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STRUCTURE AND PROPERTIES OF REINFORCING ROLLED COILS BY V-ALLOYED DUAL-AND MULTI-PHASE C-MN-SI-STEEL

Summary. The aim of the work was to study the influence of vanadium doping on two- and multi-phase steels. The schemes of thermomechanically controlled rolling on the wire line of the sectional rolling mill 400/200 for the production of reinforcing wire with a diameter of 6.0 mm in rolls were studied. For the production of reinforcing wire, vanadium alloyed C – Mn – Si steels, which have two-phase (DP – ferritic-martensitic (bainite)) and multi-phase (MP – ferritic-martensitic (bainite) - pearlitic) microstructures, were used. During thermomechanical controlled rolling, TMCR charts were used, including TLH stacking head temperatures of 1024°C to 1063°C. It was established that the applied rolling modes ensure the formation of the MP microstructure. In this 6.0 mm wire, high tensile strength and ductility indicators were achieved in the bends ($YS_{0.2}$ = 530-550 MPa; TS = 785-885 MPa; El_5 = 15.0 - 29.0 %), which fully corresponded specification requirements of national standards such as ASTM A 615 (USA), JIS G 3112 (Japan) and KSD 3504 (Republic of Korea).

Keywords: thermomechanical controlled rolling, wire line, reinforcing wire in bays, V-microalloyed C-Mn-Si-steel, microstructure.

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Introduction. Thanks to a unique combination of tensile strength and placticity properties, high strength low-alloyed dual- and multi - phase (DP – and MP, respectively) steels are usefully applied in the automotive industry for weight reduction of cold-formed components, in the heading industry, in the gas and oil industry for manufacture of transmission pipelines, including those laid in seismic and permafrost regions [1-5]. Recently, high strength reinforcing steel wires with DP - and MP microstructures have found wide application in the construction industry. Principally, to obtain DP - and MP microstructures in low-alloyed steel rolled products two methods are applied: heat treatment and thermo-mechanical controlled rolling (TMCR) (figure 1) [1].

The heat treatment method (figure 1, left-hand side) involves heating of steel to 1063 K (790°C), a dual-phase (α + γ) temperature range (intercritical temperature range (ICTR)), annealing at that temperature for a certain time, quenching in water for obtaining martensite islands in the structure, and tempering at 913 K (normally, 500-550°C) to relief stresses and to reduce aging effects. There are numerous versions of the above described heat treatment method that are applied in continuous annealing furnaces for commercial production of cold rolled plates from low-alloyed DP - and MP steels. A TMCR method involving controlled cooling of hot - rolled steel products is shown in figure 1 (on the right). A schematic overlay of the lines of austenite phase transformation in low-alloyed steels (continuous-cooling transformation diagram, CCT-diagram) in the controlled cooling temperature range shows, that martensite/pearlite islands in the structure of low carbon steel to an extent of 15-20%, which ensure the highest tensile strength and hardness (HB = 371, figure 1), are formed from microareas of austenite (γ -phase) left untransformed in this steel at 873 K (600 °C) (after the completion of γ→α - transformation) as a result of quenching in water. Development of TMCR method for commercial production of high strength and high-technology types of hot rolled plates, bars and wire rods from low-alloyed DP - and MP steels has been the subject of numerous investigations, but mainly on the laboratory level.

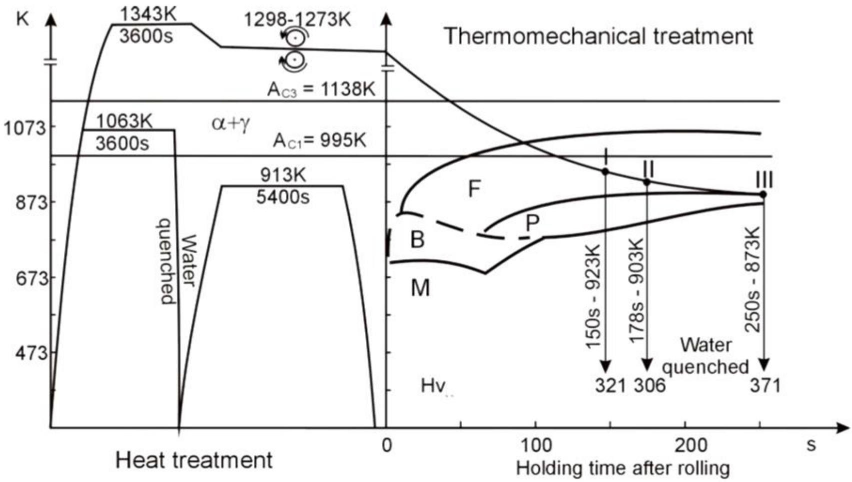

Figure 1 – Schematic diagram of heat treatment and TMCR schedules that are applied for obtaining DP - and MP structures in low-alloyed steel rolled products [1].

