ISSN 0967-0912, Steel in Translation, 2016, Vol. 46, No. 1, pp. 65–73. © Allerton Press, Inc., 2016.
Original Russian Text © I.G. Rodionova, V.A. Uglov, A.I. Zaitsev, A.V. Protasov, P.A. Mishnev, R.R. Adigamov, S.I. Pavlov, S.A. Las'kov, O.A. Nikolaev, A.A. Kiryushin, A.K. Tikhonov, V.G. Ryabchikov, 2016, published in "Stal'," 2016, No. 1, pp. 46–54.

A New Generation of Economical Automotive Steel

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Received January 15, 2016

Abstract—To meet the demands of the auto industry, facilitate import substitution, and improve the global competitiveness of Russian products, there is a pressing need for new high-quality economical steels with excellent stamping properties, strength, and corrosion resistance. Between 2001 and 2011, intensive research permitted the development of high-technology production processes for a new generation of automotive steels; these technologies have no counterparts around the world. A fundamentally new approach was adopted: the required structure and properties of the metal are obtained by regulating the deposition of nonmetallic excess phases, the state of the solid solution, the grain boundaries, and the types of impurities at all stages of production. On the basis of extensive research, including more than 1000 trial melts, production technologies for more than 30 grades of automotive steel that match—and in many respects outperform—their foreign counterparts have been introduced at OAO MMK and OAO Severstal'.

Keywords: automotive steel, new-generation steel, import substitution, modernization, plant upgrades, high-technology production, steel strength, stamping properties, excess nonmetallic phases, impurity types, solid solution, grain boundaries, economical alloying

DOI: 10.3103/S0967091216010125

By the end of the last century, there was a clear need for a new generation of high-quality economical steels in the global auto industry: not only steel with excellent stamping properties for use in auto bodies (cold-rolled high-extrusion steel, including galvanized steel) but high-strength steel for safety components and for reducing the vehicle weight.

However, Russian steel plants had not met that demand. This failure to match global quality standards may be attributed to the limited range of available techniques for ensuring stable chemical composition of the steel, with minimal content of impurities and nonmetallic inclusions; the lack of vacuum-treatment equipment for the production of ultralow-carbon steel; and the lack of up-to-date rolling mills, etching systems, furnaces for annealing in hydrogen, continuous hot-galvanization systems, and other equipment. In addition, until recently, communication between steel plants and research institutes was inadequate.

For those reasons, the Russian auto industry—primarily OAO AvtoVAZ—was obliged to import high-quality steel sheet worth more than $150 million each year, especially after the introduction of a new generation of vehicles with improved design, operational safety, fuel consumption, and emissions. In those circumstances, the Russian steel industry faced the urgent task of introducing high-quality economical steels to meet the demands of the domestic auto industry and to improve the global competitiveness of its products.

NEW APPROACHES AND NEW TECHNOLOGIES

In the 1990s, on the initiative of OAO AvtoVAZ, together with Bardin Central Research Institute of Ferrous Metallurgy and the Committee on Metallurgy, Russian steel companies developed a program for introducing new types of steel for use at OAO AvtoVAZ (with planning to 2000, followed by extensions to 2005, 2010, and 2015). The focus of these programs, which became increasingly interdisciplinary and drew in other Russian automakers, was to meet the demand of the auto industry for new high-quality steels. In this process, the requirements on new high-quality economical steels were formulated.

Besides analysis of the prospective demand for such steel in Russia, attention was paid to global experience in the production of up-to-date auto steels, the requirements on such steels, their production technology, and the advantages and disadvantages of existing steels. That permitted identification of the scope for improvements in quality and reductions in production costs. The basic deficiencies of foreign high-strength steels arise because the relevant standards (EN 10346, EN 10268, etc.) permit considerably instability in the strength—that is, a large difference between the minimum and maximum values within a single strength class—and also low plasticity. Therefore, in the production of analogous Russian steels, the goal was not only to match the performance of foreign steel but to improve the plasticity and the stability of the strength. To ensure high corrosion resistance, plans were made for the production of cold-rolled sheet from steel with good stamping properties and also from high-strength steels with and without zinc coatings.

