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ON THE INFLUENCE OF RARE-EARTH OXIDE ADDITIVES ON KINETICS OF BORATED LAYER FORMATION AND BORON DIFFUSION ALONG GRAIN BOUNDARIES DURING STEEL BORIDING

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Abstract. Metallographic studies showed that the use of rare-earth oxide (REO) additives during liquid electrolysis-free boriding increases the borated layers depth, with these additives not interacting with the treated product material. Addition of lanthanum and yttrium oxides increases the borated layer depth by 30 – 40 %, while addition of scandium oxide either has no effect or decreases the layer depth. *X*-ray phase analysis of boriding alloys with REO additives was conducted in this study. It was shown that REO additions to the melt result in formation of low-melting rare-earth borates ($LaBO_3$, YBO_3, $ScBO_3$), which enhance grain boundary diffusion and significantly intensify the boriding process. Estimated values of bulk and grain boundary diffusion coefficients were obtained. The addition of yttrium oxide increased the bulk diffusion coefficient in VKS-5 steel by 280 %. In Kh12MF steel, addition of lanthanum oxide resulted in an 83 % increase in the bulk diffusion coefficient. For 40Kh steel, no increase in the bulk diffusion coefficient was recorded in any of the investigated cases. The grain boundary diffusion coefficient increased in VKS-5 and Kh12MF steels by 1000 % with addition of lanthanum oxide. Addition of yttrium oxide increased the grain boundary diffusion coefficient by 1000 % in VKS-5 steel, by 135 % in Kh12MF steel, and by 87 % in 40Kh steel. Addition of scandium oxide increased the grain boundary diffusion coefficient by 160 % in VKS-5 steel. The diffusion coefficient values at grain boundaries obtained through modeling calculations agree well with the experimental data.

Keywords: boriding, borated layers, rare-earth element, lanthanum oxide, yttrium oxide, scandium oxide, liquid borating, modification, morphology of borated layers, diffusion

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К ВОПРОСУ О ВЛИЯНИИ ДОБАВОК ОКСИДОВ РЕДКОЗЕМЕЛЬНЫХ ЭЛЕМЕНТОВ НА КИНЕТИКУ ОБРАЗОВАНИЯ БОРИРОВАННЫХ СЛОЕВ И ДИФФУЗИЮ БОРА ПО ГРАНИЦАМ ЗЕРЕН ПРИ БОРИРОВАНИИ СТАЛЕЙ

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Аннотация. Проведены металлографические исследования, показывающие, что применение добавок оксидов редкоземельных элементов (РЗЭ) при жидкостном безэлектролизном борировании приводит к увеличению глубины борированных слоев, причем данные добавки не взаимодействуют с материалом обрабатываемого изделия. Добавка оксидов лантана и иттрия увеличивает глубину борированного слоя на 30 – 40 %, добавка оксида скандия не влияет или приводит к снижению глубины борированного слоя. В данной работе проведен рентгенофазовый анализ сплавов для борирования с добавками оксидов РЗЭ. Показано, что при добавке оксида РЗЭ в расплаве образуется легкоплавкий борат РЗЭ ($LaBO_3$, YBO_3, $ScBO_3$), который способствует зернограничной диффузии, что приводит к значительной интенсификации процессов борирования. Получены оценочные значения коэффициентов объемной и зернограничной диффузии. Добавка оксида иттрия увеличивает коэффициент объемной диффузии в стали ВКС-5 на 280 %. В стали Х12МФ добавка оксида лантана привела к увеличению коэффициента объемной диффузии на 83 %. На стали 40Х во всех исследуемых случаях увеличение коэффициента объемной диффузии не зафиксировано. Коэффициент зернограничной диффузии увеличился в сталях ВКС-5 и Х12МФ на 1000 % при добавке оксида лантана. Добавка оксида иттрия привела к увеличению коэффициенту зернограничной диффузии на 1000 % в стали ВКС-5, на 135 % в стали Х12МФ и на 87 % в стали 40Х. Добавка оксида скандия позволила увеличить коэффициент зернограничной диффузии на 160 % в стали ВКС-5. Значения коэффициентов диффузии по границам зерен, полученные путем модельных расчетов, хорошо согласуются с экспериментальными данными.

