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Study of Two-Stage Cooling Regime of Boron- and Vanadium-Microalloyed C80D2 Steel Rolled Wire

V. V. Parusov[1], E. V. Parusov[1], L. V. Sagura[1], A. I. Sivak[1], A. P. Klimenko[2], A. B. Sychkov[3]

[1] Z.I. Nekrasov Iron & Steel Institute of National Academy of Sciences of Ukraine
1 Academician Starodubov Square, Dnipropetrovsk 49050, Ukraine
[2] Ukrainian State University of Chemical Technology
8 Gagarin Ave., Dnepropetrovsk, 49005, Ukraine
[3] JSC "Mechel"

Austenite continuous cooling transformation diagram for electric steel C80D2 microalloyed with boron and vanadium is constructed. The effect of cooling rate and heat of phase transformations on perlite dispersability is shown. Theoretically substantiated regime of C80D2 steel rolled wire cooling on Stelmor line is developed.

Keywords: KINETICS OF AUSTENITE TRANSFORMATIONS, STRUCTURE FORMATION, HIGH-CARBON STEEL, MICROALLOYING, BORON, VANADIUM, ROLLED WIRE, COOLING MODE

Introduction

High-carbon steel stabilized reinforcing ropes are the base of current effective construction technologies of precast concrete production with preliminary and subsequent tendon jacking.

The task of present research is to study the kinetics of austenite transformations and determine the basic regularities of structure formation in steel of type C80D2 (EN 10016) microalloyed with vanadium and boron at continuous cooling with various speeds. The knowledge of structure formation regularities can help develop scientifically-grounded technological solutions concerning two-phase cooling of rolled wire meant for reinforcing rope production.

Methodology

The research object is electric steel C80D2 microalloyed with vanadium and boron of the following chemical composition, %: C 0.87; Mn 0.64; Si 0.20; V 0.083; P 0.012; S 0.005; Mo 0.007; Cr 0.05; Ni 0.08; Cu 0.17; Ca 0.001; N 0.004; B 0.0025.

The kinetics of steel C80D2 austenite decomposition is studied on the laboratory-scale plant which includes furnaces for sample heating and soaking at austenitization temperature, baths with molten salts or metals, air cooling means, operating console and self-registering instruments.

Phase transformation processes are researched by differential-thermal analysis method with the application of chromium-nickel-alumel thermocouples with electrode diameter of 0.3 mm [1].

Self-recording unit КСП-4-011 recorded the cooling curves, and xy-recorder ПДП-002recorded differential curves according to which we defined the temperature intervals of austenite transformations. We used 8-channel conversion unit of analogue data ADAM 4019P with computer registration of measurement results. Initial information is processed and diagrams are constructed using "Exel".

The microstructure of samples is examined by optical microscopy method. We used microscopes Neophot-2 and Neophot-32 with add-on device for digital image registration at amplification 500, 800 and 1000 units.

Microstructure is examined according to GOST 8233-56 "Steel. Microstructure standards".

The critical point Ac_1 of examined steel is defined as a mean value of three measurements 730 °C. The critical point of vanadium carbide dissolution start (K) is 835 °C. The constructed continuous cooling trasformation diagram of austenite in steel C80D2 is presented in **Figure 1**. Austenitization temperature of examined samples is 950 °C and corresponded to temperature of rolled wire breakdown on Stelmor line (after water-cooling of hot-deformed metal at 1050-1100 °C).

At cooling rates 12.3^0C/s and lower the supercooled austenite is decomposed on perlite under diffusive mechanism with various degree of dispersion.

At the minimum investigated cooling rate 0.07 °C/s the formation of perlite structure starts at 683 °C and is completed at 680 °C. Steel microstructure after cooling at 0.07 °C/s consists of 1 point perlite 88 % (sorbitic pearlite) and 5-6 points pearlite 12 % (small - and average-lamellar perlite) according to standard scale of GOST 8233-56 (**Figure 2a**).

Increase of cooling rate to 0.14 °C/s leads to insignificant spreading of temperature interval of supercooled austenite transformation in perlite. The transformation starts at temperature 680 °C. Thus, the transformation takes place almost under isothermal conditions and is completed at 673 °C due to phase transformation heat (afterglow heat). The microstructure consists of 1 point perlite 89-90 % and 5-6 points perlite10-11 %.

At increase of cooling rate to 1.5 °C/s the supercooled austenite starts decomposing at 630 °C. The ratio of cooling rates and phase transformation heat evolution elevates the temperature of transformation end to 640 °C which is by 10 °C more than the temperature of transformation start (630 °C). The microstructure consists of sorbitic pearlite 94-95 % and 5-6 points perlite 5-6 %.