A comprehensive study of prospects for the application of 5.5-mm-diameter low - carbon wire rod (0.08 C; 0.77 Mn; 0.21 Si; 0.017 P; 0.012 S, in % by weight) with DP microstructure in the construction industry is so interest [6]. ADP microstructures in the laboratory samples of wire rod under study were obtained by a heat treatment process, that involved annealing them at ICTR (795, 810, 820 and 840 °C) for 15 minutes and quenching in water. Micro-structural characteristics, hardness and mechanical properties of the these samples were analyzed and compared with similar parameters of ATR 500N cold deformed reinforcement wire manufactured in accordance with IRAM-IAS U500 526, Argentina (table 1).

The experimental data allowed the authors of work to conclude, that values of strength properties [6], $TS/YS_{0.2}$ - ratio, ultimate elongation El^, Vickers hardness (HV) were close to these obtainable in commercial ATR 500N cold deformed reinforcement wire, could be observed in a obtained wire with a high volume (50%) fraction of martensite after Extension Underload of 2 % (table 1, DP 820 (2 % EUL)). They state, that the obtained materials had a greater capacity of energy absorption and likewise a higher strength exponent, than traditional commercial products (ATR 500N), thus offering a promising potential for their use in construction in seismic zones.

Table 1 – Micro-structural characteristics, hardness and mechanical properties of 5.5-mm-diameter low - carbon wire rod [6].

Sample	Volume fraction of martensite, %	Hardness, HB	$YS_{0.2}$, MPa	TS, MPa	TS / $YS_{0.2}$	El_{10}, %
Hot-rolled wire rod, 5.5 mm	–	139±5	304	426	1.40	32.7
DP* 795	25±5	184±1	333	656	1.97	14.9
DP 810	40±5	226±1	337	675	2.00	13.5
DP 820	50±5	252±8	356	693	1.95	12.5
DP 840	65±5	268±2	407	698	1.72	10.5
DP 810 (2 % EUL.)***	40±5	227±2	588	689	1.17	12.7
DP 820 (2 % EUL.)	50±5	261±4	633	698	1.19	9.5
ATR 500N	–	240±4	670	708	1.06	7.8
Standard requirements of IRAM-IAS U500 526, Argentina	–	–	500**	550**	1.03**	6.0**

* DP – steel wire rod, the digital designations – the temperatures of samples' holding at the ICTR.
** Minimum value.
*** 2% EUL (Extension Underload of 2%) was applied to simulate cold-deformation induced stresses in steel by the ribbing of the wire's surface.

Hot - rolled reinforcing wire in coils can vary in chemical composition and mechanical properties. It, for instance, was shown by the basic standard specifications ASTM A615/A615M (USA), JIS G 3112 (Japan) and KSD 3504 (the Republic of Korea) (table 2 - 5).

According to ASTM A 615/A615M (USA), hot - rolled reinforcing wires in coils Gr. 40 ($YS_{0.2}$ > 300 N/mm^2) and Gr. 60 ($YS_{0.2}$ > 420 N/mm^2) are manufactured from semi-killed carbon steel (table 2) and low-alloyed carbon steel (table 3) respectively.

According to Japanese and Korean national standards, hot - rolled reinforcing wires in coils of different strength classes are manufactured from the same grade of low-alloyed steel (tables 4, 5).

However, they require calculating the carbon equivalent, Ceq (tables 4, 5), which is derived from the following equation:

$$C_{eq} = C + \frac{Mn}{6} \qquad (1)$$

Table 2 – Chemical composition as per ASTM A 615, JIS G 3112, KSD 3504.

