Scientific and Technological Principles of Development of New Cold-Resistant Arc-Steels (Steels for Arctic Applications)

O V Sych¹, E I Khlusova¹, E A Yashin¹
¹ National Research Centre Kurchatov Institute – Central Research Institute of Structural Materials Prometey, 49 Shpalernaya str., St. Petersburg, RU-191015, Russia

E-mail: oknir@crism.ru

Abstract. The paper presents the results of quantitative analysis of C, Mn, Ni and Cu content on strength and cold-resistance of rolled plates. Relations between the ferritic-bainitic structure morphology and anisotropy and steel performance characteristics have been established. Influence of thermal and deformation rolling patterns on steel structure has been studied. The steel chemical composition has been improved and precision thermomechanical processing conditions for production of cold-resistant Arc-steel plates have been developed.

1. Introduction
Analysis of the current state of the shipbuilding industry shows that construction of high-technology marine facilities for Arctic applications (high duty ice-breakers, ice-going research vessels, off-shore ice-resistant platforms of various types, tankers, container ships, supply vessels, etc.) is the priority development area for the domestic shipbuilding. The Russian Maritime Register of Shipbuilding has developed requirements to steels for Arctic applications to be applied without limitation in the Arctic conditions for all types of structural elements. These requirements have been made part of “Rules …” of the Russian Maritime Register of Shipbuilding and GOST R 2927-2015. Arc-index is given to steels which reliably meet the additional requirements at a desired temperature ($T_d$). To ensure that there will be no brittle fracture, Arc-steels must meet the following additional requirements as to: ductile-to-brittle transition temperatures $T_{cb}$ and nil-ductility temperatures $NDT$, crack resistance characteristic (critical crack tip opening) CTOD (Crack Tip Opening Displacement) at $T_d$ for base metal (BM) and heat-affected zone metal (HAZ) (Table 1) [1].

1 $T_d$ – minimum service temperature of material up to which a given steel grade may be used for all structural elements without limitations.
2 $T_{cb}$ – critical brittle point, at which during three-point ultimate static bending of a full-thickness specimen with a notch as a concentrator no less than 70% of the fibrous constituent is observed in the fracture.
3 $NDT$ – nil-ductility temperature defined as the maximum temperature at which destruction of a standard-size specimen with a brittle weld deposit and crack initiating notch takes place under impact loading.
The fundamental difference of Arc-steels from F steels is that their performance characteristics must be guaranteed by the production process. In view of the current tasks of the year-round exploration of the Northern Sea Route, development of offshore fields and coastal infrastructure, as well as transportation facilities in the Arctic regions, development of new cold-resistant Arc-steels is important and well-timed work.

As known, performance characteristics can be improved by means of efficient grain refinement [2], ensuring high metallurgical quality of steel [3] and forming a favorable deformation texture [4].

Searching for dependencies between the steel performance characteristics and structure parameters [5, 6] is a promising area of research, with the analysis of the collected data necessitating further review and improvement of the criteria for evaluation of steel performance [7, 8].

The challenging task of development of new generation low-carbon low-alloyed Arc-steels with high performance may be solved due to the balanced content of costly alloying additions in steel and special precision thermo-mechanical processing [9–13]. This became possible with the development of new techniques for recognition and quantitative analysis of structural constituents [14–16].

The purpose of this work is development of an integrated method for creation of new cold-resistant Arc-steels with the guaranteed yield strength of 355 and 390 MPa. This method is to include:
- Improvement of the chemical composition;
- Finding new scientific and technical solutions for selection of thermo-deformation rolling patterns for roughing and finishing rolling.

2. Materials and experimental technique

The material selected for the examination is low-carbon low-alloyed cold-resistant rolled steel plate 40–60 mm thick with the guaranteed yield strength of 355–390 MPa.

Mechanical tests were conducted in accordance with GOST R 52927-2015. Ductile-to-brittle transition temperature \( T_{cb} \) was determined in accordance with “Rules …” of the Russian Maritime Register of Shipbuilding, nil-ductility temperature NDT was determined in accordance with “Rules …” of the Russian Maritime Register of Shipbuilding and ASTM E208. Crack resistance test (CTOD test) was conducted according to BS 7448 P.1 and “Rules …” of the Russian Maritime Register of Shipbuilding.

