficients of friction [6]: *à*) $\mu \ll 0.1$; *b*) $\mu \approx 0.2$; *c*) $\mu \geq 0.35$.

of cracks. In their turn, these two processes depend on a number of factors such as the environment, the profiles of the rail and of the wheel, the road radius, the structure of the materials used, the lubrication, the metallurgical processes of the production of rails, the characteristics of the rolling stock, the deviations of the road geometry, and the used kind of rail grinding. All these factors may be used for lowering the contact fatigue and controlling the latter [5]. The amplitude and the arrangement of the stresses causing crack nucleation change as a function of the geometry of the contact, of the load, and of the friction conditions [5].

The friction coefficient (μ) in the zone of contact of the wheel-rail system characterizes the relation between the tangential (T) and normal (N) stresses, and its value depends of the place of application of the maximum tangential stresses. Figure 2 presents the results of an evaluation of tangential stresses in rails with different lubricants [6]. Under the conditions of strong friction ($\mu = T/N > 0.35$), the tangential stresses are very high, but act at a very low depth, i.e., virtually on the surface of the rail (Fig. 2*c*). This gives rise to surface contact fatigue cracks (defect 12 in [3]). Under weak friction ($\mu = T/N < 0.1$), the maximum tangential stresses are lower, but act at a greater depth in the head of the rail (Fig. 2*a*); contact fatigue defects develop in this zone. At a friction coefficient ranging within $0.1 < \mu < 0.35$ (Fig. 2*b*), the tangential stresses exhibit two maximums, i.e., under the surface and on the surface. A crack nucleates on the working surface; a second crack appears in parallel to the working surface when the second maximum is attained and causes flaking-off of the metal [6].

Contact fatigue defects commonly start to form with easy cracking of the working surface of the rail, which becomes more and more frequent, grow in size, transform into flaking and then into detachment of the metal from the surface. Surface defects appear due to repeated plastic strain on the working surface of the rails, which interacts with the wheels of the rolling stock. When the ductility margin of the metal is exhausted, this yields contact fatigue cracks on the surface and may lead to subsequent fatigue failure [5, 7]. Contact fatigue defects on the surface of a rail are presented in Fig. 3 [7].

Transverse contact fatigue cracks nucleating in the head of a rail are the most frequent defects dangerous for the mo-