Ключевые слова: борирование, борированные слои, редкоземельный элемент, оксид лантана, оксид иттрия, оксид скандия, жидкостное борирование, модифицирование, морфология борированных слоев, диффузия

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INTRODUCTION

Although the use of rare-earth metal (REM) additives in liquid boriding increases the depth of borated layers, promotes the formation of complex borides, and improves mechanical properties [1; 2], their application has not become widespread in boriding technologies due to the high cost of such additives. Recent studies on the use of rare-earth oxide (REO) additives in powder boriding [3 – 5] have shown that they produce similar effects. Research into REO additives in liquid electrolysis-free boriding has demonstrated an increase in the depth of borated layers and, in some cases, changes in their morphology [6; 7]. It has been noted that REO additives do not interact with the material being treated and instead act as catalysts in the boriding process [8; 9].

A key factor in controlling the boriding process when using REO additives is understanding the mechanism by which they influence the kinetics of borated layer formation and boron diffusion into the metal [10 – 12].

Although no traces of rare-earth elements are detected in the structure of the treated steels, their presence in the melt can affect the boriding process in several ways [13 – 14].

- Rare-earth oxides may act as catalysts that accelerate chemical reactions in the melt. This can lead to an increased rate of formation of active boron atoms, which diffuse into the steel and ultimately result in deeper borated layers.

- The presence of REO additives alters the physicochemical properties of the melt, such as viscosity, surface tension, and ion distribution. These changes may promote more uniform and active interaction between boron and the steel surface, enhancing boron penetration depth.

- REO additives may influence the structure and defectiveness of the oxide layer on the steel surface, facilitating more active diffusion of boron atoms into the metal.

- Rare-earth oxides can affect the formation of intermediate phases in the melt or at the steel–melt interface, thereby intensifying the boriding process.

A study reported in the international literature [15] describes the positive effect of cerium oxide addition on the depth of borated layers produced on a Ti6Al4V titanium alloy. The beneficial effect is attributed to the formation of low-melting rare-earth borates, which enhance the transport capacity of the boriding agent. However, that study focuses solely on powder boriding and does not consider the contribution of low-melting RE borate phases to grain boundary diffusion of boron into the material.

The aim of this study is to analyze the effect of rare-earth oxide additives on boron diffusion during the formation of borated layers in steels with different compositions.

MATERIALS AND METHODS

The steel samples were subjected to liquid electrolysis-free boriding in a melt composed of sodium tetraborate and boron carbide, with lanthanum, yttrium, or scandium oxides added in amounts of 1, 5, 10, and 20 wt. %. The boriding process was conducted at 1000 °C for 8 h, followed by air cooling of the samples.

This study investigated VKS-5, Kh12MF, and 40Kh steels, selected for their varying carbon content and alloying element composition. Their chemical compositions are listed in Table 1.

The microstructure of the samples was examined using a Jeol JXA-iSP100 electron probe microanalyzer. Microstructure images were obtained with a backscattered electron detector.

X-ray phase analysis of the boriding alloy was performed using a BRUKER D2 PHASER *X*-ray diffractometer.

RESULTS AND DISCUSSION

As previously shown, the addition of rare-earth oxides has a significant impact on the depth, properties, and, in some cases, the morphology of the resulting borated layers. All steel samples treated in the various melts described in this study were examined using an electron microscope. Fig. 1 presents the microstructures of borated layers formed on VKS-5 steel in a standard melt and in melts containing 1, 5, 10, and 20 wt. % lanthanum oxide. These images were selected as they clearly illustrate the characteristic features of borated layer formation during liquid boriding with REO additives.

As seen in Fig. 1, the addition of 1 wt. % lanthanum oxide promotes the formation of higher-quality borated layers. With 5 wt. % lanthanum oxide, the penetration depth of the dark, boron-rich FeB phase increases, although this phase forms unevenly. Increasing the additive content to 10 wt. % leads to even deeper FeB penetration, with the dark phase displaying greater continuity. Notably, the deepening zone of the borated layer consists of light, acicular regions that appear as a continuation of the dark layer. This zone reflects the initial accelerated diffusion of boron along the grain boundaries of the matrix, followed by boron penetration into the grain volume from the boundaries, which act as diffusion sources. However, as the diffusant concentration at the boundaries decreases beyond a certain depth, the grains are no longer fully saturated with boron, resulting in a jagged interface at the bottom of the borated layer. Boron partially decorates the grain boundaries, which become visible in the transition to the underlying structure. A network of boride phases along the grain boundaries in the transition zone is observed in all the presented microstructures.

Table 2 presents the data on the depth of borated layers formed in melts with various additives for the steels studied.

