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High-strength heat-treated microalloyed constructional steel for car-building

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Abstract

A new heat-treated low carbon steel, microalloyed by nitride- and carbide-stabilizing elements (titanium, aluminum, nitrogen) with high performance characteristics for car-building is developed.

Key words: *constructional steel, high-strength mill products, microalloyed steels, bake hardening*

Ukraine, a major producer of a wide mix of metal products, unfortunately, has a very high index of the national income metal intensity - it is more than two times higher than the indexes of industrialized countries. So, the Ukraine specific metal intensity of the rolling stock is 50% higher, agricultural machinery and equipment for it - 30% higher, tractors - 20% higher, road transport - 30% higher, road-building machines - 2-3 times more than the foreign specific metal intensity. Consequently, the fuel and energy consumption per unit of effective capacity in the home made technology is 1.3-1.7 times higher than in the foreign.

World experience of metal products using is characterized by a stable trend growth of the use share of high-strength steels and, in particular, low-alloyed with carbonitride hardening most often alloyed by nitrogen (0,015-0,030 %) and vanadium (0.07 - 0.15%).Expensive and critical elements (nickel, molybdenum, niobium, etc.) are further added to their structure when required to ensure a high level of strength (typically, $\sigma_F \geq 420$ MPa), in conjunction with sufficiently high moldability ($\delta_5 \geq 21\%$) and impact hardness $KCU^{-70} \geq 29$ J/cm^2).

The constructural steels microalloyed by titanium, aluminum and nitrogen [1, 2] were proposed to develop cost-effective high-strength mill products, what fundamentally changes the mechanism of the microstructure formation, as titanium carbonitrides are already formed in the crystallization process. Titanium nitrides (carbonitrides) being the crystallization centers do not merge during the subsequent heating of metal for rolling and the heat treatment. The existence of these thermally stable particles during the cooling after heating temperatures for normalization or thermohardening conduce the nucleation of acicular ferrite ("intragranular" bainite) on their surfaces, that is in the body of austenitic grain, and not at its edge. As a result, a very fine-grained structure and therefore a combination of high strength and impact hardness is provided.

Proposed technology of microalloying of low-carbon steel has been successfully tested at “Dneprospetsstal” plant while hot-rolled steel manufacturing.

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Metallographic analysis showed that hot-rolled products of steel St3sp with the proposed carbonitride hardening have ferrite-pearlite microstructure of a high degree of dispersion corresponding to 10-11 score in accordance with GOST 5636-87 for the mill products section of 60x60 mm and to 11-12 score - for the section of 40x40 or less. Found that the complex mechanical properties of hot-rolled steel with St3sp carbonitride hardening in section up to 40 mm (Table 1) practically corresponds to the steel grade of 345 according to the GOST 19281-89, which is now provided only with low-alloyed steels 09G2S, 15GF, 15CHSND in production conditions. In the part of impact hardness the hot-rolled products from ordinary carbon steel St3 with carbonitride hardening exceeds significantly the requirements for low-alloy steels at temperatures up to 70 °C (Table 1).

Table 1 Mechanical properties of hot-rolled steel St3sp with carbonitride hardening

Mill products section, mm	Rupture strength, σ_R, N/mm^2	Flow limit, σ_F, N/mm^2	Percentage extension, δ_5, %	Impact hardness KCU at temperature minus 70 °C, J/sm^2
27x27	465	355	40.5	92
40x40	460	350	40.3	85

The fine structure investigation with a transmission electron microscope Jeol-2010FEG showed that a relatively constant concentration of nitrogen and aluminum (0.018-0.020 and 0.028-0.029%) the reduction of titanium concentration from 0.016 to 0.003% results in a sharp increase in the total number of particles of nitrides and carbonitrides from 187 to 519 per one ferrite grain. This determined the ability to control the sizes and quantity of carbide and nitride phases and, consequently, the structure formation process. The X-ray spectrometry by EDX method established that the excessive nitrogenous constituents are presented by titanium carbonitride Ti(C,N), aluminum nitride A1N and complex compounds of indicated constituents, sometimes additionally containing sulfides MeS. Aluminum nitrides are formed during cooling of already crystallized metal, and also during its hot deformation and have sizes from 40 to 200 nm (rarer up to 500 nm) at a maximum amount of particles having a size of 60-100 nm.

Proceeding from the high cost of alloying elements, the issue of using the hot-rolled even sparingly alloyed steel types in such high metal-intensive fields as machine industry, building industry, transport, mining should be considered in a new light. Experience shows that the most effective use of alloying elements for the manufacturing of mill products for wide use is technically and economically feasible in most cases, using this material in a heat-treated state. Thus, the potential opportunity of the alloying elements are used more fully - strength properties increase by 30-40%, brittle failure temperature significantly decreases.

