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Scientific and Technological Aspects of High-Grade Rolled Wire Production

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Results of investigations carried out at JSC "Moldova Steel Works" for last 25 years are presented in this paper. Scientifically-grounded technological solutions related to enhancement of qualitative parameters of rolled wire with a wide grade range were worked out. This rolled wire is featured by high workability.

Keywords: STEEL, INOCULATION, MICROALLOYING, ROLLED WIRE, WIRE, STRUCTURE, PROPERTIES

Introduction

Rolled wire for wire production from low, average and high-carbon not alloyed and alloyed steels is in demand in the world market now. Further, this wire produced without softening annealing prior to drawing is used for springs, ropes, steel wire cord, welding electrodes and coppered wire for welding of building constructions, ships hulls, large-diameter pipes and gas-oil pipelines.

The following are short results of investigations carried out at JSC "Moldova Steel Works" for last 25 years, which allowed working out scientifically-grounded technological solutions regarding increase of rolled wire quality.

Results and Discussion

Low-carbon steel rolled wire for drawing without annealing

Softening effect of boron microadditives and softening thermo-mechanical treatment were used on line Stelmor with adjustable air cooling to produce a deformable rolled wire (for drawing wire with diameter to 0.5 mm without annealing) [1, 2].

This low-carbon rolled wire production technology from continuous cast billet with cross-section 125×125 mm provides the following: electric steel inoculation by calcium and boron microalloying with the ratio B/N ≈ 0.8 + / - 0.15; application of basic linings of ladle and intermediate ladle; complete or partial protection of metal stream from secondary oxidation; temperature of hot-rolled breakdowns before wire block after water cooling in zero section not more than 950-970 °C; coiling temperature 940-970 °C; speed of rings motion on the rolling table not faster than 0.3-0.4 km/s; adjustable air cooling blocks by jet cooling blocks: 3 and 4 jet cooling blocks with engine speed 600-800 min^{-1} depending on the rolled wire diameter and with metal cooling rate not faster than 5 °C/s.

Rolled wire made of low-carbon killed steel of grades 1005, C4D and C9D (ASTM A 510M; EN 10016) successfully competes with rolled wire made of unkilled steel of similar composition in relation to ductility level. Such metal can be subjected to drawing without annealing at the rate 40 km/s from diameter 5.5 mm in the wire with diameter 0.5 mm ($\varepsilon_{\sum}$ = 99.2 %).

Regressional relationship with high statistical values (R, S_{res}, F) of adequacy to the real process was developed to forecast mechanical properties and to control low-carbon steel rolled wire production. Chemical composition (C, Mn, Si, Cr, Ni and Cu, expressed in terms of carbon equivalent – C_e = Mn/5 + Si/7 + (Cr + Ni +

Cu)/12), coiling temperature and rolled wire diameter have the most considerable effect on mechanical properties (σ_{TS}, σ_{YS}, $\delta_{5/10}$, ψ) of low-carbon rolled wire. Effect of metal cooling time and boron concentration in steel is less considerable, which can be explained by insignificant variation of these parameters in the process of low-carbon rolled wire production for drawing without annealing.

Low-carbon rolled wire cooled on Stelmor line has specific mass of oxide scale on a surface within 8-12 kg/t. Oxide scale is removed completely by mechanical and chemical methods. However, the oxide scale removed in chemical way should be dense and consist primarily from wustite; such oxide scale is formed at reduced coiling temperatures (~ 900 °C). Thicker layer of wustite oxide scale formed at 950 °C and above is required for mechanical scaling off.

Approximately 250 thousand t/year of high-quality low-carbon rolled wire with diameter 5.5 mm is produced at JSC "Moldova Steel Works" for drawing without annealing.

Rolled wire for cold die forging

Continuous cast billets of large cross-section (200-400 mm) are applied to produce rolled wire for fixing arrangements production by cold die forging method. These billets are deformed for almost complete elimination of cast structure.

