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Peculiarities of structure and thermomechanical strengthening of martensitic structural steels microalloyed by nitrogen

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Abstract. The effect of thermomechanical treatments on structure and properties of structural C(0.35-0.50)CrNiMoV steels microalloyed by nitrogen were studied using optical microscopy, X-ray diffraction analysis and mechanical testing. The hardness of martensite change as a function of austenitization temperature is presented for the steels with the same main composition but various summary C and N contents. Microalloying of structural steels by nitrogen results in complication of phase transformations and raising austenitization temperature for quenching and HTMT. A small quantity of undissolved carbonitrides promotes fine-grained structure preservation and heredity of the initial as-cast structure. The heat and thermomechanical treatment regimes were determined which allowed the use of nitrogen-microalloyed structural steels as high-strength ones. A complete dissolution of special carbonitrides during HTMT and following low-temperature tempering provide high strength level (by 300-500 MPa higher than for nitrogen-free analogs) combined with sufficient ductility and fracture toughness.

1. Introduction

Progress in many fields of modern technology is determined at a great extent by possibilities to create high-strength structural steels which strength and plasticity are sufficient for practical application. One of the effective methods for improvement of metal quality is nitrogen alloying. Introduction of even small quantity of nitrogen in a steel allows improvement of a combination of strength, fracture toughness and corrosion resistance. Nitrogen is also effective and economical substitute for the expensive nickel, manganese, molybdenum and tungsten [1-4]. The heat and thermomechanical treatment create possibilities to lower a metal mass in structures and to increase a lifetime due to improvement of the combination of mechanical properties [5-10]. Thus, for nitrogen-containing steels, a well-founded choice of nitrogen or/and nitrogen plus carbon as well as optimum treatment regime for a given steel are required. The aim of the present work is studying the effect of high-temperature thermomechanical treatment (HTMT) on structure and properties of nitrogen-containing structural steels.

2. Materials and processing

The chemical composition of studied steels is presented in Table 1. Melting and nitrogen alloying of the steels were carried out in a high-vacuum electrical furnace equipped with a tungsten heater. The main part of the raw material was a carbonyl iron which ensured low impurity content in a finished metal. The nitrogen microalloying was performed by means of saturation of the melt with nitrogen under an atmospheric pressure. The ingot mass was from 500 to 600 g.

Table 1. Chemical composition of studied steels.

Steel	Element content, wt. %							
	Cr	Ni	Mo	V	Mn	Si	C	N
C0.35CrNiMoNV	1.50	1.30	0.66	0.25	0.50	0.23	0.342	0.020
C0.4CrNiMoNV	1.38	1.25	0.50	0.24	0.35	0.29	0.368	0.024
0.5CrNiMoNV	1.78	1.43	0.30	0.50	0.55	0.39	0.510	0.023

The ingots were hot-forged to bars and then cut. For a reference treatment, the samples were water-quenched from 900, 920, 950, 1000 and 1050 °C. Then the structure and hardness were studied.

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The hot deformation in a cycle of HTMT of hot-forged samples was carried out by two-pass rolling using a laboratory rolling mill Duo-210. The inter-pass pause was not longer than 1 s. The summary reductions were 33% for 0.35CrNiMoNV and 0.5CrNiMoNV steels, and 36% for 0.4CrNiMoNV steel. After the second pass, the samples were immediately water-quenched. A final treatment was low-temperature tempering at 180-200 °C, 1 hr.

3. Results and discussion

To determine an optimum heating temperature for quenching, the hardness of hot-forged and quenched from various temperatures samples had measured (Fig.1). The hardness of quenched 0.35CrNiMoNV samples reached its maximum value after quenching from 920°C. For the 0.4CrNiMoNV steel, it was approximately the same after quenching from all temperatures. For the 0.5CrNiMoNV steel, the maximum hardness was reached after quenching from 900 and 1000 °C, i.e., there were two hardness maximums (see Fig.1).