Table 2 Properties of steel in hot-rolled (HR) and heat-strengthened (HS) states

Type of steel	State of mill products	Type of additional treatment	Steel grade	Mechanical properties			
				Flow limit, σ_F, N/mm^2	Rupture strength, σ_R, N/mm^2	Percentage extension, δ_5, %	KCU, J/sm^2 (-40 °C)
				not less than			
10G2S1	HR		295	295	430	21	29
14G2	HR	-	325	325	450	21	39
17G1S1	HR	-	325	325	450	21	39
10G2S1	HR	HS	390	390	510	19	44
14G2	HR	HS	390	390	510	19	44
17G1S1	HR	HS	375	375	510	20	39

Works on creation of high-strength heat-treated mill products from low-carbon steel St3sp microalloyed by titanium, aluminum and nitrogen were made in view of these positions (Table 3).

Executed to date studies showed that the obtainment of bainitic structure in steel can significantly increase its strength without significant reduction in plastic properties inherent to martensite structure [4]. At the same time, the reduction in values of dynamic characteristics, particularly impact hardness at low temperatures is quite noticeable in some cases for steels with different structural states. This is obviously due to the carbide precipitation along the edges of α-phase rails in case of upper bainite structure obtainment, as well as co-direction of α-phase rails in the lower bainite packet. In case of the main crack extension along bainite packet, the structure resists weakly to the enlargement of main crack. The structure of "intragranular" acicular ferrite, characterized by a high degree of bainitic rails misorientation is formed In heat-treated steel, microalloyed by nitrogen, titanium and aluminum, whereby the main crack propagation in it will be impeded almost in any direction. This explains the increase of impact hardness of steels with "intragranular" acicular ferrite structure compared with similar steels with bainite or tempered martensite structure.

Table 3 Properties of steels for car-building

Types of steel	Flow limit, σ_F, N/mm^2	Percentage extension, δ_5, %	KCU, J/sm^2	
			-40 °C	-70 °C
	not less than			
09G2D	295	21.0	29.0	-
10CHSND	390	18.0	34.0	29.0
New heat-treated steel St3sp with carbonitride hardening	550	21.0	-	35.0

The studies of the drawback temperature influence on the properties of hardened steel were held in order to optimize the processes of the developed steel heat hardening (Table 4).

Table 4 Mechanical properties of the heat-treated microalloyed steel in tempered state

Drawback temperature, °C	Flow limit, σ_F, N/mm^2	Rupture strength, σ_R, N/mm^2	Percentage extension, δ_5, %	Impact hardness, KCU, at temperature minus 60 °C, J/sm^2
	not less than			
450	629	777	18.0	35
550	567	707	20.5	53
600	558	705	23.8	93
650	472	625	24.1	112

The most essential changes in complex of performance characteristics start at drawback temperatures above 550 °C. In this case, a regular decrease in strength properties (flow limit

σ_F and rupture strength σ_R) occurs with the drawback temperature increase and the simultaneous increase of plastic characteristics (percentage extension δ_5) and impact hardness at low temperatures (KCU^{-60}).

Obviously, the additional use of individual drawing-back operation at different temperatures of heat-treated modified steel St3sp allows to get a wide range of high-strength materials with satisfactory value of toughness and impact hardness. On this basis, the optimum temperature of heat-treated microalloyed steel (600 °C), which fully provides a range of mill product properties corresponding to the promising requirements of RR (Russian Railways) and UR (Ukrainian Railways) applied to metal products for railway transport was determined.

The studies of fatigue strength - the most important characteristic for metal products working under alternate load conditions, showed that a new microalloyed steel in heat-treated state significantly exceeds the indicator of currently used metal products for car-building (Fig. 1).

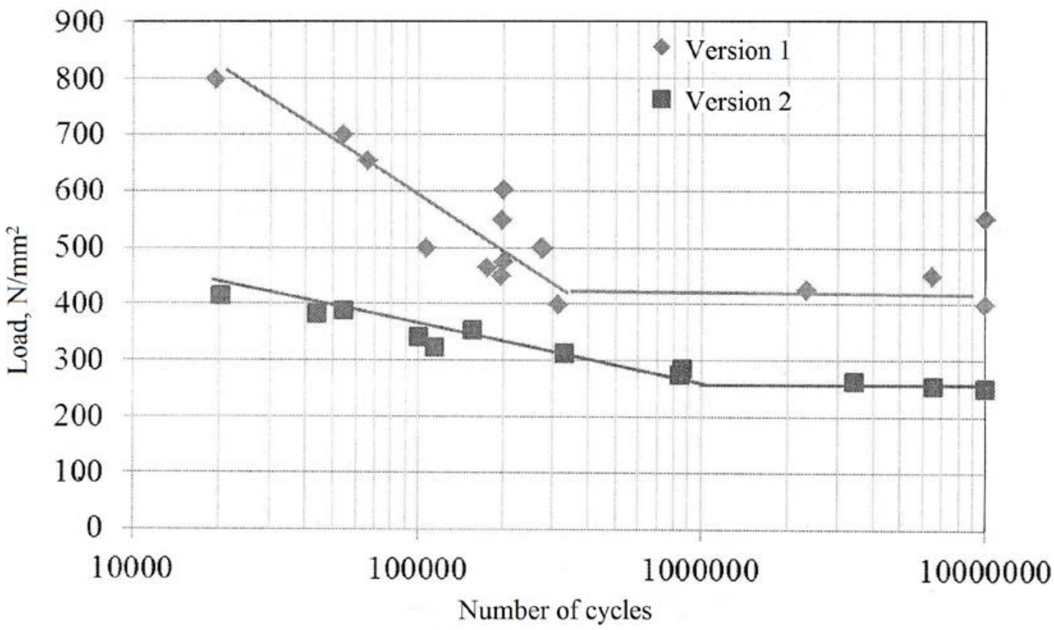

Figure 1 Fatigue curves of mill products for car-building: version 1 - a new microalloyed heat-treated steel with acicular ferrite structure; version 2 - traditionally used steel with ferrite-pearlite structure