Country, standard specification	Class of reinforcing steel	$YS_{0.2}$, MPa	TS, MPa	El, %
USA, ASTM A615/A615M	Gr.40(300) Gr.60(420)	≥ 300 ≥ 420	≥ 420 ≥ 620	$El_{200} \geq 11$ $El_{200} \geq 9$
Japan, JIS G 3112	SD 40 SD 50	390-510 490-625	≥ 560 ≥ 620	$El_5 \geq 16$ $El_5 \geq 12$
The Republic of Korea, KSD 3504	SD 40 SD 50	392-510 490-528	≥ 559 ≥ 618	$El_5 \geq 16$ $El_5 \geq 12$

Table 3 – Chemical composition as per ASTM A 615 (USA).

Class of rolled product	Elements in % by wt. (less than or equal to)				
	C	Mn	Si	S	P
Gr 40	0.28-0.38	0.50-0.80	0.10	0.050	0.040
Gr 60	0.32-0.38	0.80-1.20	0.60-0.90	0.045	0.040

Table 4 – Chemical composition as per JIS G 3112 (Japan).

Class of rolled product	Elements in % by wt. (less than)					Ceq, % (less than)
	C	Si	Mn	P	S	
SD390	0.29	0.55	1.80	0.040	0.040	0.55
SD490	0.32	0.55	1.80	0.040	0.040	0.60

Table 5 – Chemical composition as per KSD 3504 (the Republic of Korea).

Class of rolled product	Elements in % by wt. (less than)							Ceq, % (less than)
	C	Si	Mn	S	Cr	Ni	Cu	
SD40	0.29	0.55	1.80	0.050	0.15	0.15	0.30	0.55
SD50	0.29	0.55	1.80	0.050	0.15	0.15	0.30	0.60

Today, Mesh and Welded Wire Concrete Reinforcement (WWR) technology, which has been intensively developing (Wire Enforcement Institute (WRI), 2014), is using considerable quantities (up to 50% of the total consumption of reinforcing steels) of the reinforcing wires in diameters up to 12 mm in coils. Reinforcing wires in coils has the merit of being suitable to automatic machine welding of meshes, fabrics, embedded light reinforcing materials, generating no or low waste such as short ends, as distinct from reinforcing steel in cut lengths, which can generate minimum 5-7% of this type of waste. There is a high demand for reinforcing wires in coils in the construction industry (up to 90% of the total demand for reinforcing steels in diameters up to 12 mm). It is thus important to study structural and mechanical characteristics of reinforcing wires in coils made from low-alloyed DP - and MP steels subjected to treatment by TMCR on the wire line of a section rolling mill.

Materials and Research Techniques. Considering the increasing demand for reinforcing wire in coils with higher tensile strength properties ($YS_{0.2}$ > 400 MPa) [6, 7], C - Mn - C – steel micro-alloyed by V was used as a test steel in plant experiments carried out on the wire line of a 400/200 section rolling mill with the aim to develop production methods for these rolled products, with a referenced low - carbon steel micro-alloyed by B. Chemical compositions of the steels are listed in table 6. The layout of the wire block with a STELMOR line (400/200 rolling mill) is shown in figure 2.

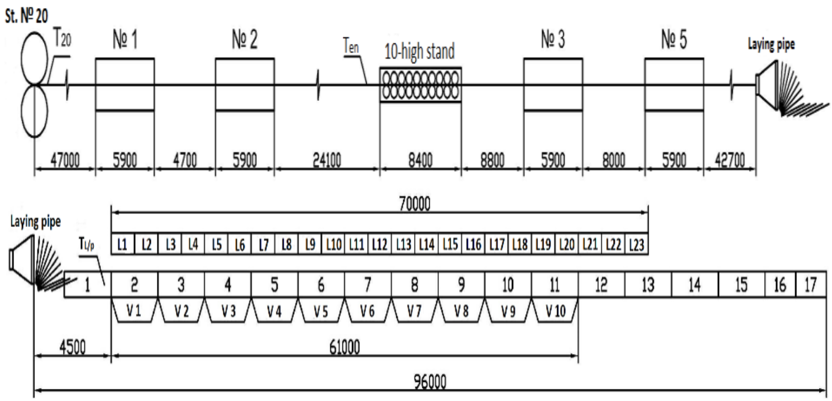

Figure 2 – Schematic diagram of a 400/200 rolling mill with a STELMOR line: T_{20} – the last stand (stand № 20); No. 1-5 – water cooling boxes; T_{en} – 10-stand finishing block; laying pipe (laying head); L_1-L_{23} – thermos-insulated covers; 1-17 – sections of the wire rod conveyor; V_1-V_{10} - blowers.