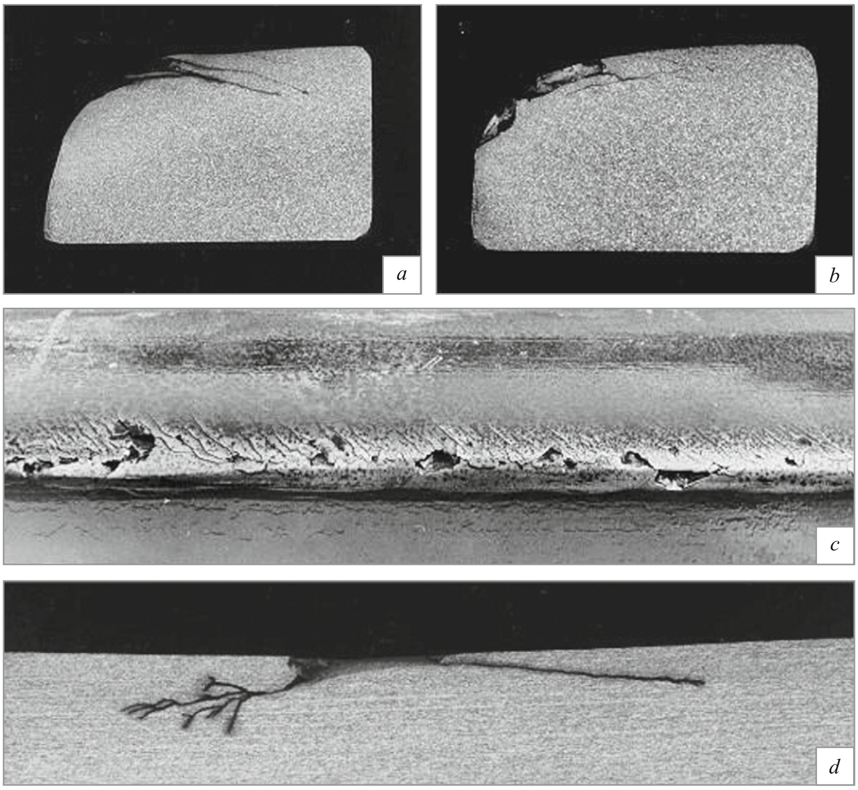

Fig. 3. Early development of surface cracks in cross section (*a*, *b*) [7], late stage of their development with flaking-off of the metal from the working surface (*c*) [7], early development of local collapsing in longitudinal section (*d*) of rails [7].

ving train. Their frequent appearance is associated with enhanced axial loads, growing speed of rolling stock, increasing stresses and high hardness of the railroad frack. The trajectory of the track is also important; the more curvilinear is the region and the shorter its radius, the more frequently defects appear. A necessary condition for formation of contact fatigue defects is the presence of tangential stresses. They appear when the wheel slips on the rail because of its conical profile and due to changes in the mode of motion of the rolling stock (acceleration and stopping) and displacement of compression of the wheel flange to the head of the rail on curvilinear regions of the track. These interactions produce normal and tangential stresses in the rail head. The normal stresses are maximum on the surface of the head, while the tangential stresses (Fig. 2*a*) are maximum at a specific depth (3 – 7 mm) from its surface [8].

In the zone of the action of maximum tangential stresses in the head of the rail (Fig. 2*a*) contact fatigue defects start to develop as internal longitudinal fatigue cracks. The place of crack nucleation (also known as the focus of the crack) is a specific linear accumulation of nonmetallic inclusions having the form of a path oriented in the rolling direction. The type of the nonmetallic inclusions depends of the method of deoxidation of the steel. These inclusions are mostly aluminum, titanium, manganese, calcium, or silicon oxides or titanium nitrides. The most dangerous as a potential focus of nucleation of longitudinal cracks are band-like inclusions of Al_2O_3. Contact fatigue cracks propagate by two mechanisms, i.e., (*1*) the cracks continue to develop as longitudinal ones, which causes detachment of the metal from the surface of the rail head and (*2*) a contact fatigue crack propagating as an internal longitudinal one changes its trajectory with respect to the initially horizontal direction. It has been shown that this change of trajectory, i.e., transformation of a longitudinal crack into a transverse one, occurs when the crack length is below 35 mm. If the longitudinal crack passes this distance without turning into a transverse crack, it continues to propagate as a longitudinal crack and finishes its development with detachment of a small piece of metal (defect 12). If the propagating transverse crack does not reach the surface of the head, it is classified as an internal crack, and its surface is clean and not oxidized. When the growing transverse crack reaches the surface of the head, its starts to oxidize, is “oiled” and darkens. In the classification such defects are denoted 21 and 22 [3].

Speed of Propagation of Fatigue Cracks in Bainitic Steels

By the data of some studies, bainitic steels possess better strength and ductility properties than pearlitic steels and, therefore, we may expect very good crack resistance in the former. This makes it interesting to compare both the standard characteristics of pearlitic and bainitic steels [9 – 13] and the properties determining the rate of crack growth in them. Table 1 presents the chemical compositions of the rail steels tested [10, 11].

We have devoted special attention to the time required for nucleation and propagation of contact fatigue cracks. The dependences of crack length *a* on the number of cycles *N* for

TABLE 1. Chemical Compositions of the Rail Steels Studied

Steel	Content of elements, wt.%							
	C	Si	Cr	Ni	Mn	Mo	Cu	Other*
Pearlitic	0.72 – 0.78	0.1 – 0.6	0.25 – 0.5	0.25	0.6 – 1.25	0.10	–	V, S, P
Bainitic	0.23	1.96	1.84	0.14	1.93	0.43	0.13	V, W, B, Al, Ti, S, P

* In an amount of up to 0.05%.

bainitic and pearlitic steels are presented in Fig. 4 [10, 11]. It can be seen that the time of service of the bainitic steel subjected to contact fatigue loading is much longer than that of the pearlitic steel.