It was obvious that the production of a large range of the new steels would be impossible without technical re-equipment of steel plants and auto plants. In the 1990s, Russian steel plants—OAO MMK, Cherepovets Metallurgical Works (OAO Severstal'), and OAO NLMK—began introducing up-to-date equipment of the highest available quality; this process continued into the new century. Hot-rolling mills were reconstructed; cold-rolling mills were introduced; up-to-date etching departments were installed; annealing of auto steel was switched to new cupola furnaces with a hydrogen atmosphere; and continuous hot-galvanization systems were purchased from the world's leading producers. The key step in the production of ultralow-carbon steel was the transition to converter production of steel using vacuum-treatment systems. Much of the equipment was developed by Russian specialists. Thus, in accordance with the technological specifications of the Bardin Institute and Magnitogorsk Gipromez, a portion-by-portion vacuum-treatment system was introduced in the oxygen-converter shop at OAO MMK. On the initiative of the Russian Research Institute of Metalworking Machinery, a vacuum-system design permitting both portion-by-portion and circulatory vacuum treatment within a single unit was developed (the first such system in the world). In circulatory mode, this was the largest vacuum system in the world.

This system underwent hot trials on September 30, 1995. The main components and systems exhibited high reliability and efficacy. Comparative tests of the two vacuum-treatment methods showed that the residual content after circulatory treatment was practically half as much and was attained more quickly than in portion-by-portion vacuum treatment. After refining the design with the active participation of plant specialists, the vacuum system conformed to the technical specifications [1, 2]. It has been successfully used in the mass production of auto sheet, including high-extrusion ultralow-carbon steel.

In this period, auto plants acquired new equipment for the production of high-quality economical steels, including high-strength steels and hot-galvanized steels. Thus, new stamping lines, a completely automated welding shop, and new painting shops for galvanized sheet were installed at OAO AvtoVAZ. The double-sided electrodes in the welding shop permit the welding of coated steel. At OAO KamAZ, automated systems for plasma and laser cutting of metal sheet went into operation (including the FICEP 602 DZ TT system for drilling holes and plasma cutting of a high-strength rolled-steel profile).

Modernization is a necessary but insufficient condition for the production of high-quality economical steels. The new steels must not only match the performance of the best foreign steel but provide better plasticity and stability of the strength. The steel must also be more economical than its foreign counterparts. That calls for the selection of the most economical alloying systems, the development of technologies ensuring excellent steel performance even with a high impurity content, and maximum energy and resource conservation. Russian steelmakers were confronted with the challenge of developing approaches that had no counterparts in world practice, approaches based on the latest achievements in metallurgy and materials science. In the approach ultimately selected, the required structure and properties of the metal are obtained by regulating the deposition of nonmetallic excess phases, the state of the solid solution, the grain boundaries, and the types of impurities at all stages of production.

Comprehensive research on the phase transitions, the conditions of deposition and solution of excess-phase particles, and the types of impurities in the steel includes thermodynamic analysis of the regions where excess phases exist [3]; metallographic and electron-microscope study of the steel microstructure by X-ray microspectral analysis so as to determine the composition of the nonmetallic inclusions; determination of the content of interstitial impurities in the solid solution by the internal-friction method; X-ray structural analysis; investigation of segregation kinetics of impurities at the grain boundaries [4–7]; mechanical tests; laboratory modeling of rolling and recrystallizing annealing; and dilatometric investigation of $\alpha \to \gamma$ and $\gamma \to \alpha$ phase transitions. This approach permits the identification of the production parameters for steel of specific composition such that the nonmetallic excess phases formed are of optimal morphology and, likewise, the impurities are present in favorable forms.

That, in turn, creates a favorable structure and ensures the required properties and their stability within a narrow range, on the basis of the most economical alloying system.

IMPROVING THE STAMPING PROPERTIES OF COLD-ROLLED LOW-CARBON AUTO STEELS

Even in the 1990s, thanks to new equipment at Russian steel plants, it was possible to produce cold-rolled 08Ю steel sheet corresponding to the first surface-finish group and high extrusion categories after annealing in cupola furnaces—in particular, as a result of reduction in the sulfur and nitrogen content in the steel.

In the first decade of this century, problems arose in that some batches of rolled steel exhibited a sharp reduction in stamping properties—in particular, higher yield point and lower relative elongation than is required for steel of extrusion categories VOSV and VOSV-T. Research showed that, on reducing the steel's sulfur content below 0.015% and the nitrogen content below 0.003%, with constant content of the other elements and no change in the parameters, one result is to modify the conditions in which excess phases MnS and AlN are formed, as well as the number and morphology of such deposits. That reduces the grain size beyond permissible limits for the given steels [8, 9]. On the basis of research regarding particle formation as a function of the sulfur and nitrogen content in the steel, the technological parameters were corrected, with significant improvement of the steel's properties. Thus, one recommendation in optimizing the morphology of aluminum-nitride particles (that is, minimizing its deposition as submicronic particles in hot-rolled sheet on annealing in the initial stages of recrystallization) is to reduce the rime between the end of rolling and the onset of accelerated cooling.[1] That was possible at Cherepovetsk Metallurgical Works (OAO Severstal') thanks to reconstruction of the laminar system in the 2000 mill—in particular, the introduction of two additional segments in the first sections in May 2005. Other recommendations relate to the correction of the optimal Al/N ratio (10–18 in place of 6–10, with a nitrogen content of 0.004–0.006%) and the use of smaller reduction in the last cells of the 2000 broad-strip rolling mill.