From the above data it can be concluded that the heat hardening of mild steel St3sp with complex carbonitride hardening, forming predominantly bainitic structures with a high degree of rails misorientation, provides the possibility of obtaining high-strength mill products with flow limit of 550-630 N/mm^2, impact hardness guarantee at temperature minus 60 °C, and high levels of resistance to fatigue failure (σ_{-1} = 400 N/mm^2) as well as the required level of other operating characteristics.

Testing of the mill products of steel St3sp microalloyed by nitrogen and nitride-forming elements with subsequent thermal hardening on the tendency to hardness ageing was held in accordance with GOST 7268-82 "Steel. Methods for determining the tendency to hardness ageing with the blow-bending test". Mill products in four heat-treated states: in the quenched without drawing-back, in the quenched and tempered at temperatures of 550, 600, 650 °C were subjected to investigation.

Table 5 Impact hardness of heat-treated mill products after hardness ageing

Sample number	State of samples	Impact hardness, J/sm^2	Average impact hardness, J/sm^2

1-1	original quenched without drawing-back	108.13	105.48
1-2		102.82	
2-1	drawing-back 550 °C	108.71	114.04
2-2		119.37	
3-1	drawing-back 600 °C	173.00	181.95
3-2		190.91	
4-1	drawing-back 650 °C	199.08	213.16
4-2		227.25	

Testing of the new steel for resistance to atmospheric corrosion compared with the steel, massively used in car-building today, was held in accordance with the requirements of GOST 9.908-85 "Metals and alloys. Methods for determination of the values of corrosion and corrosion resistance". Test samples were made of hot-rolled steel 09G2D and heat-treated and experimental mill products. The evaluation of corrosion resistance of samples was determined by the weight loss per unit of surface area.

The test results (Fig. 2) showed the increased corrosion resistance of experimental mill products compared with rolled steel 09G2D. In this case, the utilization efficiency of the new steel compared to the steel 09G2D used today increases with time, which is particularly relevant considering that the operational life of new generation wagons is 32 years.

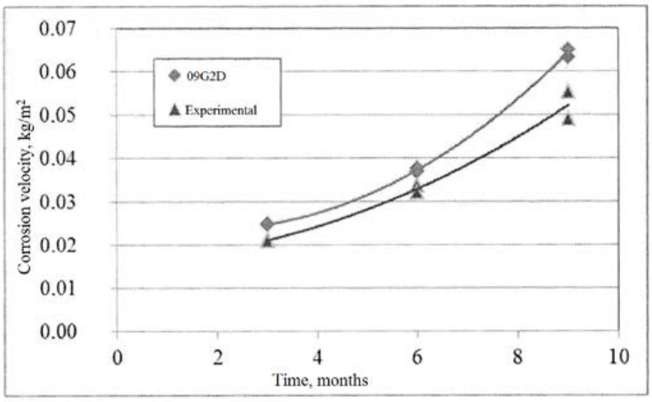

Figure 2 Corrosion resistance of experimental steel and steel 09G2D

Preliminary studies of weldableness of heat-treated steel, held by the Paton Electric Welding Institute of NAS of Ukraine, showed that it is not inclined to the change of properties under the influence of burn, has a good resistance to low-temperature cracking with a limited content of diffusion hydrogen in the metal deposit, is capable to provide the required toughness in the range of cooling rates of $5 \leq W_{6/5} \leq 15$ °C/s and can be taken as basic in the development of high-strength mill products for the new generation wagons.

On the basis of the whole complex of studies it was found that the mechanical and working properties of heat-treated rolled steel St3sp with carbonitride hardening significantly exceeds the requirements of OST 32,153 [5] and performance specifications of UR (Table 6) to the main carrier and filling elements of the new generation wagons. The data obtained allow us to recommend the use of developed mill products in car-building and are the basis for its inclusion in the Program for creation the high-strength metal products for rail transport of Ukraine, including the new generation wagons.

Table 6 Mechanical properties of rolled steel of main carrier filling body elements of the new generation wagons in accordance with performance specifications of UR 2010

Flow limit, σ_F, not less than	500
Rupture strength, σ_R, N/mm^2, not less than	600
Percentage extension, δ_5, %, not less than	18.0
Impact hardness, KCU, at temperature minus 60 °C, J/sm^2, not less than	29.0
Impact hardness, KCU after hardness ageing at temperature plus 20 °C, J/sm^2 , not less than	29.0
Endurance range at reverse bend σ_{-1}, N/mm^2, not less than	240
Bend angle of 180° on the simple male punch with diameter (d) and thickness (h), d/h	1.5

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