Dependences of the rate of crack growth da/dN on the length of the crack a for two kinds of rail steels are presented in Fig. 5. It can be seen that the rate of crack growth in the bainitic rail steel is lower than in the pearlitic steel [10, 11].

We may conclude from the results of the tests that the bainitic rail steel possesses higher mechanical properties than the pearlitic steel. The time of contact fatigue crack of nucleation and propagation in the bainitic steel is longer than in the pearlitic one. The mean service life of bainitic steels in tests for contact fatigue has been shown to be 7 times longer than that of pearlitic steels under the same experimental conditions [10, 11]. It should also be noted that the critical depth of a crack in bainitic rails (the depth of occurrence of brittle fracture) is 40% higher than in pearlitic rails [14].

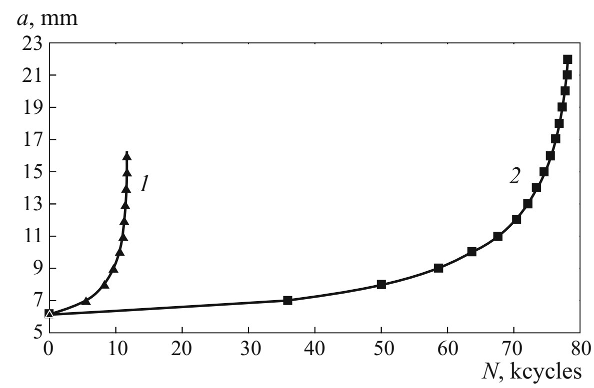

Fig. 4. Crack length a in pearlitic (*1*) and bainitic (*2*) rail steels as a function of the number of loading cycles N [10, 11].

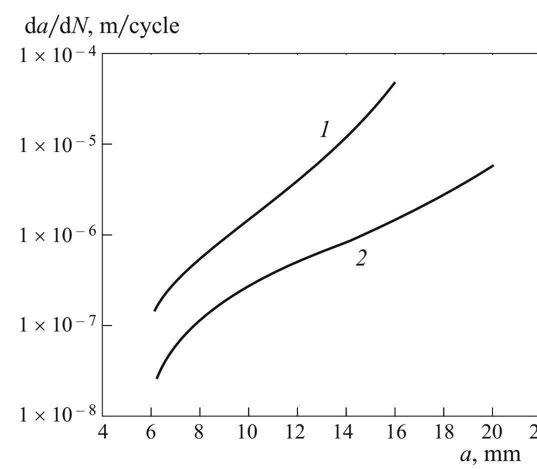

Fig. 5. Rate of growth of fatigue crack in pearlitic (*1*) and bainitic (*2*) rail steels as a function of its length [10, 11].

Wear and Contact Fatigue of Bainitic and Pearlitic Rail Steels

The difference in the wear resistances of bainitic and pearlitic steels is very important from the standpoint of development of contact fatigue damage in rails.

One of the methods for fighting contact fatigue cracks is creation of low-carbon bainitic steels, which wear at a higher rate than pearlitic steels [15]. In such rails, the surface layer with fatigue damage is removed to a certain degree as a result of wear. Such rails are used in rectilinear track regions or regions with a medium curvature radius.

Figure 6 [15] presents the results of wear tests of pearlitic and bainitic steels. In can be seen that at any value of ultimate strength the wear of the bainitic steels is higher than that of the pearlitic steels. In both types of steel, the wear resistance grows with the ultimate strength [15].

We tested samples of the developed bainitic rail steels for contact fatigue and observed no crack prior to 1×10^7 cycles of contact interaction in six of the seven tested samples. In the seventh sample of bainitic steel cracks appeared after 4.5×10^6 cycles of contact interaction. For the pearlitic steels the figure was $(4 - 4.5) \times 10^7$ rotations. It is obvious that the bainitic steels have better resistance to contact fatigue than the pearlitic steels [15].