To improve the morphology of MnS particles in steel with low sulfur content, we recommend increase in rolling temperature in the roughing cells ($T_5 \geq 1100°C$), the use of heat-protecting screens, and other measures.

[1] V.Ya. Tishkov, S.V. Zhilenko, and O.V. Dolgikh participated in this research.

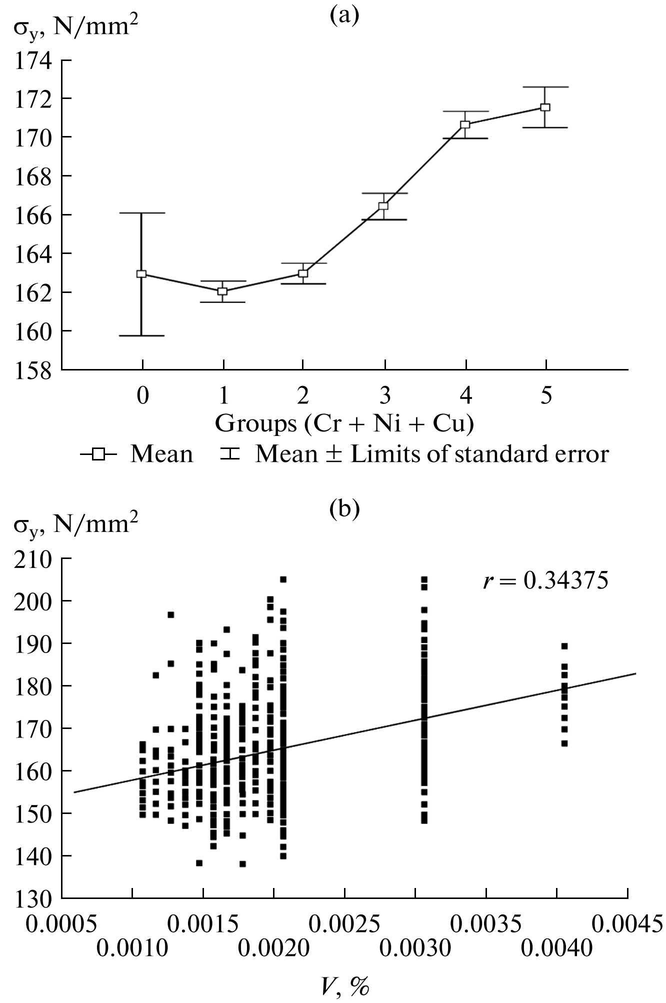

Fig. 1. Yield point of 08Ю steel as a function of the total Cr + Ni + Cu content (a) and the vanadium content (b). Groups for Cr + Ni + Cu: (0) up to 0.04%; (1) 0.04–0.06%; (2) 0.06–0.08%; (3) 0.08–0.1%; (4) 0.1–0.12%; (5) >0.12%.

In contrast to sulfur and nitrogen, the content of many other impurities in the steel (especially Cr, Ni, Cu, and V) has increased recently on account of the increased use of metal scrap containing such impurities (Fig. 1). That may impair the stamping properties if the technological parameters remain unchanged. However, more stringent requirements on the content of these impurities in the batch will necessarily increase production costs; that is unacceptable in large-scale production. Accordingly, between 2007 and 2011, work on optimizing the production parameters for 08Ю steel was undertaken at OAO Severstal' [10–12]. It was shown that, besides silicon and phosphorus, whose content must be limited on account of solid-solution hardening, the content of elements such as Cr, Ni, and Cu, which displace recrystallization to higher temperatures when present in excessive