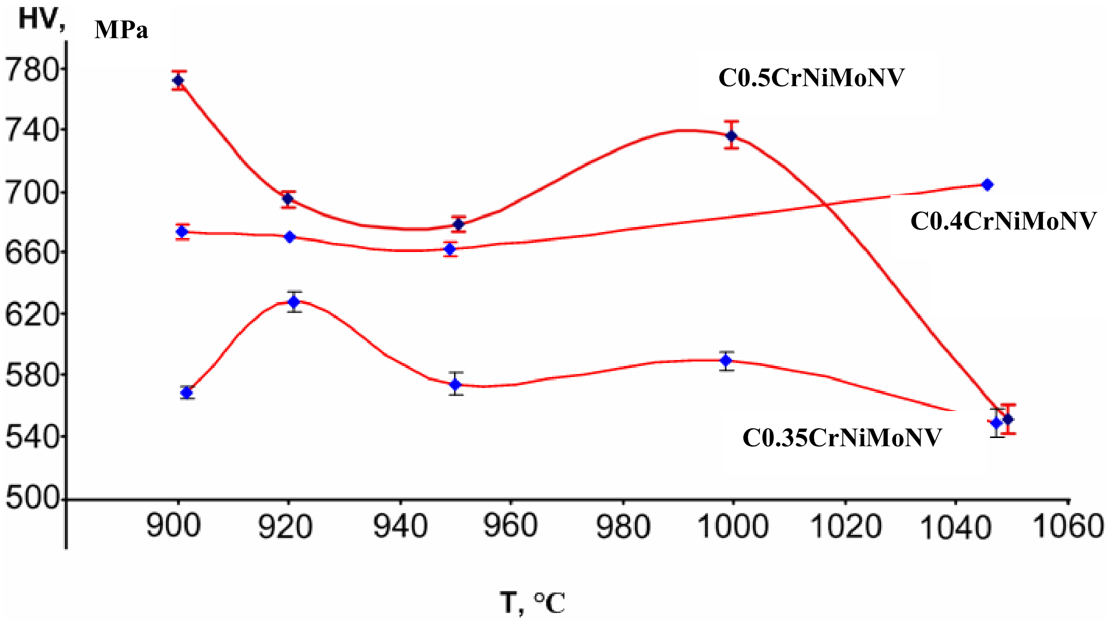

Fig.1 Changes of hardness with heating temperature before quenching.

Heating at lower temperatures is not reasonable due to ferrite preservation after quenching. Heating at higher temperatures leads to more homogeneous distribution of C+N in the austenite, more pronounced dissolution of carbonitrides and austenite grain coarsening, the latter is intensive after the complete dissolution of the carbonitrides (Fig.2). The hardness inhomogeneity is determined mainly by the non-uniformity of the grain structure in this case.
A quick coarsening of the austenite grains is connected to the carbonitride particles dissolution. The higher the summary nitrogen and carbon content, the higher the temperature of intensive grain growth. For all the steels, the grain size at 950 °C is pronouncedly higher than 920 °C. This is because the former temperature is higher than the temperature of phase re-crystallization which is accompanied with structure re-crystallization. Thus, for the studied steels, the 900-920 °C temperature range is the favourable for austenitization before quenching since it ensures high hardness and fine-grained structure. At higher heating temperatures, the grain growth causes the hardness decrease, while at lower temperatures there is not enough carbonitride dissolution. The hot deformation temperature in the HTMT cycle is usually 30 – 50 °C higher than the heating temperature for the quenching, i.e., it is taken as 950 to 970 °C.