The greatest temperature raise of austenite decomposition end over its start temperature is observed at cooling rate 2.6 °C/s: decomposition starts at 620 °C and is finished at 633 °C. The microstructure consists of sorbitic pearlite 92-93 % and 5-6 points perlite 7-8 %.

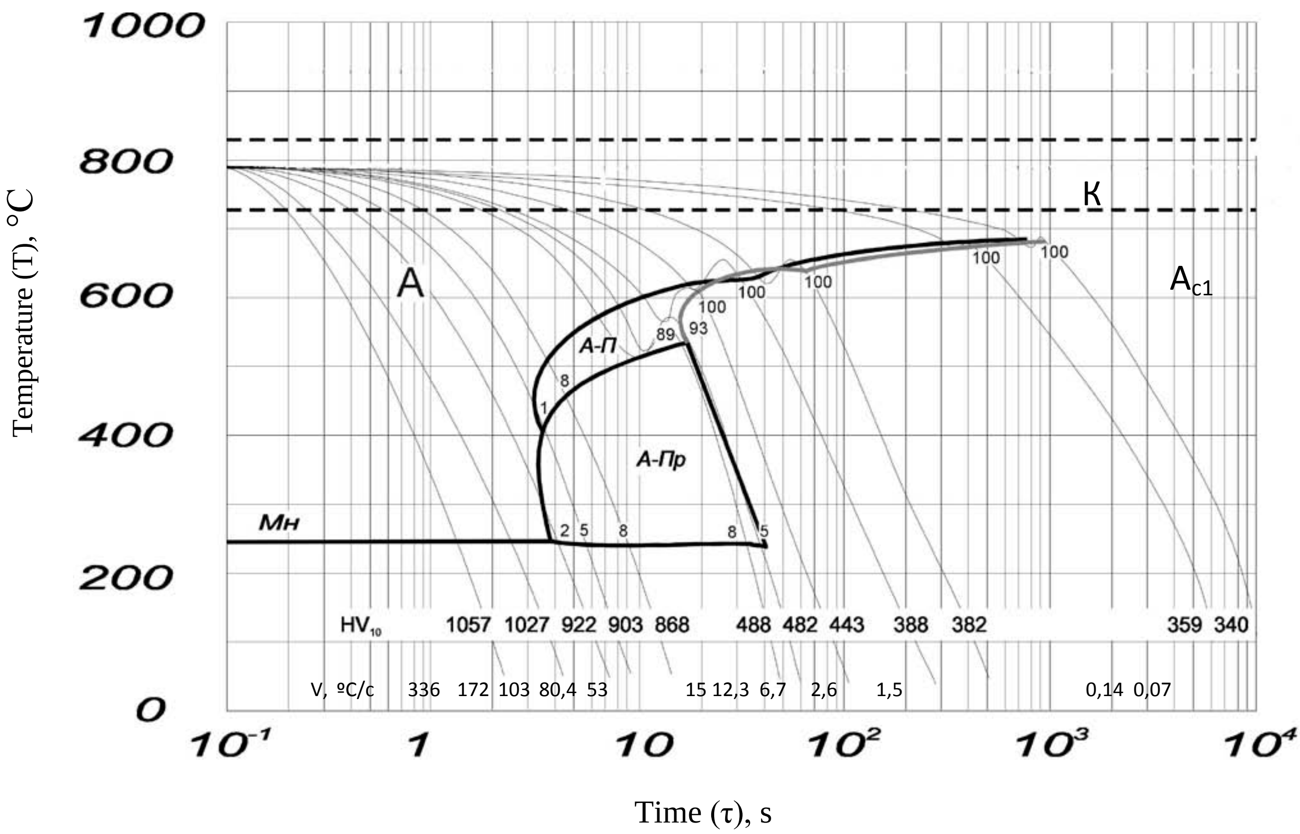


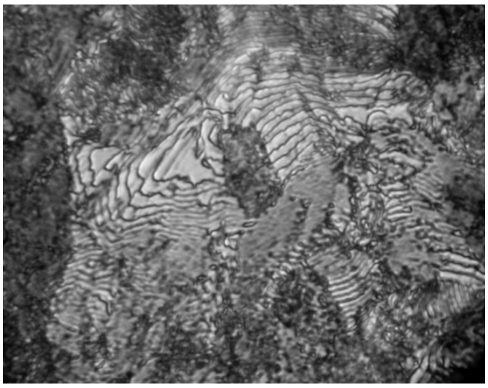
Figure 1. Austenite continuous cooling transformation diagram for vanadium-microalloyed steel C80D2