Propagation of Contact Fatigue Cracks in Bainitic Rails

Let us consider some examples and the results obtained for the properties of rails from bainitic steels. Bainitic steels for railroad transport are produced today by such companies as Voestalpine, TataSteel, Nippon Steel&Sumimoto Metal, and other producers. Table 2 presents the chemical compositions and some mechanical properties of bainitic rails *1 – 3* produced in Austria [16, 17]. For comparison, we give in Table 2 the characteristics of high-strength pearlitic rails *4 – 6* and of pearlitic rails *7 – 9* of the EN 13764 European standard.

TABLE 2. Chemical Compositions and Mechanical Properties of Rails of Different Grades

Rail		Structure	Content of elements, wt.%				Mechanical properties		
			C	Si	Mn	Cr	$\sigma_{r\,min}$, MPa	δ_{min}, %	Hardness, *BNH*
Dobain 340	(*1*)	Bainite	0.76 – 0.84	0.20 – 0.35	0.80 – 0.90	0.40 – 0.55	1100	11	340 – 380
Dobain 380	(*2*)		0.76 – 0.84	0.20 – 0.35	0.80 – 0.90	0.40 – 0.55	1250	10	380 – 420
Dobain 430	(*3*)		0.76 – 0.84	0.20 – 0.35	0.80 – 0.90	0.40 – 0.55	1400	9	> 430
400UHC	(*4*)	High-quality pearlite	0.90 – 0.95	0.20 – 0.35	1.20 – 1.30	0.25 – 0.30	1240	9	> 400
380UHC	(*5*)		0.90 – 0.95	0.20 – 0.35	1.20 – 1.30	0.25 – 0.30	1200	9	> 380
370LHT	(*6*)		0.70 – 0.82	0.40 – 1.00	0.70 – 1.10	0.40 – 0.70	1175	9	> 370
R350HT	(*7*)	Standard pearlite	0.72 – 080	0.15 – 0.58	0.70 – 1.20	≤ 0.15	1175	9	350 – 390
R260	(*8*)		0.62 – 0.80	0.15 – 0.58	0.70 – 1.20	≤ 0.15	880	10	260 – 300
R220	(*9*)		0.50 – 0.60	0.20 – 0.60	1.00 – 1.25	≤ 0.15	770	12	220 – 260

Note. The alloys are numbered conventionally in the parentheses.

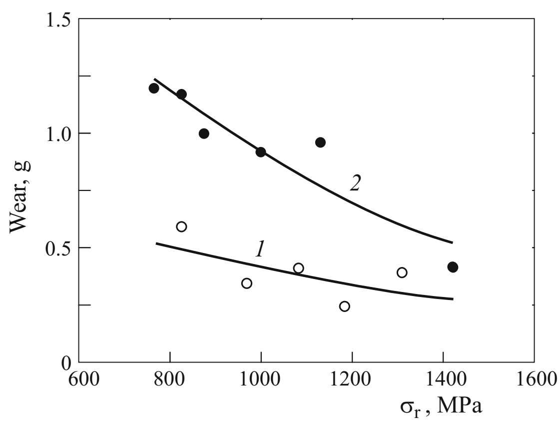

Fig. 6. Dependences of the wear of rails on the ultimate strength of pearlitic (*1*) and bainitic (*2*) steels [15].