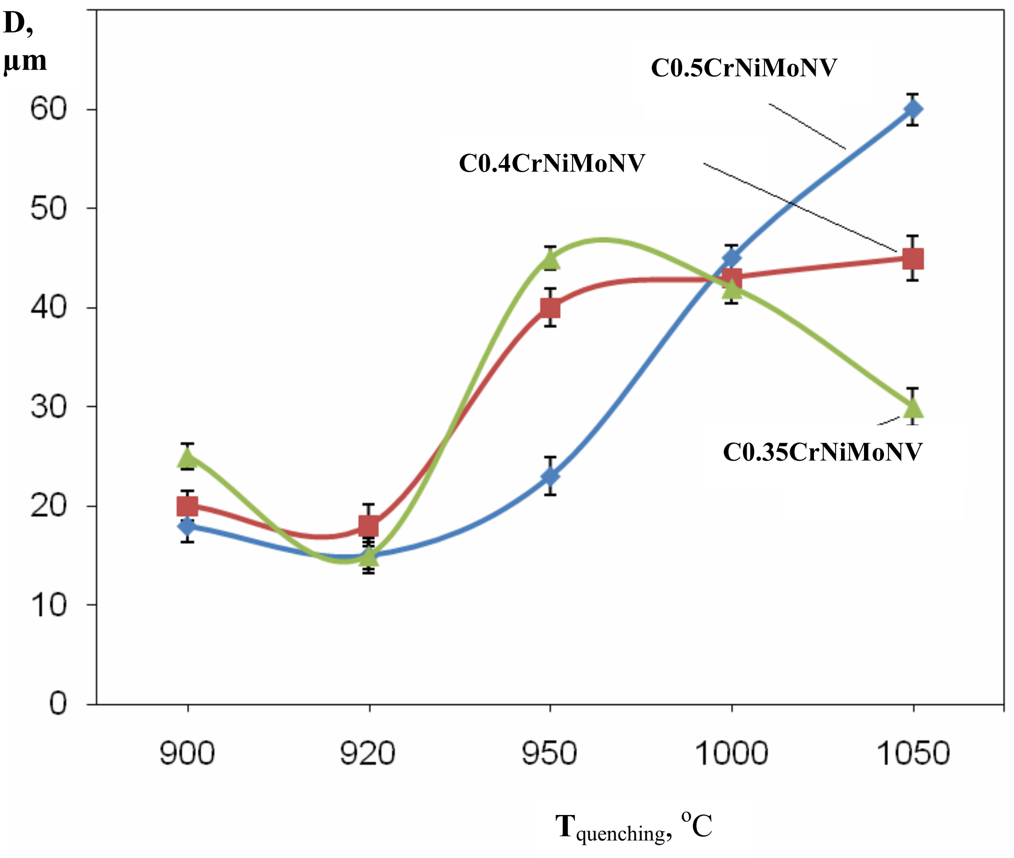

Fig.2. Dependence of grain size on heating temperature before quenching.

HTMT of 0.35CrNiMoNV and 0.5CrNiMoNV steels results in additional grain refinement due to the recrystallization. Recrystallization was accelerated by the finer initial grain in the first case (Table 2) and higher heating temperature relative to Ac_3, higher strain resistance and accelerated diffusion due to higher C content in the second case. A partial recrystallization is observed in 0.4CrNiMoNV steel, an average grain size after HTMT is equal to that after quenching from 950 °C (see Table 2). A striped structure inherited from the initial state is observed after quenching and HTMT.

Table.2. Average grain size of austenite after different treatments.

Steel	State	$\overline{D} \pm \Delta D$, µm
C0.35CrNiMoNV	initial	47±14
	quenching	23±8
	HTMT	15±7
C0.4CrNiMoNV	initial	42±14
	quenching	40±14
	HTMT	39±18
C0.5CrNiMoNV	initial	42±10
	quenching	45±17
	HTMT	21±7

HTMT leads to additional strengthening of all studied steels as compared to the quenching. The hardness after HTMT is higher than after quenching: 58 and 54 HRC for 0.35CrNiMoNV steel, 58 and 53 HRC for 0.4CrNiMoNV steel and 63 and 57 HRC for 0.5CrNiMoNV steel, respectively. The highest strengthening after HTMT is observed for the 0.5CrNiMoNV steel, which has a maximum hardness after quenching.

X-ray studies confirmed that carbides and carbonitrides dissolve almost completely in these steels during heating. Martensite lattice spacing in all steels after hardening became larger, than after high-temperature thermomechanical treatment. However, after tempering at 300-400°C, when martensite dissolution had mostly finished but carbides had not appeared yet, the lattice spacing of α phase was almost equal to the calculated lattice spacing for basic alloyed ferrite. At temperatures higher than 400°C, carbides may form, or, most probably, the cementite is alloyed by alloying elements, which gives smaller experimental lattice spacing compared to the theoretical value.