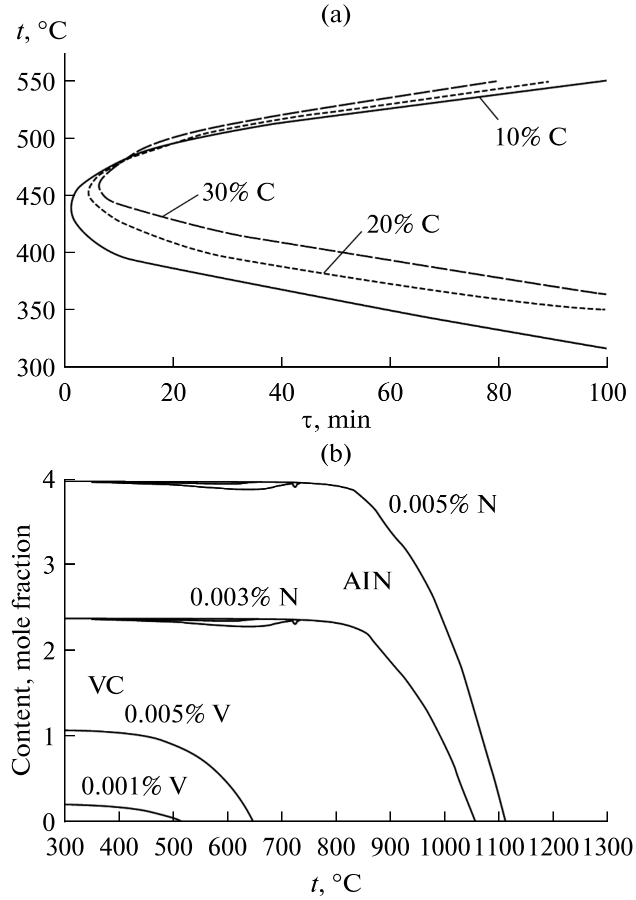

Fig. 2. Segregation of carbon at the grain boundaries of 08Ю steel and temperature dependence of equilibrium content of the excess phases in steel with 0.001 and 0.005% V (b).

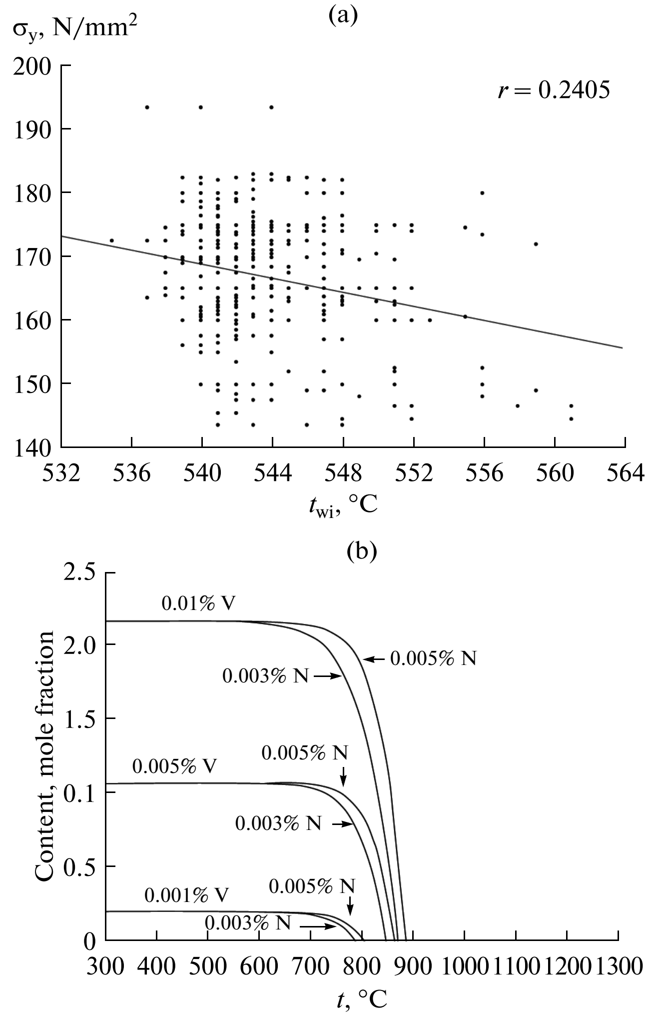

Fig. 3. Dependence of σ_y on the winding temperature for thin sheet (a) and temperature dependence of the vanadium-carbonitride content (b).

quantities, may be reduced by correcting the technological parameters—for example, by 30–50°C increase in the temperature of intermediate holding on annealing.

The reason that the stamping properties of the steel decline with increase in vanadium content is that grain-boundary segregations of carbon are formed on annealing in cupola furnaces (especially with slow heating in the initial stages of recrystallization—around 450–500°C), as we see in Fig. 2a. In steel with low vanadium content, such segregations dissolve at higher temperatures. With an elevated vanadium content, vanadium-carbide nanoparticles form along the grain boundaries, which slows recrystallization and impairs the stamping properties. With the existing annealing technology (Fig. 2a), the temperature corresponding to the greatest rates of carbon segregation is found to be equal to the temperature of intermediate holding on annealing (~450°C). Obviously, increase in the temperature of intermediate holding on annealing slows segregation and the formation of vanadium-carbide nanoparticles.