The feature of rolled metal production at Moldova Steel Works is steel teeming in continuous cast billets of small section (125×125 mm). Production experience showed that steel crystallization conditions improve, inhomogeneity of chemical elements along the length of billet and shrinkage are eliminated thanks to smaller size of continuous cast billet cross-section in comparison with those usually applied. However, such continuous cast billet rolling is featured by a smaller reduction of metal, as a result there are cast structure residuals in the finished rolled products.

The basic requirement to hot-rolled metal for cold die forging is ability to be upset as cold on strain value 66 or 75 %. According to GOST 10702-78, upset samples should not have surface tears and fractures, separate scratch marks not deeper than 0.1 mm are allowed for rolled metal in diameter up to 20 mm and not deeper than 0.2 mm for rolled metal in diameter 20 mm and more.

In the international practice [3], surface quality of upset samples is evaluated by a special scale which provides five classes of defects: 0; 1; 2; 3 and 4, and for cold die forging defect class not more than 1 is allowed and weighted average value of this index (so-called *sedimentation coefficient F*) should be within 0.3-0.7 (depending on whether cold or hot upsetting will be applied).

The statistical investigations carried out for 2 years revealed that low-carbon steel 1005-1022 rolled wire with diameter 5.5-14.0 mm produced at Moldova Steel Works under current orders meets upsetting requirements for group 66 - the basic requirement to rolled metal for cold die forging in 86 % of cases.

Considering all aspects mentioned above, manufacturing practice of steel rolled wire with diameter 5.5-14.0 mm from continuous cast billet of small cross-sections (125×125 mm) was developed and implemented at Moldova Steel Works and has no analogues in the world practice.

The manufacturing technique of rolled wire for cold die forging consists in the following [4]. Steel 20Г2Р is made without microadditions of Al and Ti that traditionally deoxidate steel and bond N. B is added in amount of 0.001-0.005 % and increases hardenability of steel.

Deep steel deoxidation for cold die forging is carried out with the use of Ca, and B in amount 0.008-0.012 % enhances steel hardenability. This amount of boron is defined by expression:

$$B = N_{total} + 0.003, \qquad \text{(Eq. 1)}$$

where N_{total} - the total nitrogen concentration in steel.

Nitrogen fixation in ductile compounds BN raises deformability of rolled metal for cold die forging also due to decrease of strain aging effect [1].

High ductility of 20Г2Р steel rolled wire is caused also by application of softening thermal-mechanical treatment on line Stelmor [2] consisting in high-temperature coiling at 940-960 °C and long quasiisothermal soaking under heat-insulating covers without air supply (metal cooling rate 0.25-0.15 °C/s at speed of rolled wire coils transportation on the roller table 0.09-0.12 km/s). Following mechanical properties of rolled wire are ensured: $\sigma_{TS} \leq 580$ N/mm^2, $\psi \geq 60$ %.

Welding rolled wire made of alloyed steel

There are two techniques of welding wire production with the use of steel rolled wire [5]. The traditional method includes chemical scaling off, drawing of rolled wire with diameter 5.5-6.5 mm in a wire with diameter 5.0-0.8 (0.6) mm with application of 1 or 2 operations of softening heat treatment (recrystallization annealing) and the subsequent copperization. To enhance effect of structure recrystallizing (restoration of plastic properties), some contributors recommend application of hardening treatment (coiling temperature drop or rolling finish in two-phase (γ + α) interval of temperatures). Such flow diagram of welding wire production from alloyed steels is ineffective because cost-based and essentially pollutes environment.

The new current technique provides production of coppered welding wire of necessary diameters without softening heat treatment, which is obtained due to unique complex of rolled wire properties - ability to be strained to the final diameters 0.8 (0.6) mm and more (depending on steel grade and its purpose for further welding operations). The current technique of rolled wire drawing without annealing consists of following stages: mechanical scaling off, rolled wire dry drawing for intermediate diameter 5.15-1.70 mm (depending on steel grade), then drawing without intermediate heat treatment (or wet drawing) combined with electrochemical copperization of wire surface with diameter 1.6-0.8 (0.6) mm or dry drawing of wire with diameter 5.0-2.0 mm and copperization. So, advantages of new welding wire manufacturing technique are obvious.

