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EFFECT OF MICROALLOYING SYSTEM AND THERMO-DEFORMATION TREATMENT PARAMETERS ON THE STRENGTH OF LOW-CARBON STEELS

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Abstract. Low-alloyed low-carbon steels are widely used in the manufacture of objects for various purposes due to the excellent combination of their service and technological properties. The desire of manufacturers to use material resources in the most economical way determines the relevance of searching for optimal chemical compositions and corresponding technological modes. The article presents the results of a study of hot-rolled low-carbon steels microalloyed with Nb, Ti, V and Mo in various combinations and concentrations produced in laboratory conditions. Optical and electron microscopy methods were used to study the structural state. An analysis was made of the influence of the final stage of thermo-deformation treatment and the microalloying system on the structural state, including formation of nanosized phase precipitates of different types, implementation of strengthening mechanisms and, accordingly, the mechanical properties of the rolled products. Different combinations of the values of temperature of hot rolling end, the cooling rate to the coiling temperature, and the coiling temperature with the microalloying system lead to implementation of different strengthening mechanisms. At high cooling rates in steels with molybdenum, the microstructure of bainitic ferrite is formed, but interphase precipitates do not have time to form. For steels microalloyed with vanadium, these rates do not prevent the precipitation of carbides by the interphase mechanism, since due to the small size vanadium atom has a higher diffusion mobility compared to niobium. The amount of interphase precipitates in Nb–Ti microalloyed steels is less than in steels with molybdenum. The amount of precipitates formed in austenite is also greater in the case of complex Nb–Ti–V–Mo microalloying. Elevated temperatures of the rolling end and coiling contribute to implementation of the precipitation hardening mechanism due to interphase precipitates. At too low values of these temperatures, the diffusion mobility of atoms during cooling of the wound roll is low, which limits the formation of nanosized precipitates in an amount sufficient for effective precipitation hardening.

Keywords: low-alloyed low-carbon steels, yield strength, tensile strength, ferrite morphology, precipitation hardening, nanosized precipitates, interphase precipitates, carbide precipitates

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ СИСТЕМЫ МИКРОЛЕГИРОВАНИЯ И ПАРАМЕТРОВ ТЕРМОДЕФОРМАЦИОННОЙ ОБРАБОТКИ НА ПРОЧНОСТЬ НИЗКОУГЛЕРОДИСТЫХ СТАЛЕЙ

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Аннотация. Низколегированные низкоуглеродистые стали широко востребованы при изготовлении объектов различного назначения благодаря превосходному сочетанию их служебных и технологических свойств. Стремление производителей к наиболее экономному использованию материальных ресурсов обуславливает актуальность поиска оптимальных химических составов и соответствующих технологических режимов. В статье представлены результаты исследования произведенного в лабораторных условиях горячекатаного проката низкоуглеродистых сталей, микролегированных Nb, Ti, V и Mo в различных сочетаниях и концентрациях. Для исследования структурного состояния использовались методы оптической и электронной микроскопии. Проведен анализ влияния режима завершающего этапа термометаллургической обработки в зависимости от системы микролегирования на структурное состояние, в том числе образование наноразмерных фазовых выделений разных типов, реализацию механизмов упрочнения и, соответственно, механические свойства проката. Различное сочетание значений температуры конца горячей прокатки, скорости охлаждения до температуры смотки и температуры смотки с системой микролегирования приводит к реализации разных механизмов упрочнения. При высоких скоростях охлаждения в сталях с молибденом формируется микроструктура бейнитного феррита, однако межфазные выделения не успевают образоваться. Для сталей, микролегированных ванадием, эти скорости не препятствуют выделению карбидов по межфазному механизму, поскольку из-за малого размера атом ванадия обладает большей диффузионной подвижностью по сравнению с ниобием. Количество межфазных выделений в сталях, микролегированных Nb–Ti, намного меньше, чем в сталях с молибденом. Выделений, образовавшихся в аустените, также больше в случае комплексного Nb–Ti–V–Mo микролегирования. Повышенные температуры конца прокатки и смотки способствуют реализации механизма дисперсионного твердения благодаря межфазным выделениям. При слишком низких значениях этих температур диффузионная подвижность атомов при охлаждении смотанного рулона низкая, что ограничивает выделение наноразмерных выделений в количестве, достаточном для эффективного дисперсионного твердения.