Examination of the structure was done by means of optical metallography on the “AxioObserverA1M” microscope and by means of automated analysis of electron back-scattering diffraction patterns (EBSD-analysis) with the use of the “Quanta 3D FEG” SEM [14]. The structure anisotropy coefficient was determined with the use of the Thixomet image analyzer in collaboration with FGAOU VO SPbPU (St. Petersburg Polytechnic University) [15]. Examination of the fine structure was done on the Tecnai G2 30 S-TWIN transmission electron microscope at the accelerating voltage of 120 kV.

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Table 1. Requirements to cold resistance and operational performance of Arc-steel grades F36W and F40W.

| Rolled steel thickness, mm | NDT, °C | \( T_{cb} \), °C | CTOD at \( T_{cb} \), mm |
|---------------------------|---------|-----------------|-----------------------|
|                           | Arc30   | Arc40 | Arc50 | Arc30 | Arc40 | Arc50 | F36W\(^{Arc}\) | F40W\(^{Arc}\) | F36W\(^{Arc}\) | F40W\(^{Arc}\) |
| 25–30                     | –45     | –55   | –65   | –30   | –40   | –50   | 0.15       | 0.15      | 0.10       | 0.10       |
| 31–35                     | –50     | –60   | –70   | –15   | –25   | –35   | 0.15       | 0.15      | 0.10       | 0.15       |
| 36–40                     | –55     | –65   | –75   | –5    | –15   | –25   | 0.20       | 0.20      | 0.10       | 0.15       |
| 41–50                     | –60     | –70   | –80   | 0     | –10   | –20   | 0.20       | 0.25      | 0.15       | 0.20       |
| 51–60                     | –60     | –70   | –80   | 0     | –5    | –10   | 0.20       | 0.25      | 0.15       | 0.20       |
| 61–70                     | –60     | –70   | –80   | 0     | –5    | –10   | 0.20       | 0.25      | 0.15       | 0.20       |
3. Experimental part

3.1. Improvement of the chemical composition

Chemical composition was improved due to adjustment of the content of carbon and main alloying elements which strengthen the metal component of the interatomic bond (nickel, manganese, copper). The study included quantitative analysis of the changes in strength and impact energy at low temperatures as the content of the stated elements was varied within the range required under GOST 52927-2015 (Table 2).

Statistical analysis of mechanical properties was conducted for 70–120 steel plates of each chemical composition. The plates 40–60 mm in thickness of cold-resistance grades E and F with the yield strength of no less than 355–390 MPa were produced in industrial conditions. The most stable combination of steel strength and ductility was achieved in steel plates having a carbon content of 0.05–0.07%, a manganese content of 1.2%, a nickel content of 0.7%, a copper content of 0.2%, microalloyed with niobium.

Table 2. Influence of carbon, manganese, nickel and copper content on the stability of the strength and ductility combination in low-carbon low-alloyed steel plates.

| Carbon content, % | Contents of main alloying elements | Chemistry No. | Microalloying | Yield strength $\sigma_{0,2}$, MPa | Ultimate strength $\sigma_{\text{u}}$, MPa | Impact energy KV, J. at $-60$ $^\circ$C | % of poor impact energy results |
|------------------|-----------------------------------|--------------|---------------|-----------------------------------|--------------------------------------|---------------------------------|---------------------------------|
| 0.08-0.10        | 0.8% Mn+ 0.2% Ni                  | 1            |               | 350-405                           | 480-510                               | 424-300                         | 166-300                         | 0                               | 0                              |
|                  | 1.2% Mn+ 0.2% Ni                  | 2            |               | 383                               | 493                                  | 294                             | 291                             | 4                               | 8                              |
|                  | 1.40% Mn                           | 3            | V+Nb          | 400-460                           | 485-560                               | 20-300                          | 38-300                          | 4                              | 8                              |
|                  | 1.2% Mn+ 0.7% Ni                  | 4            |               | 444-506                           | 564-637                               | 118-300                         | 10-300                          | 0                              | 28                             |
|                  | 1.2% Mn+ 0.7% Ni                  | 5            |               | 481                               | 601                                  | 218                             | 126                             | 8                              | 55                             |
| 0.05-0.07        | 1.2% Mn+ 0.7% Ni+ 0.2% Cu         | 6            | Nb            | 472                               | 572                                  | 261                             | 201                             | 2                              | 13                             |

Requirements of GOST R 52927-2015 to steel of maximum strength grade F40Wm:

| Surface        | Center       | % of poor impact energy results |
|----------------|--------------|---------------------------------|
| No less than 390 | 510-660     | 0                               |
| No less than 50  |              | 4                              |

Note: * Impact energy KV at a testing temperature of $-40$ $^\circ$C.