Adoption of alloyed steel welding rolled wire production has been started from steel Св-08Г2С (analogue LNT/LNM 25 – Lincoln Electric (USA)) at Moldova Steel Works. At the first stage this steel was intended for welding wire production under traditional scheme, and only since 2003 - under the modern technology [7]. The rolled wire with extremely high ductility - ability to cold strain with considerable total extent ($\varepsilon_{\sum}$ to 98.8 %) is required for current welding wire manufacturing process. Considering the experience of adoption and implementation of the newest Св-08Г2С steel rolled wire manufacturing technique and positive results regarding its drawing without annealing in a coppered wire with diameter to 0.8 (0.6) mm, rolled wire production from other steel grades have been developed and introduced [5].

Implementation of modern metallurgical equipment (VD, long line Stelmor) and new technologies (steel microalloying with boron, calcium inoculation of nonmetallic inclusions, decrease of concentration of carbon, manganese, phosphorus and sulfur in steel, application of softening thermal-mechanical treatment) allowed ensuring substantial increase of technological ductility of rolled wire.

Results of laboratory research of rolled wire made of steel grades Св-08ХГ2СМФ, Св-08Г1НМА, Св-08ГНМ (GOST), etc. show that the highest indexes of ductile properties correspond to isothermal soaking in the temperature range 600-700 °C, for Св-08Г2С - 550-600 °C, during 20-30 min. These temperature-time treatment parameters promote transformation of austenitic into ferrite and perlite.

15 thousand t/year of high-quality alloyed steel rolled wire is made at Moldova Steel Works according to developed technique for coppered welding wire production by drawing without annealing.

High-carbon steel rolled wire

High-carbon (C ≈ 0.50-0.90 %) rolled wire is used for manufacture of wire for elevating and transmission ropes, springs, wiring and strands, steel wire cord.

The most critical types of high-carbon steel rolled wire is the rolled wire intended for steel wire cord manufacture and high-strength reinforcing ropes. The features of such rolled wire production are resulted below.

Rolled wire for steel wire cord

Production of high-carbon rolled wire of cord purpose at minimetallurgical complex was a difficult scientific and technical problem. It was caused by following: vacuum degassing and electromagnetic circulation of steel was not provided when making this steel and continuous casting; scrap was used as the charge; steel was teemed on light section continuous cast billets (square billet 125×125 mm).

The basic requirements to quality indexes of steel, continuous cast billets and rolled wire for steel wire cord manufacture are as follows: control of chemical element concentration - C, Mn, Si, Cr, Ni, Cu; decrease of detrimental impurity concentration - P, S, As, Zn, Pb, Sn, etc.; improvement of steel purity in relation to nonmetallic inclusions; rationing of nonmetallic inclusions with complicated chemical composition and low amount of Al_2O_3; production of continuous cast billets with satisfactory surface quality, minimum liquation, porosity, without impurities; homogeneous structure and mechanical properties of rolled wire along the length of wire coil; obtaining sorbitic pearlite in the structure in amount > 50 % at minimum quantity of structurally-free ferrite or cementite;

absence of hardening structures.

Chemical composition of steel

Steelmaking practice and out-of-furnace treatment of steel at Moldova Steel Works ensures precise chemical composition of cord steel of grades 70КРД, 80КРД, 85КРД with insignificant variation of mass fractions of elements: Δ C = 0-0.01 %; Δ Mn = 0-0.03 %; Δ Si = 0-0.03 %; spread in values between smelting operations is: Δ C = 0-0.04 %; Δ Mn = 0-0.05 %; Δ Si = 0-0.05 %. Concentration of phosphorous and sulfur are not more than 0.015 and 0.006 %, which is rather good index. When steelmaking from selected scrap with pig-iron addition to 30 % or other raw materials, residual concentration of nonferrous impurities reaches high values. Application of "pure" raw materials (metalized pellets) for rolled wire production for steel wire cord is rather expensive. So, in view of our investigations [6] it is possible to state that such composition as Cr ≤ 0.15 %; Ni ≤ 0.15 %; Cu ≤ 0.25 % does not have a negative effect on rolled wire properties for steel wire cord.