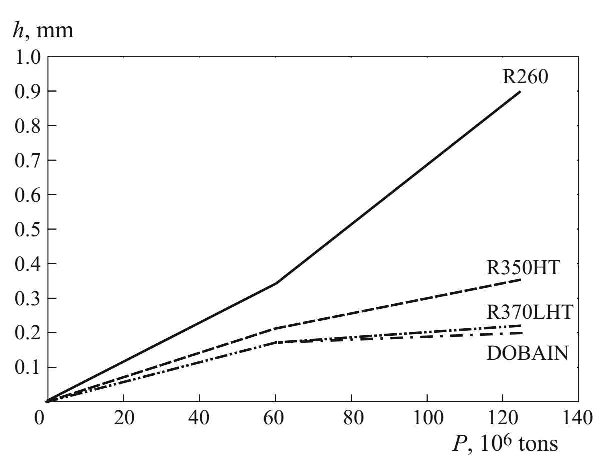

Fig. 7. Depth of crack propagation as a function of the load on rails of different grades (presented at the curves) at a track radius of 1400 mm [17].

These rails have been tested by different railroad companies at different operating conditions [16]. The results show that they are reliable in railroad tracks with radii ranging within 500 – 3300 m, because contact fatigue defects appear primarily in such regions. The railed bainitic steels and high-strength pearlitic steels have been controlled during at least 3 years or up to a gross traffic volume of over 100 million tons. The length of the cracks in the heads of the rails was determined automatically by the eddy current method.

After reaching a load of 60 million tons, the lengths and the depths of the cracks were as follows: 0.8 and 0.34 mm (R260 rails), 0.5 and 0.21 mm (R350HT and Dobain 380), and 0.4 and 0.17 mm (370 LHT and Dobain 430). Figure 7 presents the results of the evaluation of the depth of crack propagation for different rails after a load of 125 million tons. It can be seen that the depth of the cracks is the highest in regions of pearlitic rails R260; with growth in the surface hardness the cracks become thinner and less deep [16]. Figure 8 presents the results of field tests performed in Germany for a road track radius of 600 m. After a load exceeding 15 million tons the rails of the pearlitic class exhibited contact fatigue cracks, whereas in the bainitic rails cracks were absent (Fig. 8*a* and *b*). These results have been proved by laboratory tests in a special bench [18, 19] for determining the behavior of rails under contact fatigue loading and wear. The bench reproduces the interaction between wheels of the rolling stock and rails under various operating conditions and loads. Figures 8*c* and *d* present the results of testing of heat-treated pearlitic and bainitic rails for contact fatigue. It can be seen that cracks appear in the pearlitic rails after 30,000 passes (turns) of the wheel, whereas in the bainitic rails cracks do not appear even after 500,000 turns.

It should be noted that the good resistance of bainitic rails to contact fatigue cracking is mostly a result of the combination of two mechanical properties. On the one hand, the lower rate of development of contact fatigue cracks decelerates penetration of the cracks into the head of a bainitic rail as compared to pearlitic rails. On the other hand, the nucleated but still short contact fatigue cracks in bainitic rails are "ground-off" or "abraded" under the action of the rolling