Ключевые слова: низколегированные низкоуглеродистые стали, предел текучести, предел прочности, морфология феррита, дисперсионное твердение, наноразмерные выделения, межфазные выделения, карбидные выделения

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INTRODUCTION

Low-alloyed low-carbon steels are widely used in the manufacture of products for various applications. Their widespread use is attributed to a favorable combination of high strength, ductility, formability, fatigue resistance, corrosion resistance, and advantageous technological properties [1 – 3]. Manufacturers of modern automotive sheet steels of this class aim to achieve the highest possible strength while ensuring efficient use of energy and material resources. Accordingly, current research efforts are focused on identifying optimal concentration ranges of alloying and microalloying elements, as well as corresponding technological modes [4 – 6]. Despite the progress achieved, the full potential of these steels has not yet been fully realized. For example, the production of hot-rolled steels of grades S315MC–S700MC for mechanical engineering applications is carried out in accordance with the requirements of the European standard

EN 10149–2:1995, which specifies only the upper limits for elements such as carbon, manganese, silicon, niobium, titanium, and vanadium. This drives the development of cost-effective alloying and microalloying systems and necessitates systematic investigation of the regularities governing the formation of the structural state and, consequently, the level of mechanical properties of steel as a function of alloying and microalloying element content and the parameters of thermo-deformation treatment.

Enhancement of the strength characteristics of the steels under consideration is achieved through the combined action of several strengthening mechanisms. The primary mechanisms – grain refinement and precipitation hardening – are controlled by precipitates of excess phases formed by microalloying elements. Among these, titanium, vanadium, and niobium are the most widely used, forming carbides, nitrides, and carbonitrides in steel [7 – 12]. However, the contribution of these precipitates to strengthening differs, as it depends on the tempe-

rature intervals over which they form [13]. For instance, titanium nitride does not dissolve in austenite at reheating temperatures prior to rolling and therefore acts as a phase that inhibits austenite grain growth during heating. NbC and NbN compounds can precipitate in austenite during hot deformation, contributing to grain refinement [3; 7]; however, their formation is kinetically retarded [14]. In contrast, vanadium carbide and vanadium nitride exhibit the highest solubility. Strengthening via the precipitation hardening mechanism is associated with precipitates formed during or after the $\gamma \rightarrow \alpha$ phase transformation. These precipitates are conventionally classified as interphase and ferritic precipitates, respectively. Interphase precipitates are arranged in rows, whereas precipitates formed in ferrite are distributed in a non-ordered manner [9; 12; 13]. The extent of strengthening is governed by both the number of precipitates and their size [15].

Recent studies have demonstrated the significant role of molybdenum in achieving high strength levels [3; 16 – 20]. This effect is attributed to suppression of proeutectoid ferrite formation and the development of a bainitic structure [18], as well as to the precipitation of Mo₂C carbide and (M, Mo)(C, N) carbonitride, where M denotes a microalloying element [16].

Thus, various temperature intervals and kinetic features of nitride, carbonitride, and carbide formation of microalloying elements determine their different roles in strengthening mechanisms. The aim of the present study was to identify the regularities governing the influence of thermo-deformation treatment parameters on the level of mechanical properties for various combinations of microalloying elements.

MATERIALS AND METHODS

Three series of hot-rolled low-carbon steels produced under laboratory conditions and microalloyed

with Nb, Ti, V, and Mo in various combinations and concentrations were investigated. The first series included the Nb–Ti, Nb–Ti–Mo, and Nb–Ti–V–Mo microalloying systems; the second series comprised Ti–Mo, V–Mo, and Nb–V–Mo; and the third series involved V–Mo, Nb–V, Nb–V–Mo, Ti–V–Mo, Nb–Ti–Mo, and Nb–Ti–V–Mo systems. The concentration ranges of the main elements are listed in Table 1. It should be noted that the manganese concentration and the total content of microalloying elements (Nb + Ti + V) were highest in the steels of the first series.