Table 6 – Chemical composition of the steels under study.

Steel grade	Chemical composition in % by wt.								
	C	Mn	Si	S	P	Cr	Ni	V	B
Micro-alloyed by V C - Mn - Si - steel	0.17	1.25	0.75	0.002	0.016	0.02	0.02	0.112	–
Referenced micro-alloyed by B low - carbon steel	0.21	1.02	0.27	0.002	0.016	0.04	0.02	0.001	0.006

The choice of V as a micro-alloying element of low - alloyed C - Mn -Si – steel was based on its high ability to form carbides and nitrides in these steels in the austenite transformation region during cooling through a wide range of temperatures (AT - from 1060-1080 °C to 400°C) at medium cooling rates [8]. Therewith, mechanisms of ferrite precipitation strengthening are known to take action contributing higher tensile strength properties to the steel [8]. The referenced low- carbon steel was micro-alloyed by B in order to raising its plasticity. The plasticizing effect of B in low - carbon and low-alloyed steels was clearly described in the studies [9-12].

The billets employed in the experiments were 410 x 500 mm in cross section, created via continuous casting and subsequently re-rolled into 150 sq. mm billets for further rolling on a 400/200 section rolling mill.

The re-rolled 150 sq. mm billets from the steel under study were heated in a continuous furnace of the rolling mill at 1160-1165 °C (Zone 5), 1145-1150 °C (Zone 6), 1110-1130 °C (Zone 7). The average temperature of the semi-rolled product after Stand 20 (figure 2) was 1090 °C.

To implement TMCR method (figure 1, right-hand side) in order to manufacture 6.0 - mm-diameter reinforcing wire in coils by V-alloyed C - Mn - Si – steel with DP - and MP microstructures and a required combination of tensile strength and plasticity properties, rib geometry, a series of industrial experiments were conducted at different laying head temperatures (T_{LH}) (figure 2).

Optical microscopy and scanning electron microscopy (SEM) methods were used by studying structures of reinforcement wires.

Results and Discussions. The micro-structural analysis has shown that MP - (ferrite-pearlite-martensite(bainite)) structures formed in 6.0 - mm-diameter profiled reinforcing wire from V-alloyed C - Mn - Si - steel at higher temperatures TLH under the conditions of rolling schedules 3 and 5, while DP - (ferrite - martensite (bainite)) structures - at lower temperature TLH under the conditions of rolling schedule 10 (figure 3, table 7).

Also, wires treated under the conditions of TMCR schedules 3, 5 and 10 exhibited a high quality of the rib geometry, as it appeared in figure 4.

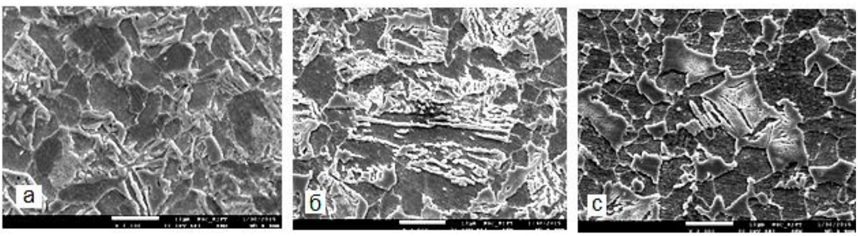

Figure 3 – SEM micrographs of 6.0-mm-diameter profiled reinforcing wire from V-alloyed C - Mn - Si - steel: a, b, c – the microstructures obtained under the conditions of TMCR schedules 3, 5 and 10 respectively.

The specific heat of iron (steel) is p = 4.6 x 10^2 J/kg K [13]. It means that the amount of heat to be removed to lower the temperature of 1 kg of steel by 1°C is

4.6 x 10^2 J. In the experiments, the heat was removed from the rings of reinforcing wires on the Stelmor conveyor by the streams of air from blowers below the rings with opened insulated covers (figure 2, table 7). These operating conditions remained unchanged for all TMCR schedules.

Figure 4 – Samples of 6-mm-diameter V-alloyed C - Mn - Si – steel reinforcing wires manufactured under the conditions of TMCR schedules 3, 5 and 10.

Table 7. Most favorable TMCR schedules* and obtained mechanical properties.