The results of tensile and fracture toughness tests demonstrate a possibility to reach high mechanical properties of the studied steels (Fig.3). Rather high strength characteristics are obtained in thermomechanically treated steels without loss of plasticity. The higher C+N content in the steel, the higher the strength and lower plasticity values. A maximum ultimate tensile strength of 2500 MPa is obtained for C0.5CrNiMoNV steel, while the minimum of 2000 MPa for 0.35CrNiMoNV steel. It should be noted that sufficient plasticity was obtained after HTMT even for C0.5CrNiMoNV steel. The UTS level of the studied nitrogen – containing steels is 300-500 MPa higher than this for nitrogen-free analogs (Fig.3). The analogs, especially 0.4CrNi2Mo, have higher plasticity, but the plasticity and toughness of our steels can still be increased by grain size reduction (Fig.4). The analog steels have much finer grain.

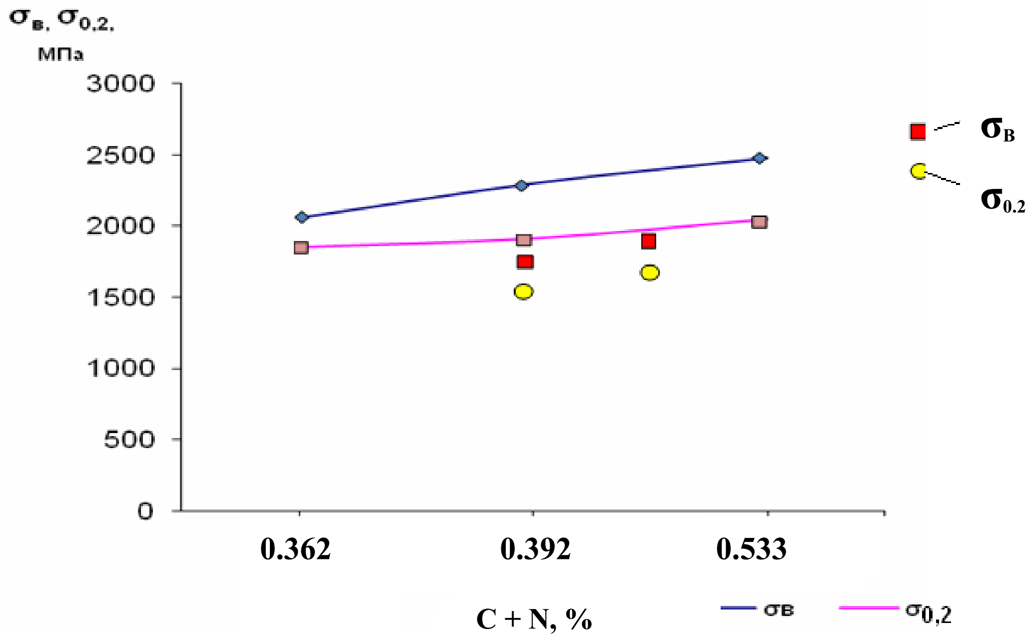

Fig.3. Dependence of ultimate tensile strength and yield stress on summary C+N content in steels (analogs: 0.4CrNi2Mo and 0.45CrNi2Mo steels after oil-quenching from 850 °C and tempering at 200 °C).

The obtained images of fracture surface of tensile-tested samples show that the fracture in C0.35CrNiMoNV and C0.4CrNiMoNV steels is ductile. There are many small pits in the fibrous fracture surface. Preliminary impact bend tests of the 0.4CrNiMoNV steel sample resulted in KCU = 0.625 MJ/mm^2, which is higher than that of nitrogen-free 0.4CrNi2Mo steel and 0.45CrNi2Mo steel (0.59 and 0.47 MJ/mm^2, respectively). The fracture of 0.5CrNiMoNV steel is mixed ductile-brittle, the small quantity of pits and brook-like tracery was observed in the fracture surface.