Another method of preventing impairment of the stamping properties is to increase the winding temperature of the hot-rolled strip above 550°C (Fig. 3a) [6]. In that case, vanadium is bound not in a carbide but in a nitride in the hot-rolled strip on cooling the wound coil. That is confirmed by thermodynamic calculations (Fig. 3b). We see that, in the winding range 550–580°C, vanadium nitride may be deposited, but the deposition of aluminum nitride is suppressed. That prevents the deposition of vanadium carbide on annealing and improves the stamping properties.

The proposed correction of the winding temperature and the annealing conditions at OAO Severstal' ensured 100% yield of rolled 08Ю steel strip of extrusion category VOSV with increased impurity content.

Before its introduction, 12% of the strip was rejected at quality control.

PRODUCTION OF ULTRALOW-CARBON AUTO STEEL

Besides the formation of optimal microstructure, excess phases, solid solution, and grain boundaries, corresponding to excellent stamping properties of low-carbon steel, another approach is to minimize the content of interstitial impurities in the solid solution by complete binding of the carbon and nitrogen in stable compounds (carbides, nitrides, carbonitrides, etc.) using alloying elements such as Ti and Nb.

By reducing the C and N content, the content of alloying elements required to remove interstitial atoms from the solid solution may also be reduced [13, 14]. That lowers the cost of the steel. Therefore, for the production of rolled auto sheet with good stamping properties, increasing use is made of ultralow-carbon steels (with 0.002–0.005% C), which contain no C and N atoms in the solid solution and are microalloyed with Ti and/or Nb. These are known as IF steels (interstitial free steels). They are characterized by a low limit on the fluidity, high plasticity, and excellent stamping properties, with no susceptibility to aging. These properties are obtained with less stringent requirements on the technology—in particular, on the recrystallizing annealing, which may be conducted not only in cupola furnaces but in continuous-action systems (continuous annealing or hot galvanization). That is especially important for hot-galvanized strip.

On the basis of IF steels, ultralow-carbon (ULC) steels with the bake hardening (BH) effect were developed, combining low initial yield point (which is important for stamping) with significant hardening after stamping and drying of the paint coating on the finished automobile. That prevents denting of external bodywork and hence expands the applicability of such steels for door panels, hoods, and roofs, most often in combination with galvanization. In physical terms, the BH effect involves attachment of the dislocations that appear in the steel after stamping by carbon atoms, whose mobility in the ferrite solid solution sharply increases at elevated temperatures. That leads to strengthening of the stamped parts when the paint is dried at $t = 150$–$200°C$. The BH effect appears with a certain concentration of carbon atoms in the solid solution—optimally 6–20 ppm [15–18]. Standard assessment of the BH effect requires 2% extension of samples of rolled steel and subsequent heating to 170°C with 20-min holding (aging). The increase in yield point after 2% extension of samples of rolled steel and subsequent aging is known as the BH effect and is denoted by BH_2. In Japanese steel (produced by Sumitomo Metal Industries [15] and Nippon Steel [16]), BH_2 must be at least 40 N/mm^2. Bethlehem Steel (United States) produces steel with BH_2 no less than 25 N/mm^2 [17]. The chosen carbon content in the solid solution (≥6 ppm) ensures the required BH effect. With ≥20 ppm carbon in the solid solution, the steel may be susceptible to natural aging.

In Russia, the production of IF steels and steels with the BH effect only became possible in the twenty-first century after the introduction of vacuum-treatment systems (after the introduction of continuous hot-galvanization systems). But even in the 1990s the Bardin Institute established that excellent properties of IF steels may be ensured in two versions of microalloying: with Ti alone or with Ti + Nb. For steel with a BH effect, microalloying with Ti alone reduces the reproducibility of the results, especially the BH effect. For 006/IF steel, microalloying with Ti + Nb was adopted at OAO MMK. The development of the corresponding smelting technology entailed ensuring an ultralow carbon content, low content of nitrogen, sulfur, and other impurities, and optimal Ti and Nb content within a specified narrow range [19, 20]. This was made possible primarily by the introduction of a vacuum-treatment system and circulatory vacuum treatment. The optimal content of the key elements and process parameters were determined in thermodynamic calculations and additional experiments and by comprehensive analysis of the phase transformations, the conditions of deposition and solution of excess phase, and the types of impurities.

OAO MMK supplies cold-rolled steel and hot-galvanized 006/IF steel in sheets and coils to OAO AvtoVAZ and elsewhere, in accordance with Technical Specifications TU 14-101-496–02. OAO Severstal' has introduced the production of 01Ю IF steel microalloyed only with titanium, in accordance with Technical Specifications TU 14-105-675–02.