Analysis of the data in Table 2 indicates that rare-earth oxide additives influence the depth of the borated layers. However, there appears to be a critical concentration of these additives, beyond which the boriding process slows down and the layer depth decreases. Notably, the addition of scandium oxide does not result in any increase in layer depth. The chemical composition of the steel also plays a significant role in determining the depth of borated layers formed in melts without additives. While previous studies [6; 18] have identified carbon content as the primary factor influencing layer depth, the data in Table 1 show no clear correlation. For example, the low-carbon VKS-5 steel exhibited a layer

Table 1. **Chemical composition of the studied steels**

Таблица 1. **Химический состав исследуемых сталей**

Alloy	Element content, wt. %										
	Fe	C	Si	Mn	Cr	Ni	W	V	Mo	Nb	Ce
VKS-5	base	0.15	0.68	0.41	2.80	1.30	1.20	0.41	0.58	0.10	0.03
Kh12MF	base	1.62	0.33	0.30	12.20	0.36	–	0.26	0.41	–	–
40Kh	base	0.41	0.24	0.62	1.10	0.21	–	–	–	–	–

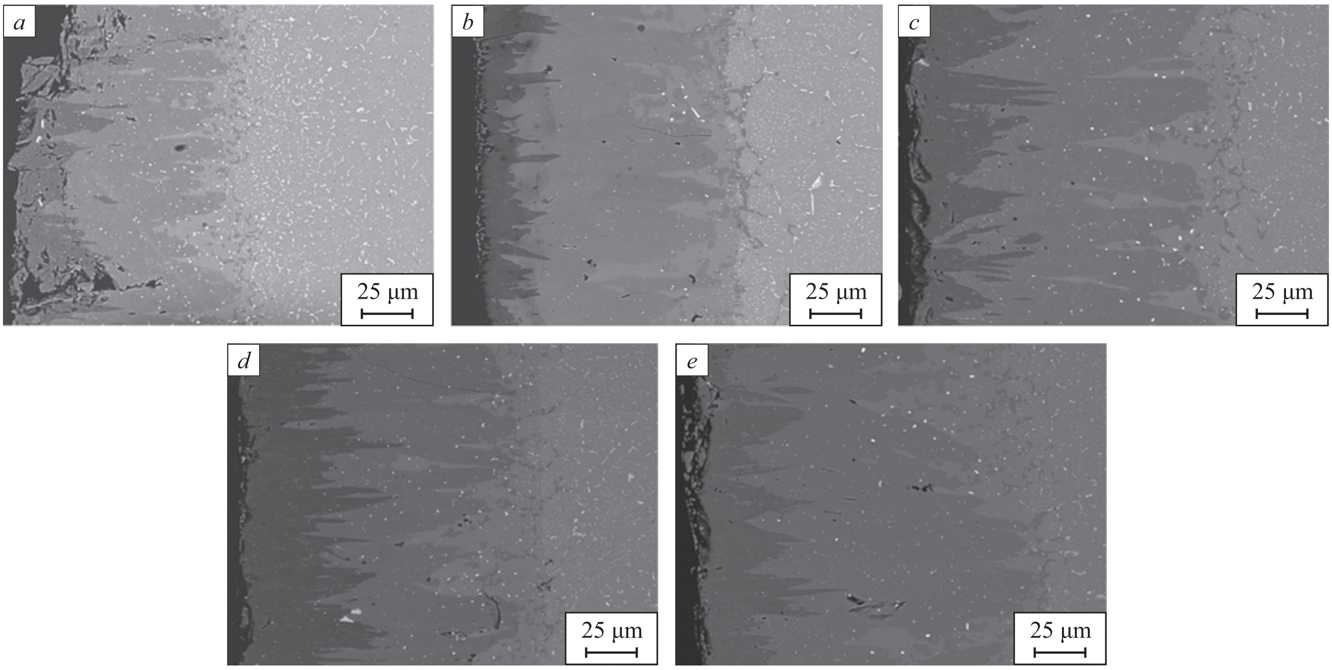

Fig. 1. Microstructure of borated layers on VKS-5 steel:
a – without lanthanum oxide addition, *b* – with 1 wt. % lanthanum oxide addition, *c* – with 5 wt. % lanthanum oxide addition, *d* – with 10 wt. % lanthanum oxide addition, *e* – with 20 wt. % lanthanum oxide addition

Рис. 1. Микроструктура борированных слоев, полученных на стали ВКС-5:
a – без добавления оксида лантана; *b* – с добавлением 1 мас. % оксида лантана; *c* – с добавлением 5 мас. % оксида лантана; *d* – с добавлением 10 мас. % оксида лантана; *e* – с добавлением 20 мас. % оксида лантана

depth of 120 – 130 μm; the medium-carbon 40Kh steel reached 240 – 250 μm; whereas the high-carbon Kh12MF steel showed a depth of only 95 – 105 μm.