Steel melting was carried out in a vacuum induction furnace, while hot rolling was performed on a DUO-300 laboratory rolling mill using three technological modes of the final stage of thermo-deformation treatment (Table 2). Prior to rolling, the billets were reheated to 1250 °C and held at this temperature for at least 1 h.

Hot rolling of the steels in Series 1 was conducted using the highest temperatures of the hot rolling end (T_{end}) and coiling (T_{coil}). All strips were cooled in an air flow to T_{coil} subsequently subjected to slow furnace cooling with the furnace preheated to T_{coil} , thereby simulating the cooling of a strip coiled into a roll. For Series 2 and Series 3, both the hot rolling end and coiling temperatures were lower. Cooling to T_{coil} was slower in Series 2 and faster in Series 3 compared with Series 1. Variations in the technological modes of the final stage of thermo-deformation treatment led to the activation of different mechanisms governing the formation of the structural state and, consequently, the level of mechanical properties.

Mechanical properties were determined in accordance with GOST 1497 using a HECKERT FP-100/1 tensile testing machine. Metallographic analysis was performed using an Axiovert 40MAT Carl Zeiss optical microscope. Transmission electron microscopy (TEM) studies were carried out on a JEOL JEM-200CX microscope at magni-

Table 1. Composition of the main elements of the studied steels, wt. %

Таблица 1. Содержание основных элементов исследованных сталей, мас. %

Element	Series		
	1	2	3
C	0.048 – 0.061	0.030 – 0.067	0.051 – 0.085
Si	0.087 – 0.150	0.210 – 0.220	0.220 – 0.260
Mn	1.230 – 1.600	0.920 – 1.020	0.510 – 0.960
Mo	≤0.210	0.120 – 0.240	≤0.193
Nb	0.010 – 0.110	≤0.034	≤0.040
Ti	0.068 – 0.170	0.002 – 0.093	≤0.054
V	≤0.200	≤0.117	≤0.098
Nb + Ti + V	0.084 – 0.278	0.095 – 0.157	0.035 – 0.150
N	0.0070 – 0.0115	0.0038 – 0.0150	0.0030 – 0.0123

Table 2. Main parameters of the final stage of thermo-deformation treatment and results of mechanical properties testing

Таблица 2. Основные параметры завершающего этапа термомеханической обработки и результаты испытания механических свойств

Series	$T_{\text{end}}, ^\circ\text{C}$	$T_{\text{coil}}, ^\circ\text{C}$	$\nu_{\text{cool}}, ^\circ\text{C}/\text{c}$	σ_u, MPa	$\sigma_{0.2}, \text{MPa}$	$\delta, \%$
1	900	650	10 – 15	600 – 765	600 – 650	12 – 18
2	860 – 880	550 – 600	≤ 10	609 – 730	496 – 630	22 – 31
3	820 – 870	≤ 550	18 – 34	443 – 737	341 – 678	18 – 38

fications ranging from 15,000 to 30,000 and accelerating voltages of 160 and 120 kV.

RESULTS AND DISCUSSION

The ranges of mechanical property values are presented in Table 2. It can be seen that the strength characteristics ($\sigma_{0.2}$ and σ_u) of the obtained rolled products vary over a fairly wide range. For the steels of Series 3, this range is considerably broader, which is attributed to a wider range of carbon and microalloying element concentrations (Table 1), as well as to differences in cooling rates. Within each series, an increase in the concentrations of the microalloying elements Nb, Ti, V, and Mo is accompanied by an increase in $\sigma_{0.2}$ and σ_u . For the steels of Series 1, the highest strength values were obtained for complex Nb–Ti–Mo microalloying with a high titanium content (0.17 wt. %), at $T_{\text{end}} = 900^\circ\text{C}$ and $T_{\text{coil}} = 650^\circ\text{C}$. For Series 2, the maximum strength characteristics were achieved for the Ti–Mo system with the highest molybdenum content (0.24 wt. %), at $T_{\text{end}} = 860 - 870^\circ\text{C}$ and $T_{\text{coil}} = 570 - 590^\circ\text{C}$. For Series 3, the highest values correspond to the Nb–V–Mo system with simultaneously high carbon (0.083 wt. %) and molybdenum (0.165 wt. %) contents, at $T_{\text{end}} = 850 - 870^\circ\text{C}$ and $T_{\text{coil}} = 510 - 530^\circ\text{C}$. No correlation was observed between the elongation values and the strength characteristics.