Comparison of the structure and properties of steel microalloyed with Ti alone and with Ti + Nb indicates that more plastic steel is obtained with titanium alone but the reproducibility of the properties is better when using Nb + Ti. Nevertheless, with a sufficiently refined technology, the properties of the steels in both cases comply fully with user requirements. Between 2004 and 2011, more than 29000 t of 01Ю steel and 006/IF steel was supplied to OAO AvtoVAZ, and more than 4000 t to OAO KamAZ.

To introduce the industrial production of steels with the BH effect at Russian plants, microalloying with titanium and niobium was chosen. For the production of IF steels and IF steels with the BH effect, including high-strength steels, the standard documents employed at OAO MMK and OAO Severstal' are largely based on foreign standards: for hot-galvanized steel, primarily EN 10292 (IF steels HX180YD–HX300YD and steels HX180BD–HX300BD with a BH effect).

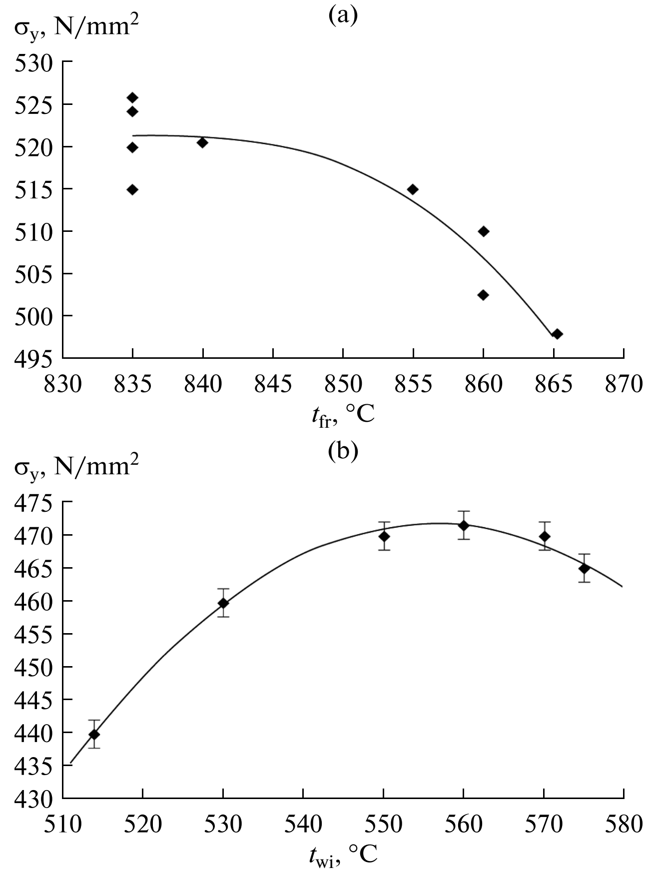

Fig. 4. Dependence of the yield point of steel containing 0.09% C, 0.007% N, 0.05% Nb, and 0.015% Ti on the final rolling temperature (a) and winding temperature (b).

PRODUCTION OF HIGH-STRENGTH MICROALLOYED STEELS

In the global auto industry, the focus is on reducing vehicle weight and increasing passenger safety, primarily by introducing new high-strength low-alloy steels with the traditional strengthening mechanisms: solid-solution strengthening with alloying by Mn and Si; and reduction in grain size and dispersional hardening by microalloying with Ti, Nb, and V. Simultaneous increase in strength and plasticity of low-alloy steels with the traditional strengthening mechanisms is a challenge. Research shows, however, that it is possible if a fixed ratio between the quantities of submicrodeposits and nanodeposits of different types that form the final structure and properties is maintained at different stages of the technological process.

The use of thermodynamic analysis in developing the alloying system and production technology for such steels shows that niobium is the main element whose carbonitrides may be deposited both in hot rolling (at 800–1150°C) in the form of submicronic particles, leading to reduction in grain size, and in subsequent cooling (including cooling after the winding of the hot-rolled strip into coils and in annealing of the cold-rolled strip) in the form of nanoparticles that produce disperse hardening. The elements that will work in the given technological system may be identified by thermodynamic analysis alone, without additional experiments. In addition, this method may be used to assess the slab temperature in rolling that will ensure complete solution of the carbonitride particles and ensure the required properties of the high-strength steel. However, rather than thermodynamic analysis, kinetic analysis and additional experiments are required to assess the influence of optimal final rolling temperatures and winding temperatures of the hot-rolled strip and the annealing conditions on the quantity of particles and their morphology and correspondingly on the properties. On that basis, it is found that, in hot-rolled steel microalloyed with niobium and a small quantity of titanium (no more than 0.02%), the strength is greatest with a relatively low final rolling temperature of 820–830°C and a winding temperature of 550–570°C (Fig. 4) [21].