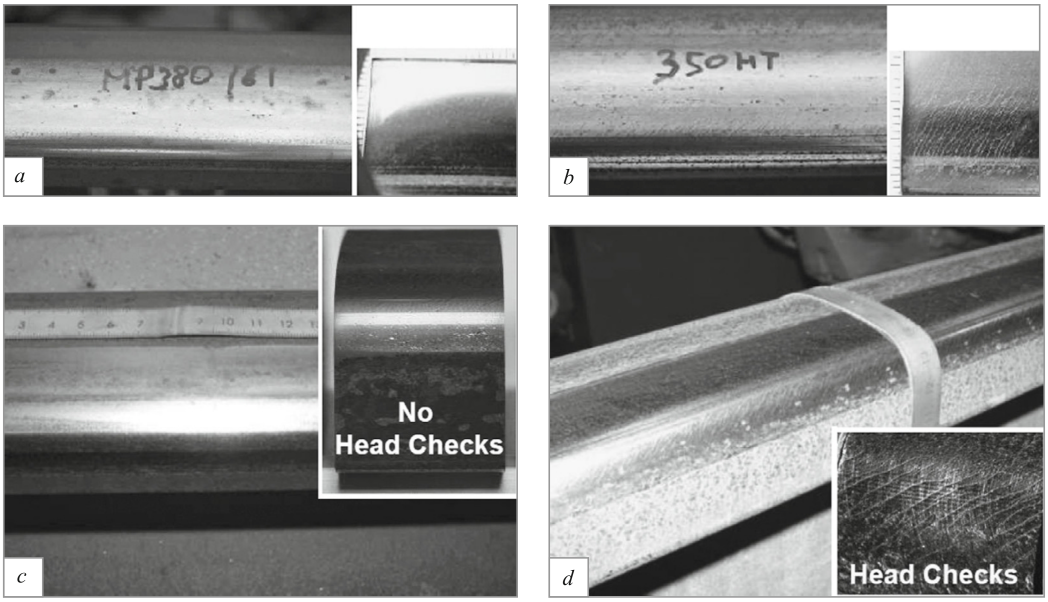

Fig. 8. Results of field tests [(*a*) Dobain 380; (*b*) R350HT] and laboratory tests [(*c*) Dobain 380; (*d*) R350HT] for development of contact fatigue cracks in rails performed in Germany [16].

wheels due to the lower wear resistance than in pearlitic rails; such cracks are virtually removed in the early stage of their appearance.

In actual service, the wear resistance of pearlitic rails grows with their hardness. Bainitic rails are comparable in their wear resistance to high-strength pearlitic steels (Dobain 380 matches R350HT; Dobain 430 matches 370LHT) [16]. By the data of laboratory tests, the wear resistance of bainitic rails is intermediate between rails of standard classes and high-strength heat treated pearlitic rails. At the same time, bainitic rails have a twice lower wear resistance than pearlitic ones at the same hardness [20]. However, the lower wear resistance of bainitic rails is compensated by no need for their grinding for preventing contact fatigue defects. It can be seen from Fig. 9 that conventional pearlitic rails serve to their design wear limit (10 years) if ground 9 times. Bainitic steels exhaust their limit after 20 years of service, and should be ground once in 10 years. High-quality pearlitic steels should be ground 9 times in the operating period equal to 20 years.

CONCLUSIONS

As compared to pearlitic steels, bainitic steels possess a better combination of strength and ductility properties. This circumstance provides very good crack resistance of bainitic steels and makes the rails produced from them more reliable in service.

Analysis of the experimental data on the operating behavior of bainitic rail steels shows that bainitic rails promise to become a new class of high-strength rails. Depending on the chemical composition, the structure and the mechanical properties, such rails can meet the recent requirements from the standpoint of resistance to the appearance of contact fatigue defects, which should also prolong the service life of the rails and lower the cost of their maintenance.

The main disadvantage of bainitic rails is their higher production cost, which is responsible for their restricted application. The main effort of the developers will be concentrated in the next 5 – 10 years on lowering their cost.

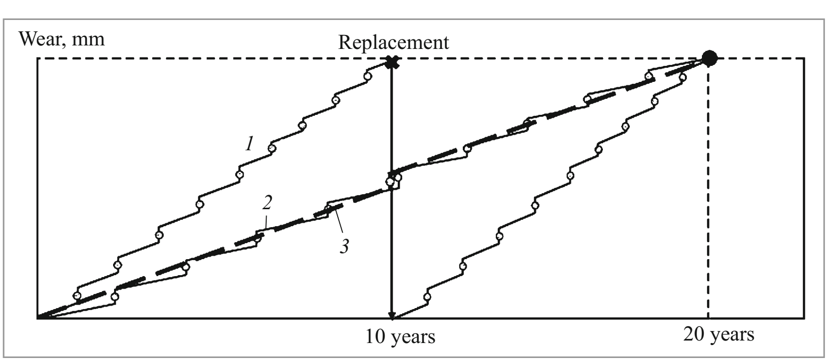

Fig. 9. Wear of pearlitic (*1*, *2*) and bainitic (*3*) rails during operation until replacement [20] (the circles present the time of grinding of the rails): *1*) R260; *2*) R350HT; *3*) Dobain 380.

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