Table 2. **Depth data of borated layers in melts with various additives on steels**

Таблица 2. **Данные по глубинам борированных слоев, полученных в расплавах с разными добавками на сталях**

Composition	Depth of borated layers, μm		
	VKS-5	Kh12MF	40Kh
No additive	120 – 130	95 – 105	240 – 250
1 % La_2O_3	120 – 130	100 – 105	240 – 250
5 % La_2O_3	150 – 160	140 – 145	260 – 270
10 % La_2O_3	160 – 170	118 – 124	270 – 275
20 % La_2O_3	150 – 160	100 – 105	268 – 274
1 % Y_2O_3	100 – 105	95 – 105	200 – 220
5 % Y_2O_3	235 – 245	120 – 130	140 – 150
10 % Y_2O_3	165 – 170	95 – 100	210 – 230
20 % Y_2O_3	105 – 115	100 – 105	160 – 170
1 % Sc_2O_3	122 – 126	95 – 110	235 – 245
5 % Sc_2O_3	128 – 134	76 – 82	155 – 162
10 % Sc_2O_3	127 – 133	87 – 96	158 – 164
20 % Sc_2O_3	64 – 79	0	103 – 113

Given that the addition of 5 wt. % rare-earth oxide (REO) consistently resulted in increased borated layer depth, the compositions of melts containing 5 wt. % REO were analyzed in detail.

Figs. 2 – 4 show the *X*-ray diffraction patterns of boriding melts with various REO additives.

These diffraction patterns reveal the formation of a new phase in all melts – rare-earth borates ($LaBO_3$, YBO_3, $ScBO_3$). According to previous studies [14 – 16], these compounds are low-melting. It was also observed during melt preparation that adding up to 10 wt. % REO improved melt fluidity.

X-ray phase analysis suggests that the presence of a low-melting phase in the melt increases its fluidity and likely promotes faster diffusion of boron atoms into the steel. Given that the boriding temperature is 1000 °C – within the range where grain boundary diffusion dominates over bulk diffusion ($T < 0.7T_m$ [17]) – it can be assumed that boron initially diffuses rapidly along grain boundaries (GB), followed by penetration into the grain interiors from these boundaries, which serve as diffusion sources. This is due to the fact that the activation energy for grain boundary diffusion is considerably lower than for bulk diffusion, making it the preferred pathway under these conditions. This assumption is supported by the observed morphology of the borated layers – specifically, the presence of light acicular regions within