Metallographic examination revealed that all samples of Series 1 and Series 2 cooled at lower rates exhibited similar ferritic microstructures, whereas the microstructure of Series 3 samples cooled at higher rates consisted predominantly of bainitic ferrite. An exception was the rolled products of molybdenum-free steels, which contained a relatively high carbon content and exhibited a two-phase ferrite–bainite microstructure.

More detailed TEM investigations made it possible to identify characteristic microstructural features. In the rolled products of Series 1 and Series 2, the metallic matrix consisted of ferrite of two morphological types: block ferrite (occasionally observed as “acicular” ferrite) and polygonal ferrite (Fig. 1). In some steels, cementite precipitates with sizes not exceeding several micrometers were observed along grain boundaries.

Most rolled products of Series 3 exhibited a microstructure predominantly composed of bainitic ferrite (Fig. 2, a). The carbon-containing constituent was low-carbon bainite (Fig. 2, b); in some cases, small amounts of high-carbon bainite and cementite were also present. In molybdenum-free steels, the matrix consisted of a combination of polygonal and bainitic ferrite, while the carbon-containing phase – whose fraction was higher due to the increased carbon content – comprised bainite and degenerate pearlite. The predominance of bainitic

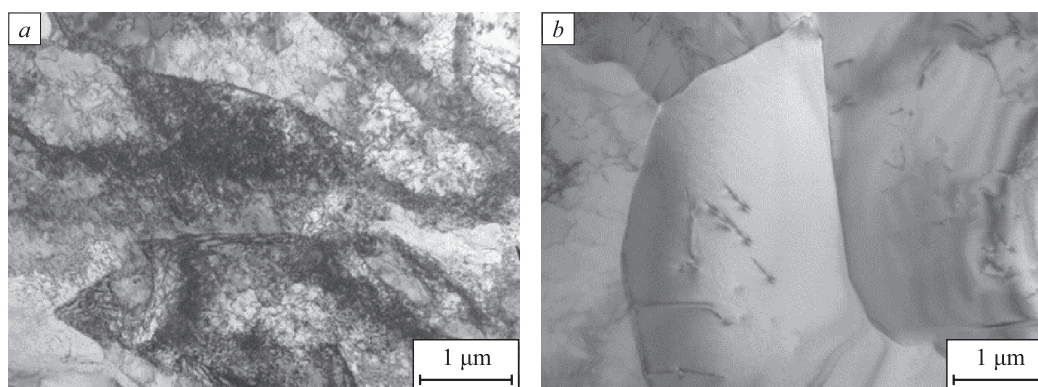


Fig. 1. Typical image of ferrite in rolled steels of series 1 and 2 of two morphological types: a – block, b – polygonal. TEM, dark-field images

Рис. 1. Типичный вид феррита в прокате сталей серий 1 и 2 двух морфологических типов: a – блочный; b – полигональный. ПЭМ, светлопольные изображения