Above-optimal winding temperature leads to the deposition of larger particles and reduction in the dispersional hardening. A low winding temperature does not ensure sufficient dispersional hardening on account of the suppression of diffusion processes.

On the basis of comprehensive research by the proposed program, the production of hot-rolled strip with $\sigma_y = 500$–550 N/mm², more stable σ_u, and high plasticity satisfying foreign standards was introduced. It is used, in particular, at OAO KamAZ for frame components.

In introducing the production of cold-rolled strip with $\sigma_y \geq 379$ N/mm² from steel alloyed with 0.80–0.85% Ti and microalloyed with 0.035–0.050% Nb, it was found, by contrast, that the strength increases with increase in the final rolling temperature (Fig. 5a), despite some enlargement of the grains (from 4 to 6 μm) [22–24]. This is associated with increased supersaturation of the solid solution before winding and correspondingly with increased contribution of dispersional hardening. According to estimates for this steel, the contributions of strengthening by decrease in grain size and dispersional hardening are approximately the same: 90–100 N/mm². The contribution of solid-solution hardening is 30–40 N/mm² (Fig. 5).

Different approaches may be used to select the optimal winding temperature of the cold-rolled strip. Statistical analysis shows that the winding temperature has a significant influence on the properties. With fixed annealing conditions, we may identify two groups of steels: (1) with $t_{wi} < 560$°C, highly plastic steel with relatively low strength; (2) with $t_{wi} > 560$°C, high-strength steel with low plasticity. However, it is not true that, as for hot-rolled strip, specified strength

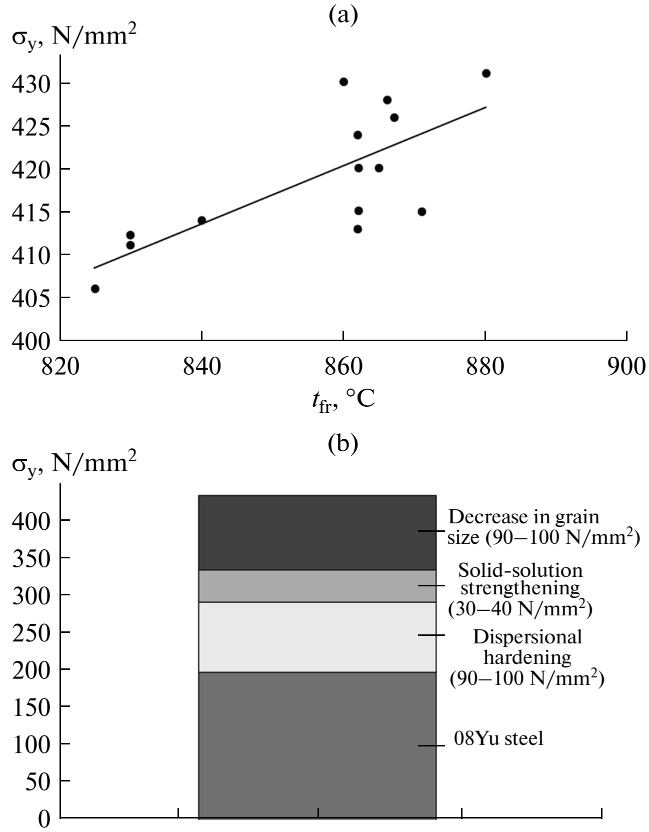

Fig. 5. Dependence of the yield point on the final rolling temperature (a) and contribution of different strengthening mechanisms to the yield point (b) for HC380LA steel.

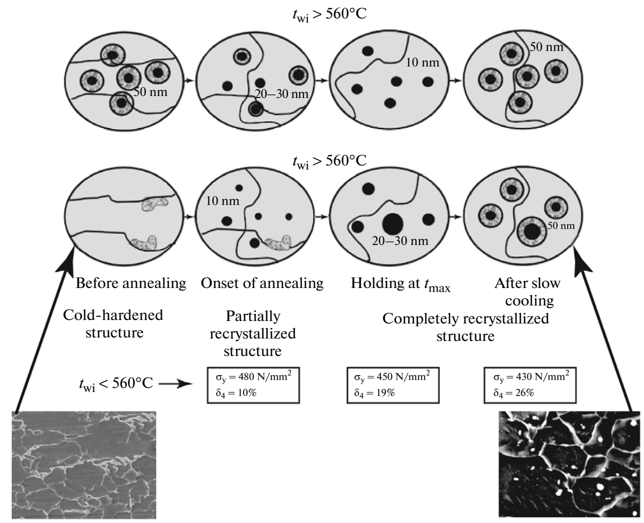

Fig. 6. Formation and transformation of Nb(C, N) nanoparticles in microalloyed high-strength steel as a function of the winding temperature: (•) Nb(C, N) particles; ( ) cementite deposits formed on cooling the coil; (◉) complex Nb(C, N) + cementite deposits.