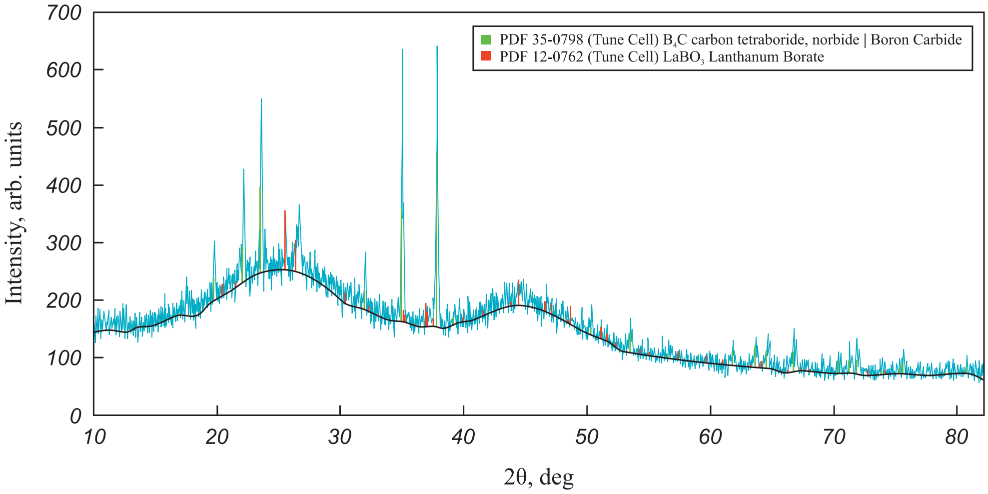

Fig. 2. Diffraction pattern of the melt with 5 wt. % lanthanum oxide addition

Рис. 2. Дифрактограмма расплава с добавкой 5 мас. % оксида лантана

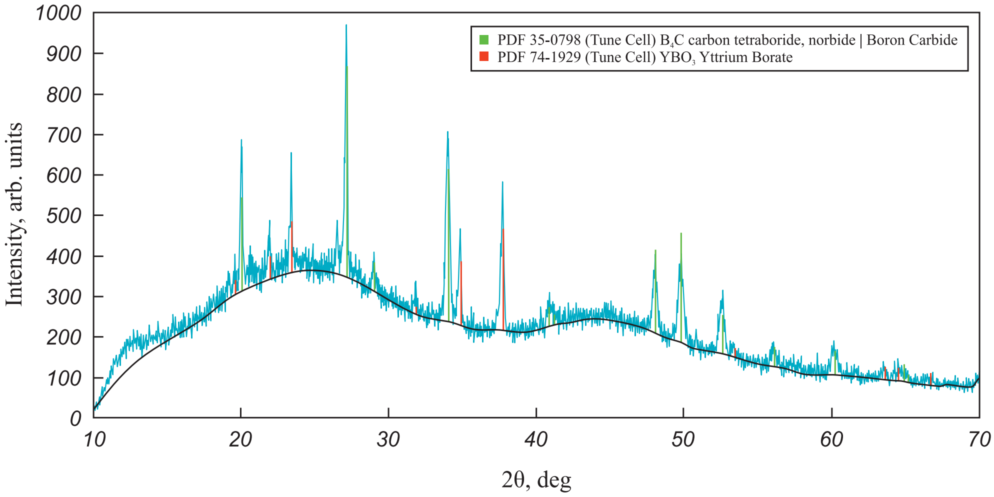

Fig. 3. Diffraction pattern of the melt with 5 wt. % yttrium oxide addition

Рис. 3. Дифрактограмма расплава с добавкой 5 мас. % оксида иттрия

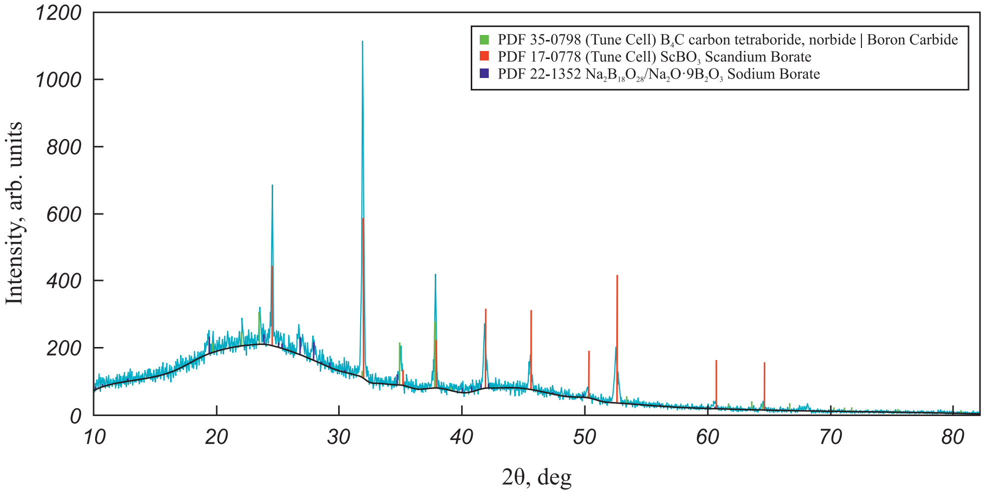

Fig. 4. Diffraction pattern of the melt with 5 wt. % scandium oxide addition

Рис. 4. Дифрактограмма расплава с добавкой 5 мас. % оксида скандия the layer and a boride network along grain boundaries in the transition zone.

It is also reasonable to hypothesize that the low-melting RE borate phase acts as a transport medium, enhancing the delivery of boron atoms to grain boundary outlets at the matrix surface. Grain boundary diffusion, being faster than bulk diffusion, creates leading boron fluxes into the steel. This results in a higher concentration of boron in the reaction zone, thereby accelerating the boriding process.

In light of the presumed substantial role of REO additives in promoting grain boundary diffusion, it is appropriate to assess the depth of boron penetration for different melt compositions and to estimate the bulk and grain boundary diffusion coefficients of boron in the studied steels.

Based on the metallographic analysis, the following characteristic depths were determined.