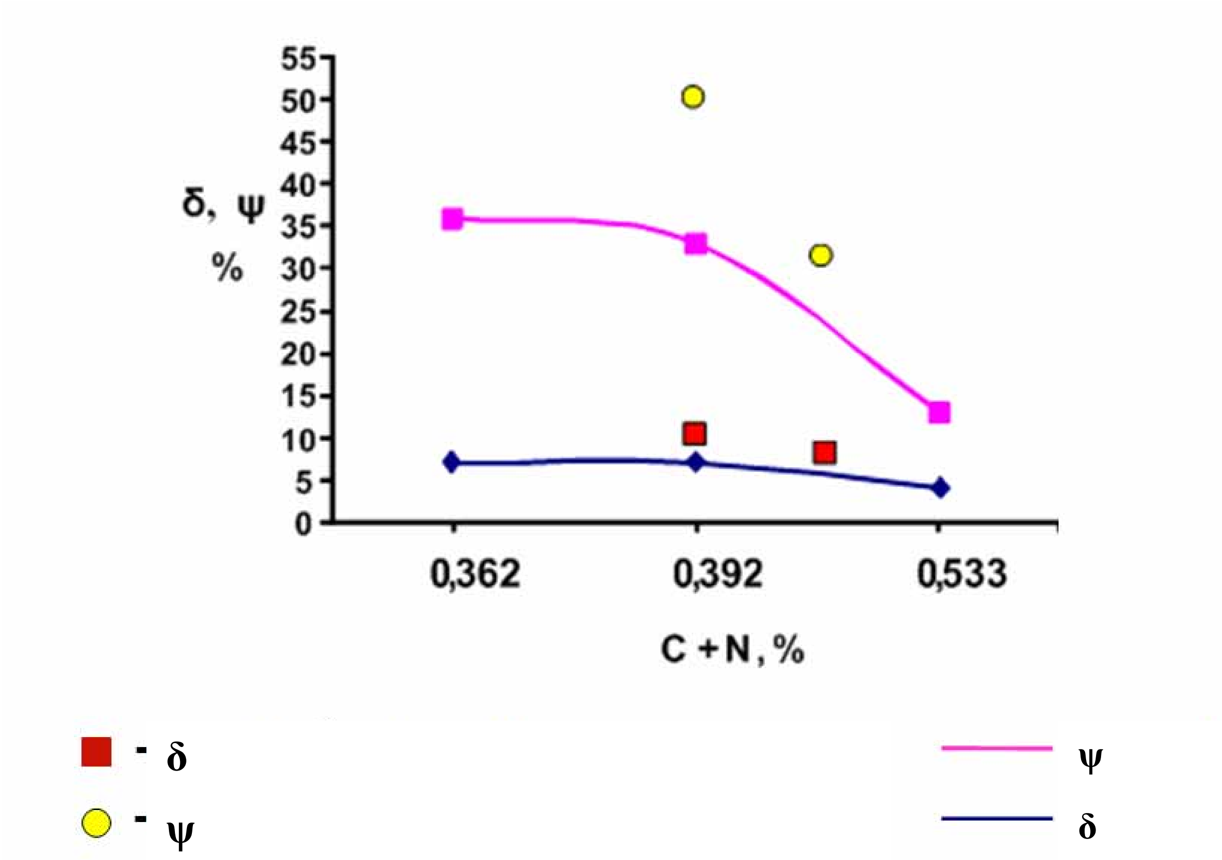

Fig.4. Dependence of δ and ψ on summary C+N content in steels (analogs: 0.4CrNi2Mo and 0.45CrNi2Mo steels after oil-quenching from 850 °C and tempering at 200 °C).

The obtained results testify to the effectiveness of HTMT application to nitrogen-containing steels. The nitrogen microalloying increases the mechanical properties of the studied structural steels, and final low-temperature tempering in the 150-250 °C range allow the use of such steels as high-strength ones.

4. Conclusions

1. Microalloying of structural steels by nitrogen leads to complication of phase transformations and requires thorough selection of heat and thermomechanical treatment temperatures. The heating temperatures before quenching and HTMT for nitrogen-containing steels should be somewhat higher than for nitrogen-free steels.
2. The parameters of heat and thermomechanical treatments for structural steels microalloyed by nitrogen are determined which allow their use as high-strength ones.
3. A most favourable heating temperature for quenching on the studied steels is 920 °C, since it leads to obtaining high hardness and fine-grained austenite structure. Further raise of the heating temperature decreases hardness while its lowering does not allow enough carbonitride dissolution.
4. After HTMT and final low-temperature tempering, the studied (0.35-0.5)CrNiMoNV steels demonstrate high strength level ($\sigma_{0,2}$ from 1850 to 2050 MPa, $\sigma_в$ from 2050 to 2500 MPa,) accompanied with sufficient plasticity ($\psi \approx 40\%$) and fracture toughness.

Acknowledgements

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