Currently, mass fractions of chromium, nickel and cuprum ≤ 0.06, ≤ 0.10 and ≤ 0.15 % respectively are possible to provide at Moldova Steel Works. As total content of chromium, nickel and cuprum in the range of values 0.15-0.45 % increase, plastic properties of wire enhance (ψ ≈ 30-36 % at first tests).

Boron microaddition fixing nitrogen in nitrides and carbonitrides diminishes degree of development of strain aging processes when drawing rolled wire. Plasticization effects of boron are revealed the most at the ratio B/N = 0.20-0.25 in cord steel.

Steel degassing ensures its deep degasification (hydrogen content before degassing is 2-6, after – 0.3-1.5 ppm and nitrogen content is 0.010-0.012 and 0.005-0.007 % respectively). Steel degassing also stipulates additional ductility of rolled wire.

Amount of detrimental impurities in steel is as follows: P ≤ 0.010; S ≤ 0.005; As ≤ 0.01; Zn ≤ 0.001; Pb ≤ 0.01; Sn ≤ 0.01 %. This additionally raises ductile properties of rolled wire and its deformability in cold condition.

Nonmetallic inclusions

Nonmetallic inclusions in the metal matrix usually have various deformability in the initial state. As a consequence, there are microcavities - metal discontinuities on the boundary of not deformed nonmetallic inclusions. It is possible to estimate deformability of nonmetallic inclusion by deformability index ν defined by a ratio of amount of reduction of nonmetallic inclusion and metal matrix. The smaller this index values, the less ductile nonmetallic inclusions and the more probable metal fracture in the course of deformation. And vice versa, the more this index, the more ductile nonmetallic inclusion. The most dangerous in this sense nonmetallic inclusions ($\nu = 0$) - aluminates and alumicalcinates with high melting temperature. Manganese sulfides ($\nu = 1$) are the most ductile with melting temperature not higher than 1400 °C. In the latter case, manganese sulfides are well strained in the course of rolled wire hot rolling, forming fine inclusion lines which also are well strained at the subsequent cold drawing [7].

Steel inoculation by calcium by means of addition of calcium-containing wire (SiCa, FeCa - flux cored wire) is effectively used at Moldova Steel Works. At the ratio Ca/a_o = 0.60-1.20 (a_o - density of active oxygen), nondeformable aluminates ($MgO \cdot Al_2O_3$, $SaO \cdot Al_2O_3$) can transform into ductile compound with reduced melting temperature - $12CaO \cdot 7Al_2O_3$ that easily become a slag. At other ratios Ca/a_o there are solid high-melting aluminates. Use of magnesium steel-teeming ladles also promotes decrease of steel impurity with nonmetallic inclusions.

Macro - and microstructure of rolled wire

Steel casting methods with maximum development of equiaxed grain at reduction of columnar crystal zone are the most effective for quality macrostructure formation, minimization of liquation phenomena in continuous cast billet and rolled wire.

Results of investigations revealed the following:

- There are liquation areas because of dendritic segregation in continuous cast billets, electromagnetic circulation increases amount of crystallization centers and promotes crystallization acceleration; zone of equiaxial crystals enlarges approximately in 1.7 times as a result of electromagnetic circulation, and central liquation and porosity are spread out;
- Liquation on macro- and microlevel stipulates formation of martensite areas from 5 to 200 microns long in the central parts of high-carbon rolled wire.

Optimization of crystallization process, conditions of electromagnetic circulation, degree of superheat over liquidus temperature allow eliminating the formation of hardening structures. Despite their harmful effect, many known companies, for example Bekaert allow their limited presence even in the rolled wire of cord purpose: martensite up to 20 microns long is in the center of rolled wire cross-section. In this connection, a special document regulating the presence of martensite areas 20 microns long in the structure of rolled wire for steel wire cord was developed at Moldova Steel Works.