It follows from analysis of continuous cooling transformation diagram where perlite transformation start temperature is below the end temperature that the structure formation starts with the formation of more disperse perlite, and then less disperse perlite is formed. This is caused by dislocation genesis of lamellar perlite formation [2]: the more temperature, the more distance between dislocation plane-polygonal walls, and vice versa. The specified abnormality in structure formation leads to that at increase of average cooling rate from 1.5 to 2.6 °C/s the amount of sorbitic perlite is decreased by 2-3 %. At further raise of cooling rate the afterglow heat is also released, however the end temperature of perlite transformation is dropped in a greater degree. In this case, the increase of 1 point perlite amount is possible to explain by cooling rate effect on the perlite dispersity [3], as a result both annihilation of one sign dislocations and the distance between plane-polygonal walls defining the genesis of perlite are reduced.

Amount of 1 point perlite increases to 98 % at increase of cooling rate to 6.7 °C/s (**Figure 2b**). Transition through the boundary value of cooling rate 12.3 °C/s is accompanied by change of supercooled austenite decomposition kinetics: 93 % of 1 point perlite in the temperature range of 586-560 °C, and at further cooling - 5 % of bainite. At 240 °C and lower (up to room temperature) austenite transforms into martensite.

In the interval of cooling rates 12.3-80.4 °C/s austenite decomposition takes place under various mechanisms: perlite structures appear to temperatures 534-407 °C, and below these temperatures - bainite-martensite structures (**Figure 2c**).

In the specified interval of cooling rates with increase of cooling rate the amount of product decomposed under diffusive mechanism is decreased, and by mixed and shear mechanism - increased. So, as a result of cooling at the rate of 15 °C/s the microstructure consists of 89 % sorbitic pearlite, 8 % bainite, the rest is martensite, at cooling rate 53 °C/s - 8 % pearlite, 8 % bainite, the rest is martensite; at cooling 80.4 °C/s - 8 % pearlite, 5 % bainite, the rest is martensite.



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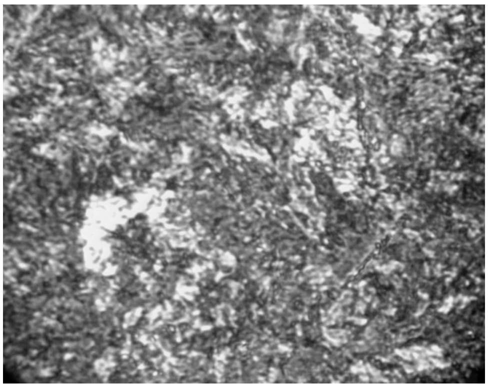
a



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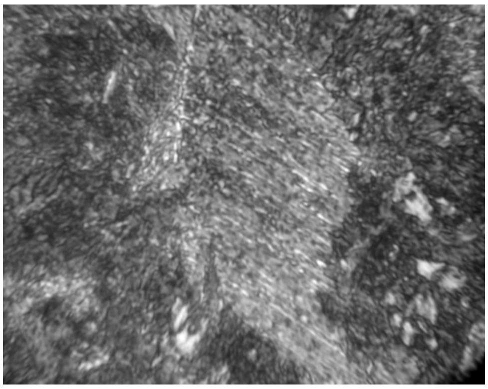
b



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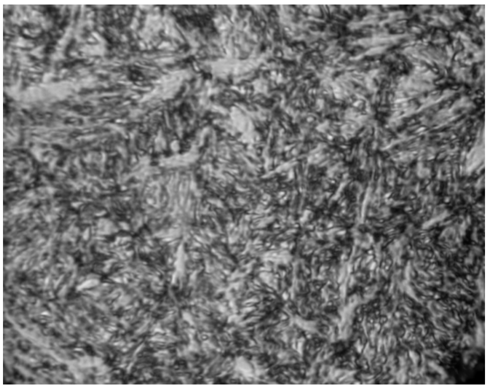
c



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d

Figure 2. Microstructure of steel C80D2 rolled wire after heating to 950 °C and cooling at the rates V_{cool}, °C/s: *a* – 0.07; *b* – 6.7; *c* - 15; *d* - 336

Austenite decomposition on bainite and martensite without perlite transformation takes place in the range of cooling rates 80.4-103 °C/s. In this case, the microstructure consists of 5-1 % bainite and the rest is martensite. The key feature of bainite transformation is that it takes place in the temperature range when there is almost no iron diffusion, but carbon diffusion is intensive.

The minimum cooling rate at which the whole austenite is supercooled to point M_n and transforms into martensite is 120 °C/s. Cooling at such rate leads to transformation of austenite into needled martensite 6-8 points (**Figure 2d**). The formation of martensite starts at 247 °C and is carried up to the room temperature. But as the temperature of martensite transformation end is in the field of negative temperatures, 2-4 % of residual austenite is in samples at normal temperature.