- h – the depth of the borated layer where bulk diffusion is the dominant mechanism. In this zone, boron enrichment occurs primarily through lattice diffusion, as the supply of boron atoms to the grain boundaries (GBs) is limited and no low-melting transport medium is present. The contribution of grain boundary diffusion in this region is minimal or absent, and the boron distribution is governed solely by bulk diffusion.
- L_b – the grain boundary diffusion path, defined as the distance from the sample surface to the depth where boron enrichment along grain boundaries significantly decreases (approximately by a factor of e).
- L_v – the bulk diffusion path of boron during the saturation of grain interiors from the grain boundaries, which act as sources of boron atoms – that is, in the presence of grain boundary diffusion fluxes.

Fig. 5 illustrates the zones within the borated layer corresponding to these parameters.

The bulk diffusion coefficient of boron in the steels was estimated using the equation provided in [18]:

$$h = \sqrt{D\tau}, \tag{1}$$

where h is the layer depth, µm; D is the bulk diffusion coefficient of boron, m^2/s; τ is the boriding time, s.

Table 3 summarizes the average values of h, L_b, L_v obtained from metallographic observations.

Analysis of the data in Table 3 shows that rare-earth oxide (REO) additives significantly affect the depth of the borated layers. In VKS-5 steel, which has a fine-grained structure (approximately 5 – 8 µm), grain boundary diffusion contributes most prominently – particularly with the addition of yttrium and lanthanum oxides – reflected in the increased L_b values. Kh12MF steel, with a slightly larger grain size (8 – 12 µm), demonstrates similar trends, though the effect is less pronounced. In contrast, 40Kh steel, with coarser grains (12 – 18 µm), shows the weakest response to REO additions. These findings confirm that fine-grained structures enhance grain boundary diffusion, while in steels with larger grains, bulk diffusion plays a more dominant role in borated layer formation.

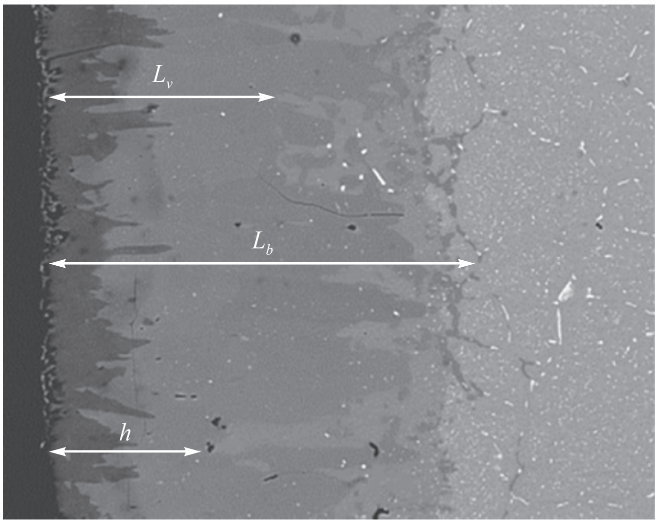

Fig. 5. Structure of the borated layer with marked depths h, L_b, L_v

Рис. 5. Структура борированного слоя с отмеченными глубинами h, L_b, L_v

To predict the kinetics of borated layer formation during liquid boriding with REO additions, estimated calculations of the grain boundary diffusion coefficient (D_b) can be performed. The L_b values can also be estimated using the formulas proposed in [19; 20] and compared with experimental values obtained through microstructural analysis. This comparison helps validate the reliability of the grain boundary diffusion coefficients derived from the experimental data.

An estimated calculation of L_b was performed using Equation (2), as proposed in [19; 20], with L_v and D values taken from Table 2. The average grain sizes were 5 – 8 µm for VKS-5 steel, 8 – 12 µm for Kh12MF steel, and 12 – 18 µm for 40Kh steel:

$$L_v = L_b\left[1 + \ln\left(1 - \frac{4}{\pi}e^{-\frac{\pi^2 D\tau}{l^2}}\right)\right], \tag{2}$$

where l is the grain size, µm.

Table 4 presents the L_b values obtained through estimated calculations using Equation (2) ($L_{b.\,\mathrm{calc}}$), alongside those determined through microstructural analysis ($L_{b.\,\mathrm{exp}}$).