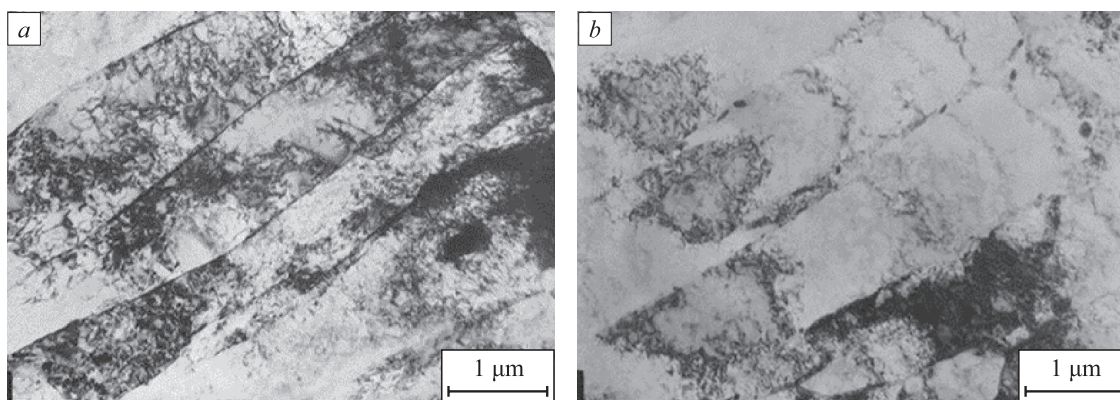


Fig. 2. Typical structural components of rolled steels of series 3 containing molybdenum:
a – bainitic ferrite, *b* – low-carbon bainite. TEM, dark-field images

Рис. 2. Типичные структурные составляющие проката сталей серии 3, содержащих молибден:
a – бейнитный феррит; *b* – низкоуглеродистый бейнит. ПЭМ, светлопольные изображения

ferrite in the microstructure of molybdenum-containing steels is most likely associated with the ability of molybdenum to promote bainitic structure formation [18].

Submicron carbonitride precipitates were detected in most samples. Their number was limited; typical particle sizes were approximately 100 – 200 nm, although individual finer and coarser particles (up to ~300 nm) were also observed.

Nanosized carbide and carbonitride precipitates were most representative in the steels of Series 1 and belonged to two types: those formed in austenite (hereinafter referred to as austenitic precipitates) and interphase precipitates. Mixed-type precipitates were also observed, formed by the interphase mechanism but subsequently coarsened in ferrite. No ferritic precipitates were detected. Austenitic precipitates exhibited an elon-

gated morphology, with lengths up to ~10 nm (in some cases up to ~15 nm) and widths not exceeding 3 – 4 nm (Fig. 3, *a*). Nanosized interphase and mixed-type precipitates were systematically present both in grains/blocks containing austenitic precipitates (Fig. 3, *a*) and in those where such precipitates were absent (Fig. 3, *b*). In most regions, the size of these precipitates did not exceed 3 – 4 nm; only rarely were areas observed where interphase precipitates reached sizes of 5 – 6 nm. According to [7], the presence of niobium in steel promotes the formation of nanosized precipitates in austenite and via the interphase mechanism. However, despite the maximum niobium concentration (0.11 wt. %) in the Nb–Ti steel, the number of such precipitates was relatively small compared with steels additionally containing molybdenum, which is consistent with reported data on the favorable effect of molybdenum on carbide nucleation [3; 18].