Steel grade	Schedule № (Sample №)	Water flow rate at water box No.3, m^3/h	T_{LH}, °C	$YS_{0.2}$, MPa	TS, MPa	El_5, %	Bending
Micro-alloyed by V C-Mn-Si - steel	3	53	1024	540	885	15.0	Pass
				530	810	26.0	Pass
	5	0 (air cooling)	1063	550	805	21.5	Pass
				550	785	29.0	Pass
	10	98	921	495	800	7.0	Pass
				490	775	11.0	Pass
Referenced micro-alloyed by B low - carbon steel	3.1	98	920	410	565	31.0	Pass

* Note: All rolling schedules were carried out under the same operating conditions: the blowers 1-5, 7-10 were switched on and all thermo-insulated covers of the Stelmor line were opened.

Since the operating conditions of the conveyor were the same for all experiments TMCR schedule 5 with Tlh = 1063°C required more time to get wire's rings cooled down to austenite transformation temperatures compared with those TMCR schedules, which had lower Tlh (table 7). The analysis of austenite CCT-diagram in C-Mn-Si-steel (figure 5), which has a similar chemical composition with C-Mn-Si-steel under study, indicated that the steel structure (figure 3 b, table 8) obtained under the conditions of TMCR schedule 5 at T_{LH} = 1063°C had been formed via austenite phase transformations that were similar to those observed along cooling curve 5.

The microstructure of reinforcing steel obtained under the conditions of TMCR schedule 3 at T_{LH} = 1024 °C (figure 3 a, table 8) indicates that austenite transformations occurred along cooling curve 3 as shown in the CCT-diagram in figure 5. The DP (ferrite-martensite (bainite)) - microstructure in the reinforcing steel under study which was formed under the conditions of TMCR schedule 10 (figure 3 c, volume fraction of martensite (bainite) - 21.10 %, table 8) is typical of the pearlite-free area range of cooling rates on the CCT-diagram (cooling curve 10, figure 5).

In 6.0 - mm-diameter reinforcing wires in coils from the referenced micro-alloyed by B low - carbon steel after treatment under the conditions of TMCR schedule 3.1, which parameters were similar to those of schedule 10 (table 7), Widmanstatten structure formed with well-defined needle-type ferrite and isolated dark areas of fine pearlite (figure 6). Generally, the volume fraction of free ferrite (FF with ferrite grain size d_{fg} = 0.00510 mm - № 12 as per ASTM E112, table 8) in the steel structure was comparable with the fraction of needle-type ferrite, which were V_{FF} = 41.43 and V_{NT} = 46.17 % respectively. The volume fraction of isolated pearlite areas was small (V_{IPA} = 12.40 %), which together with a considerable share of soft ferrite fractions (V_{FF} + V_{NT} = 87.6 %) determined a generally low level of tensile strength properties in 6.0 - mm-diameter reinforcing wire from the referenced steel (table 7).

The analysis of ferrite structures in the reinforcing steel under study indicated, that fine d_{fg} № 12 as per ASTM E112 (table 8) was formed in this steel under the controlled cooling conditions by T_{LH} = 920 °C - 1063 °C. It is beneficial for obtaining high tensile strength values in V-micro-alloyed C - Mn – Si - steel reinforcing wire in diameter 6.0 mm. For this wire the most favorable ratio of strengthening fractions (martensite (bainite) and pearlite – figure 3 b, table 8) in its structure and the combination of tensile strength and plasticity properties (table 7) can be obtained under the conditions of TMCR schedule 5 at T_{LH} = 1063 °C.

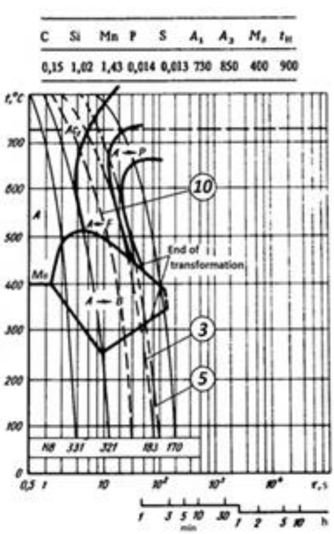

Figure 5 – CCT-diagram of austenite transformations in C - Mn -Si – steel [14, 15]. Cooling curves of TMCR schedules 3, 5 and 10 (table 7) are shown as dashed lines.