of cold-rolled strip may only be ensured with $t_{wi} > 560°C$, since the deposition of excess phases in cold-rolled strip may be controlled even in recrystallizing annealing. In fact, with $t_{wi} > 560°C$, the plasticity declines on annealing, with similar strength, since cementite is deposited on the niobium-carbonitride nanoparticles and so complex deposits are formed (Fig. 6). Even in annealing, the cementite dissolves. That reduces the size of the complex deposits, increases the strength, and reduces the plasticity. For batches with $t_{wi} < 560°C$, particles form not on cooling of the coil but in annealing, and they grow with increase in heating and holding time, which reduces the strength and increases the plasticity. Accordingly, with faster annealing, we obtain a stable set of properties and higher plasticity (up to 26%), especially with slow cooling after annealing. That leads to the deposition of cementite on the niobium-carbonitride nanoparticles, with expansion from 10 to 30–50 nm. The presence of globular cementite deposits on the Nb(C, N) particles is confirmed electron-microscopically (Fig. 6).

The benefits of the new high-strength steel strip include stability of the strength (for specified strength class, the minimum permissible value is exceeded by no more than 30 N/mm^2, rather than ≥100 N/mm^2 in European standards) and high plasticity (for HSLA steels with $\sigma_y \geq 380$ N/mm^2, the minimum value is $\delta = 25\%$, rather than 17–19%). The results indicate that high strength and plasticity may be ensured by controlling the type, quantity, size, and morphology of the deposits of excess phase.

INTRODUCTION OF THE NEW GENERATION OF STEELS

Various production technologies for economical high-quality auto steels (more than 30) have been introduced on the basis of research at OAO MMK and OAO Severstal'. Some of the steels produced are itemized in the table. That meets the demand for such steel at Russian autoplants, including OAO AvtoVAZ and OAO KamAZ, eliminating the need for imports. The consumption of such high-quality steel is more than 2400000 t/yr at OAO AvtoVAZ and 250000 t/yr at OAO KamAZ. Since the imported steel is more expensive, that reduces the purchase costs by more than 8.5 billion ruble/yr. In addition, manufacturing costs for car bodies are reduced, because the number of welding points is reduced by 40% on account of the introduction of mass stamping, the use of high-strength steel for safety components of the body, and reduction in vehicle mass. That, in turn, reduces fuel consumption and the vehicle's environmental impact.

Efforts are underway to export the new steels to foreign auto manufacturers, such as Renault, Honda, Volkswagen, and GM. So far, orders have been

New economical high-quality steel strip for the auto industry

Product	Steel	Standard document
Cold-rolled strip:		
highly extensible low-carbon steel;	08Ю; DC04; DC05; DC06	GOST 9045–93; EN 10130
hot-galvanized ultralow-carbon steel with the BH effect	HC180BD; 006/IF-BH	EN 10292; EN 10346; TS 14-101-497–2002
ultralow-carbon steel	01ЮТ; 006/IF	TU 14-105-675–2002; TU 14-105-701–02; TU 14-101-497–2002
hot-galvanized ultralow-carbon steel	006/IF; DX56D; DX57D	TU 14-101-497–2002; EN 10346
microalloyed high-strength steel	HC300LA; HC340LA; HC380LA; HC420LA	EN 10268–06
hot-galvanized microalloyed high-strength ultralow-carbon steel	HX260LAD; HX300LAD; HX340LAD; HX380LAD; HX420LAD	EN 10346–09
Hot-rolled microalloyed high-strength steel	S500MC; S550MC; S600MC; 20ГЮТ	EN 10149-2–93; STO 00186217-015–08; STO 00186217-135–11; TU 14-101-804–2010; YU 14-101-809–2010

obtained for 24 batches from OAO MMK and 27 from OAO Severstal'.

The introduction of the new steels and their production technologies has provided a total economic benefit of more than 10.5 million rub. The total output of such steels between 2004 and 2011 was more than 3.5 million t. In addition, the production of world class steel permits Russian steel companies to compete in the global market.

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Translated by Bernard Gilbert