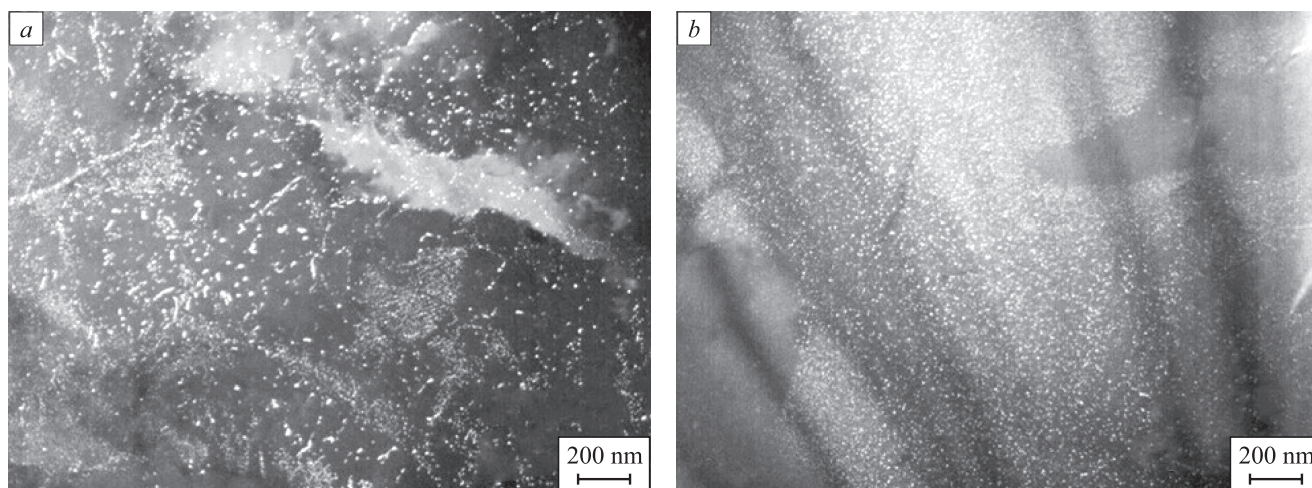


Fig. 3. Typical images of austenite (*a*) and interphase (*a, b*) precipitates.
 TEM, dark-field images in carbide (carbonitride) reflections

Рис. 3. Типичный вид аустенитных (*a*) и межфазных (*a, b*) выделений.
 ПЭМ, темнопольные изображения в рефлексах карбидов (карбонитридов)

The highest number of precipitates was observed in steels with the complex Nb–Ti–Mo–V microalloying system and maximum component concentrations.

In contrast to the steels of Series 1 and Series 2, the rolled products of Series 3 contained fewer nanosized precipitates, and neither austenitic nor interphase precipitates were detected. Only nanosized precipitates formed in ferrite were present, with sizes below 2 nm and, in some cases, up to 3 nm. An exception was the rolled product of the V–Mo steel with the highest vanadium content. In this steel, a high number density of nanosized interphase and mixed-type carbonitride precipitates with sizes of 2–5 nm was observed within ferrite grains, whereas larger carbonitride precipitates, up to 10–12 nm in size, were detected along grain boundaries. Ferritic precipitates were scarce.

Apparently, at high cooling rates after hot deformation completed at low temperatures, the $\gamma \rightarrow \alpha$ phase transformation proceeds too rapidly, while the diffusion mobility of microalloying elements and carbon is reduced. As a result, precipitate formation at the moving phase boundary does not have sufficient time to occur, and nanosized carbide precipitates form in ferrite instead. At the same time, vanadium exhibits a higher tendency toward interphase carbide precipitation because, owing to its smaller atomic size compared with niobium, it possesses higher diffusion mobility. This enables precipitation to occur even at higher $\gamma \rightarrow \alpha$ transformation rates [21]. Consequently, despite the high cooling rate, a large number of interphase and mixed-type precipitates are observed in vanadium-containing steels.

For the steels of this series, the dominant factor governing strength is the formation of a bainitic ferrite microstructure with a high dislocation density, resulting from the high cooling rate. The maximum tensile strength (737 MPa) and yield strength (678 MPa) are attributed to the simultaneously high contents of carbon and molybdenum in the steel.

Thus, the strengthening mechanism operative in this series of rolled products differs from that in the previous two series, in which precipitation hardening played a substantial role.

CONCLUSIONS

The application of different technological modes at the final stage of thermo-deformation treatment, in combination with the microalloying system, leads to the activation of different strengthening mechanisms.

For the steels of Series 1, the highest strength characteristics were achieved through complex Nb–Ti–Mo microalloying with a high titanium content (0.17 wt. %). In Series 2, maximum strength was obtained for

the Ti–Mo system with the highest molybdenum content (0.24 wt. %), whereas in Series 3 the highest values corresponded to the Nb–V–Mo system with simultaneously high carbon (0.083 wt. %) and molybdenum (0.165 wt. %) contents.

Higher cooling rates after hot rolling in molybdenum-containing steels promote the formation of a bainitic ferrite microstructure with a significantly higher dislocation density and, consequently, enhanced strength. However, under these conditions, the $\gamma \rightarrow \alpha$ phase transformation proceeds too rapidly for interphase precipitation to develop, and nanosized precipitates therefore form predominantly in ferrite.

Elevated T_{end} and T_{coil} temperatures favor the attainment of high strength through precipitation hardening via the interphase precipitation mechanism. The number of austenitic carbide and carbonitride precipitates is higher in steels with complex Nb–Ti–V–Mo microalloying. Conversely, excessively low T_{end} and T_{coil} values reduce the diffusion mobility of microalloying elements and carbon during cooling of the coiled strip, thereby limiting the formation of nanosized precipitates required for effective precipitation hardening.

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