Table 8 – Volume fraction of structures and ferrite grain sizes in V-micro-alloyed C - Mn - Si - steel reinforcing wire in diameter 6.0 mm.

TMCR schedules (T_{LH},°C)	Volume fraction, %		Ferrite grain size, d_{fg}	
	Martensite (bainite)	Pearlite	mm	Number as per ASTM E112
3(1024)	20.95	4.66	0.00465	12
5(1063)	15.02	10.44	0.00423	12
10 (921)	21.10	–	0.00443	12

Figure 6 – Microstructure of the core area in 6.0 - mm-diameter reinforcing wire of referenced micro-alloyed by B low - carbon steel; TMCR schedule 3.1 with T_{LH} = 920°C; magnification 800X.

Under the conditions of this schedule and even schedule 3, despite a higher fraction volume of martensite (20.95 % - table 8, figure 3 a), the tensile strength and the plasticity of 6.0 - mm-diameter reinforcing wire in coils by V-alloyed C – Mn – Si - steel are superior to the values specified in national standard specifications adopted in the USA, Japan and the Republic of Korea for high tensile strength rolled products (table 2). Apparently, the high tensile strength of reinforcing wire from this steel is ensured by the additive contribution of grain boundary strengthening, phase strengthening due to the formation of martensite-bainite and pearlite areas, and strengthening of ferrite by vanadium carbon-nitride precipitations.

Tensile strength and plasticity properties of 6.0 - mm - diameter reinforcing wire in coils of the referenced micro - alloyed by B low - carbon steel (table 7) meet the requirements of national standard specifications adopted in the USA, Japan and the Republic of Korea for low strength rolled products: Gr. 40 and SD40 respectively (table 2).

Conclusions

Thermo-mechanical controlled rolling (TMCR) schedules have been determined for the wire line of 400/200 section rolling mill, that ensure manufacture of 6.0-mm-diameter hot - rolled reinforcing wire in coils from V-alloyed C - Mn - Si - steel with dual-phase (DP - ferrite-martensite (bainite)) and multi-phase (MP - ferrite-martensite (bainite) - pearlite) microstructures.

It has been established that high strength and plasticity characteristics ($YS_{0.2}$= 530-550 MPa; TS = 785-885 MPa; El_5 = 15.0 - 29.0 %) were achieved in reinforcing wire of 6.0-mm diameter in coils from the steel under study, which were in full compliance with the requirements of national standard specifications adopted in the USA, Japan and the Republic of Korea (ASTM A 615, JIS G 3112 and KSD 3504 respectively) for high tensile strength reinforcing wire, when the TMCR schedules involving laying head temperatures T_{LH} from 1024°C to 1063°C were applied ensuring formation of a MP - microstructure.

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БУДОВА ТА ВЛАСТИВОСТІ АРМІРУВАННЯ РУЛОНІВ V-ЛЕГОВАНОЮ ДВО-ТА БАГАТОФАЗНОЮ C-MN-SI-СТАЛЮ

Анотація. Метою роботи було дослідження впливу легування ванадієм дво- та багатофазних сталей. Досліджували схеми термомеханічної керованої прокатки на дротяній лінії секційного прокатного стану 400/200 для виробництва арматурного дроту діаметром 6,0 мм у рулонах. Для виробництва арматурного дроту застосували леговану ванадієм C – Mn – Si – сталі, які мають двофазну (DP – феритно-мартенситна (бейніт)) і багатофазну (MP – феритно-мартенситна (бейніт) - перлітна) мікроструктури). Під час термомеханічної керованої прокатки використовувалися графіки TMCR, що включають температури головки укладання TLH від 1024°C до 1063°C. Встановлено, що застосовані режими прокатки забезпечують формування мікроструктури МП. В даному 6,0 мм дроті в бухтах були досягнуті високі показники міцності на розрив і пластичності ($YS_{0.2}$= 530-550 МПа; TS = 785-885 МПа; El_5 = 15,0 - 29,0 %), які повністю відповідали вимогам специфікації національних стандартів, таким як ASTM A 615 (США), JIS G 3112 (Японія) і KSD 3504 (Республіка Корея).

Ключові слова: термомеханічна керована прокатка, дротова лінія, арматурний дріт у бухтах, V-мікролегована C-Mn-Si-сталь, мікроструктура.

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