Comparison of continuous cooling trasformation diagram in electric steel C80D2 microalloyed with boron and vanadium and electric steel 80КРД microalloyed with boron (chemical composition, %: C 0.83; Mn 0.56; Si 0.17; Cr 0.05; V 0.001; P 0.010; S 0.001; Ni 0.08; Cu 0.15; Al 0.002; Ti 0.001; N 0.008; B 0.0015) [4] showed the following: steel C80D2 has higher critical cooling rate at hardening (120 °C/s) than steel 80КРД (73 °C/s) and lower critical cooling rate at hardening (12.3 and 29 °C/s, respectively). The lower critical cooling rate corresponds to cooling rate at which there are the first martensite sections; the higher critical cooling rate corresponds to minimum cooling rate at which there is only martensite [5].

Increase of higher critical cooling rate in steel C80D2 is caused by not only carbon sequestration in vanadium carbides but also a germinating effect of fine-dispersed carbides [6]; drop of lower critical cooling rate is caused by vanadium microalloying.

There is bainite transformation area on the continuous cooling trasformation diagram of steel C80D2 in the interval of cooling rates between higher and lower critical cooling rates, and in steel 80КРД this area is absent.

From analysis of continuous cooling transformation diagram it follows that at increase of metastable austenite cooling rate, the amount of 1 point perlite grows and reaches the maximum at V_{cool} = 12.3 °C/s (the lower critical cooling rate), and then goes down and reaches zero value at V_{cool} ≈ 80.4 °C/s. The exception is only the interval of cooling rates (~5-2 °C/s) in which the end temperature of perlite transformation exceeds the temperature of its start. Thus, increase of austenite cooling rate leads to lowering of line A_{r1}, as a result, dispersity of perlite is reduced.

In the interval of cooling rates which are between the lower and higher critical rates, the perlite transformation also takes place with afterglow heat evolution, however the temperature range between the start and end of perlite transformation is significantly increased as compared to cooling rates slower than the lower critical cooling rate.

Taking into account obtained results it is recommended to apply intercritical range of cooling rates for carbon steel sorbitizing in which perlite is formed with the greatest dispersity. Thus accelerated cooling should be stopped in the interval of temperatures 550-530 °C/s and further cooling should be carried out in smooth air that ensures austenite decomposition in disperse perlite under quasiisothermal conditions [8].

Considering the features of structure formation, two-stage cooling of rolled wire on Stelmor line is developed. According to this method, the rolled wire comes out of the wire block with temperature 1100-1050 °C and is water cooled at first - to 980-950 °C, and after coiling – air-blowing ensuring temperature drop at open heat-insulating covers to 550-530 °C at the average rate 17 °C/s. Then cooling proceeds under closed heat-insulating covers at the average rate not higher than 6.5 °C/s to temperature ~100 °C.

Conclusions

1. CCT-diagram for steel C80D2 microalloyed with boron and vanadium is constructed, microstructure parameters depending on cooling rate of austenite are defined.

2. The interval of cooling rates (~5-2 °C/s) in which the temperature of austenite transformation end exceeds the temperature of transformation start is determined. Because of specified abnormality caused by overspeeding of afterglow heat evolution over the cooling rate, the amount of 1 point perlite after austenite cooling at the rate of 2.6 °C/s is less by 2-3 % than after cooling at smaller rate – 1.5 °C/s.

3. Lowering of line A_{r1} at increase of austenite cooling rate testifies to corresponding raise of perlite dispersity which is characteristic for the whole austenitic-perlite transformation including intercritical interval of cooling rates.

4. Carbon steel sorbitizing is recommended to carry out by accelerated cooling of austenite in the intercritical interval of cooling rates to temperatures 550-530 °C, and then in

quasiisothermal conditions.

5. Two-stage cooling of steel C80D2 rolled wire on Stelmor line according to which the rolled wire coils placed on the transfer at 980-950 °C are air cooled to 550-530 °C at the average rate 17 °C/s at open heat-insulating covers is developed, and the subsequent cooling is accomplished under closed covers at the rate not higher than 6.5 °C/s.

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Разработка режима двустадийного охлаждения катанки из стали C80D2, микролегированной бором и ванадием

Парусов В.В., Парусов Э.В., Сагура Л.В., Сивак А.И., Клименко А.П., Сычков А.Б.

Построена термокинетическая диаграмма превращений аустенита электростали C80D2, микролегированной бором и ванадием. Показано влияние скорости охлаждения и тепла фазовых превращений на дисперсность перлита. Разработан научно обоснованный режим охлаждения катанки из стали C80D2 на линии Stelmor.