Interrelation between perlite amount and coiling temperature was established during investigations. According to this interrelation, there are two coiling temperature intervals in which interlamellar spacing in perlite is minimum: the first interval 950-1000 °C, the second is less than 700 °C. Almost 100 % fine perlite of 1 point (interlamellar spacing < 0.2 microns) is formed in these cases. However, there is inadmissible posthardening structure - secondary sorbite in the surface layers of rolled wire at metal temperatures below 700 °C. At high temperatures (950-1000 °C) there is another drawback - average amount of secondary oxide scale increases to 6-8 kg/t against 2-4 kg/t at coiling temperature 800-850 °C, however, in the latter case the amount of fine perlite decreased by 30-40 %.

Oxide scale formed at 950-1000 °C consists primarily from wustite, further they together with rolled wire coils are subjected to cooling by fan air in the temperature range 570-400 °C. Wustite does not transform into magnetite, this oxide scale can be easily removed before drawing in both chemical and mechanical ways.

Decarbonization and rolled wire surface quality

Positive effect of rolled wire surface decarbonization on its consumer properties is mentioned in [8]. Soft decarbonized surface ensures enhanced ductility of metal because of low stress concentrator sensitivity and high resistance to fractures.

Residual compression stresses in the surface decarburized layer lead to enhancement of endurance strength and corrosion resistance. It is necessary to ensure uniform depth of decarbonization of rolled wire on perimeter.

The comparative investigation [9] about distribution of decarburized layer on high-carbon rolled wire perimeter at various metallurgical plants showed that uniform decarburized layer as an advantage of such rolled wire is ensured at Moldova Steel Works.

High-carbon rolled wire production at Moldova Steel Works ensures low presence of defects in the surface: defect depth does not exceed 0.15 mm, and it is not more than 0.10 mm in 95 % of cases.

High-carbon rolled wire for production of high-strength guy wire and reinforcing ropes

Moldova Steel Works adopted production of high-carbon vanadium and chromium microalloyed rolled wire made of steel C82D according to EN 10016 and technical requirements. This rolled metal type is intended for manufacture of high-strength wire and wirework for reinforced-concrete constructions.

Unlike the traditional way of reinforcing rope production in CIS countries, the new way does not include patenting of rolled wire with the purpose of structure sorbitizing and increase of both strength and ductile properties of rolled wire.

It is difficult to control high strength of initial rolled wire - not less than 1150, 1200 and 1250 N/mm^2, which is caused by high strength of reinforcing ropes - not less than 1770, 1860, 2000 N/mm^2 and more.

The problem of specified structural condition and ultimate strength in the initial rolled wire is solved by steel alloying and intensive cooling on line Stelmor.

The maximum cooling rate on line Stelmor is not more than 10-12 °C/s instead of required 20-25 °C/s. So required structure and strength level of rolled wire can be achieved only when additional alloying with vanadium and/or chromium.

The mechanism of steel hardening by vanadium consists in that carbides and vanadium nitrides in the ferrite matrix of perlite in the form of dispersed particles breake dislocation motion and harden metal due to the so-called *dispersion hardening*.

Dendritic liquation in metal microvolumes is featured for vanadium and chromium. Dendritic liquation is not completely eliminated during rolling, as a result there are banded orientation, carbide inhomogeneity and martensite areas in the rolled wire microstructure. X-ray spectrum analysis of martensite area and perlite matrix showed that martensite formation is caused by liquation of Mn, Cr and V, in addition their liquation factors are in the following ranges: Cr – k_l = 2.62-3.46, Mn – k_l = 1.79-2.08, V – k_l = 3.0-7.5.

Conclusions

Scientifically-grounded technologies of high-ductile rolled wire production from steels of wide grade range and purpose were developed and implemented at Moldova Steel Works. The combination of new steelmaking methods (calcium inoculation and boron microalloying, protection of metal from secondary oxidation, degassing), rolling and thermal-mechanical treatment allowed rolled wire drawing without annealing.

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Научные и технологические аспекты производства высококачественной катанки

Парусов В.В., Парусов О.В., Чуйко И.Н., Сычков А.Б.

В статье приводятся краткие результаты исследований, проведенных в условиях ОАО «Молдавский металлургический завод» за последние 25 лет и позволивших разработать научно обоснованные технологические решения по повышению качественных характеристик катанки широкого марочного сортамента, которая обладает высокой технологичностью при переработке на метизном переделе.