The comparison shows that the calculated diffusion lengths closely match the experimental data, with deviations not exceeding 12 %. This consistency supports

Table 3. **Average values of h, L_b, L_v, D for all studied borated layers**

Таблица 3. **Средние значения h, L_b, L_v, D для всех исследуемых борированных слоев**

Composition	VKS-5				Kh12MF				40Kh			
	h, µm	L_b, µm	L_v, µm	D, m^2/s	h, µm	L_b, µm	L_v, µm	D, m^2/s	h, µm	L_b, µm	L_v, µm	D, m^2/s
No additive	39	140	91	$0.05\cdot10^{-12}$	42	105	73	$0.06\cdot10^{-12}$	100	250	150	$0.34\cdot10^{-12}$
1 % La_2O_3	52	144	91	$0.09\cdot10^{-12}$	42	105	61	$0.06\cdot10^{-12}$	75	273	125	$0.19\cdot10^{-12}$
5 % La_2O_3	64	176	96	$0.14\cdot10^{-12}$	58	145	102	$0.12\cdot10^{-12}$	54	270	162	$0.10\cdot10^{-12}$
10 % La_2O_3	68	187	119	$0.16\cdot10^{-12}$	50	124	87	$0.09\cdot10^{-12}$	83	303	165	$0.24\cdot10^{-12}$
20 % La_2O_3	62	180	112	$0.13\cdot10^{-12}$	42	104	73	$0.06\cdot10^{-12}$	81	274	164	$0.23\cdot10^{-12}$
1 % Y_2O_3	31	116	78	$0.03\cdot10^{-12}$	31	105	42	$0.03\cdot10^{-12}$	66	220	132	$0.15\cdot10^{-12}$
5 % Y_2O_3	74	269	171	$0.19\cdot10^{-12}$	52	130	78	$0.09\cdot10^{-12}$	45	150	75	$0.07\cdot10^{-12}$
10 % Y_2O_3	68	189	136	$0.16\cdot10^{-12}$	30	100	70	$0.03\cdot10^{-12}$	69	230	138	$0.17\cdot10^{-12}$
20 % Y_2O_3	46	127	80	$0.07\cdot10^{-12}$	51	100	63	$0.09\cdot10^{-12}$	51	170	102	$0.09\cdot10^{-12}$
1 % Sc_2O_3	38	139	76	$0.05\cdot10^{-12}$	44	110	66	$0.07\cdot10^{-12}$	73	245	171	$0.18\cdot10^{-12}$
5 % Sc_2O_3	40	147	94	$0.05\cdot10^{-12}$	24	82	57	$0.02\cdot10^{-12}$	48	162	113	$0.08\cdot10^{-12}$
10 % Sc_2O_3	53	146	93	$0.09\cdot10^{-12}$	29	96	54	$0.03\cdot10^{-12}$	49	164	98	$0.08\cdot10^{-12}$
20 % Sc_2O_3	23	87	55	$0.02\cdot10^{-12}$	0	0	0	0	34	113	68	$0.04\cdot10^{-12}$

the reliability of the calculation method and validates the experimental findings.

Using Equation (3), proposed in [19; 20], and the L_b values from Table 3, the grain boundary diffusion coefficient (D_b) can be estimated:

$$L_b = \sqrt{\frac{D_b \delta l}{8D} e^{\frac{\pi^2 D\tau}{l^2}}}, \qquad (3)$$

where δ is the interatomic spacing, nm, used to estimate the average grain boundary thickness.

The estimated grain boundary diffusion coefficients are summarized in Table 5.

Analysis of the data in Table 5 shows that the calculated grain boundary diffusion coefficients are generally in good agreement with the experimental values, confirming the adequacy of the chosen calculation approach. In all

Table 4. **$L_{b.\mathrm{calc}}$ and $L_{b.\mathrm{exp}}$ values**

Таблица 4. **Значения $L_{b.\mathrm{расч}}$ и $L_{b.\mathrm{эксп}}$**

Composition	VKS-5		Kh12MF		40Kh	
	$L_{b.\mathrm{calc}}$	$L_{b.\mathrm{exp}}$	$L_{b.\mathrm{calc}}$	$L_{b.\mathrm{exp}}$	$L_{b.\mathrm{calc}}$	$L_{b.\mathrm{exp}}$
No additive	137.9	140	95.7	105	213.3	250
1 % La_2O_3	138.8	144	103.9	105	268.1	273
5 % La_2O_3	164.8	176	138.5	145	274.4	270
10 % La_2O_3	164.1	187	136.9	124	306.2	303
20 % La_2O_3	196.7	180	100.4	104	260.2	274
1 % Y_2O_3	112.9	116	102.1	105	214.1	220
5 % Y_2O_3	271.6	269	118.9	130	157.1	150
10 % Y_2O_3	195.7	189	94.9	100	223.6	230
20 % Y_2O_3	123.8	127	105.9	100	171.6	170
1 % Sc_2O_3	127.9	139	104.9	110	249.5	245
5 % Sc_2O_3	135.4	147	85.2	82	169.1	162
10 % Sc_2O_3	130.4	146	106.2	96	168.9	164
20 % Sc_2O_3	81.8	87	0	0	117.3	113