3.2. Selection of the desired structural condition

Experiments have proved that in order to achieve guaranteed performance (including cold-resistance) of low-carbon low-alloyed steel plates with the yield strength no less than 355 and 390 MPa to meet the requirements to Arc-steels, it is necessary to ensure formation of fine-grained quasi-isotropic ferrite-bainite structure with similar in morphology structural constituents with the anisotropy coefficient $K_0$ [15] no more than 0.65 and a share of lath bainite no more than 20% (Figure 1).
3.3. Development of thermo-deformation rolling patterns for roughing and finishing rolling.

The work has shown that maximum austenite grain refinement due to recrystallization processes in the steels under examination, taking into account the capabilities of the modern rolling facilities, is achieved in industrial conditions by having deformation at temperatures no less than 950 °C primarily at the roughing stage – 70% of the total deformation. Decrease in deformation per pass below 10% leads to formation of individual coarse austenite grains, which, as the temperature continues to go down, transform into lath bainite. The size of the former non-recrystallized austenite grains remains unchanged, and ferrite precipitation occurs at the boundaries of such austenite grains. As a result, we obtain anisotropic structure with reduced cold-resistance.

Grain refinement at the finishing stage is achieved due to formation of well-developed subgrain austenite structure during isothermal rolling at a temperature below the recrystallization temperature (with the spread in surface temperatures between the passes not exceeding 20°C) and at 10–15% reduction per pass. It has been found that deformation during finish rolling with the surface temperatures in the range of the critical point Aₙₙ, or just above it (by 10–15°C) (which corresponds to the temperature of the end of deformation Aₐₐₙₙ(50–60)°C in the mid-thickness of the rolled plate) promotes formation of the most homogeneous structure with structural constituents similar in terms of their morphology, sizes and proportions (with the averaged crystal curvature GAM (Grain Average Misorientation) of 0.39–0.44° – Figure 2, (a)) in the section of 50 mm thick plates. With such deformation pattern we obtain a ferrite-bainite structure with 44–65% of quasi-polygonal ferrite and 35–50% of bainite, with the average size of structural constituents of 6–8 micrometers (Figure 2 (b)). These examinations were conducted with the use of EBSD-analysis and alpha constituents recognition method using the standard function GAM (Grain Average Misorientation – averaged measure for misorientations between the neighboring lattice points within the closed area. This measure reflects the degree of distortion of the crystal lattice), which proved efficient for quantitative assessment of bainite-martensite structures [14, 16]. Content of lath bainite is 13.5–16.0% (Figure 2 (c)).

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4 Examinations were conducted in collaboration with Kazakov A.A. and Kovalev P.V.
Figure 2. Influence of the temperature of the end of finish rolling: (a) on the averaged crystal curvature (GAM); (b) on the average size of structural constituents; (c) on the lath bainite content.

3.4. Industrial testing of the developed thermal and deformation rolling patterns at the roughing and finishing stages.

Industrial testing of the developed patterns during rolling of plates 50 mm thick made it possible to form quasi-isotropic structure throughout the plate thickness. The structure consisted mainly of quasi-polygonal ferrite (Figure 3 (a)) and granular bainite (Figure 3 (b)) with well-developed substructure and uniformly distributed fine carbide particles 4–12 nanometers in size (Figure 3 (c)).

Formation of this structure ensures that the required strength, visco-plastic properties and performance characteristics ($T_{cb} = -15...-20^\circ C$, NDT$= -65...-70^\circ C$, CTOD$^{av}=1.16$ mm at testing temperature $-60^\circ C$ for base metal) are achieved.

Figure 3. Structure of low-carbon low-alloyed Arc-steel with the yield strength no less than 315–390 MPa: (a) quasi-polygonal ferrite; (b) granular bainite; (c) fine carbides ($120)_{Fe3C}$ in granular bainite.

4. Conclusions

1. It has been shown that the most stable combination of the required strength and cold-resistance is found in rolled steel plates containing (0.05–0.07)%C+1.2% Mn+0.7% Ni+0.2% Cu.

2. In order to ensure that steel plates meet the performance characteristics required for Arc-steels, including cold-resistance, it is necessary to form fine ferrite-bainite structure with the anisotropy coefficient $K_p$ not exceeding 0.65 and a share of lath bainite no more than 20%.

3. We have developed thermal and deformation rolling patterns for roughing and finishing stage that ensure formation of fine quasi-isotropic ferrite-bainite structure during industrial production of Arc-steel plates with the guaranteed yield strength of 355–390 MPa.

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