Table 5. **Estimated values of grain boundary diffusion coefficients**

Таблица 5. **Оценочные значения коэффициентов диффузии по ГЗ**

Composition	Diffusion coefficients, m²/s					
	VKS-5		Kh12MF		40Kh	
	$D_{b.\text{calc}}$	$D_{b.\text{exp}}$	$D_{b.\text{calc}}$	$D_{b.\text{exp}}$	$D_{b.\text{calc}}$	$D_{b.\text{exp}}$
No additive	$0.6\cdot10^{-9}$	$0.6\cdot10^{-9}$	$0.3\cdot10^{-9}$	$0.4\cdot10^{-9}$	$0.9\cdot10^{-8}$	$0.1\cdot10^{-7}$
La_2O_3 1 %	$0.1\cdot10^{-8}$	$0.1\cdot10^{-8}$	$0.4\cdot10^{-9}$	$0.4\cdot10^{-9}$	$0.8\cdot10^{-8}$	$0.9\cdot10^{-8}$
La_2O_3 5 %	$0.2\cdot10^{-8}$	$0.3\cdot10^{-8}$	$0.1\cdot10^{-8}$	$0.2\cdot10^{-8}$	$0.5\cdot10^{-8}$	$0.4\cdot10^{-8}$
La_2O_3 10 %	$0.3\cdot10^{-8}$	$0.3\cdot10^{-8}$	$0.9\cdot10^{-9}$	$0.8\cdot10^{-9}$	$0.1\cdot10^{-7}$	$0.1\cdot10^{-7}$
La_2O_3 20 %	$0.3\cdot10^{-8}$	$0.3\cdot10^{-8}$	$0.4\cdot10^{-9}$	$0.4\cdot10^{-9}$	$0.9\cdot10^{-8}$	$0.1\cdot10^{-7}$
Y_2O_3 1 %	$0.3\cdot10^{-9}$	$0.3\cdot10^{-9}$	$0.2\cdot10^{-9}$	$0.2\cdot10^{-9}$	$0.4\cdot10^{-8}$	$0.4\cdot10^{-8}$
Y_2O_3 5 %	$0.8\cdot10^{-8}$	$0.8\cdot10^{-8}$	$0.8\cdot10^{-9}$	$0.9\cdot10^{-9}$	$0.1\cdot10^{-8}$	$0.9\cdot10^{-9}$
Y_2O_3 10 %	$0.4\cdot10^{-8}$	$0.3\cdot10^{-8}$	$0.2\cdot10^{-9}$	$0.2\cdot10^{-9}$	$0.5\cdot10^{-8}$	$0.5\cdot10^{-8}$
Y_2O_3 20 %	$0.7\cdot10^{-9}$	$0.7\cdot10^{-9}$	$0.6\cdot10^{-9}$	$0.5\cdot10^{-9}$	$0.2\cdot10^{-8}$	$0.1\cdot10^{-8}$
Sc_2O_3 1 %	$0.5\cdot10^{-9}$	$0.6\cdot10^{-9}$	$0.4\cdot10^{-9}$	$0.5\cdot10^{-9}$	$0.7\cdot10^{-8}$	$0.6\cdot10^{-8}$
Sc_2O_3 5 %	$0.6\cdot10^{-9}$	$0.7\cdot10^{-9}$	$0.1\cdot10^{-9}$	$0.1\cdot10^{-9}$	$0.1\cdot10^{-8}$	$0.1\cdot10^{-8}$
Sc_2O_3 10 %	$0.9\cdot10^{-9}$	$0.1\cdot10^{-9}$	$0.2\cdot10^{-9}$	$0.2\cdot10^{-9}$	$0.1\cdot10^{-8}$	$0.1\cdot10^{-8}$
Sc_2O_3 20 %	$0.1\cdot10^{-9}$	$0.1\cdot10^{-9}$	0	0	$0.3\cdot10^{-9}$	$0.3\cdot10^{-9}$

the steels studied – particularly in VKS-5 – an increase in boron penetration into the matrix was observed with the addition of lanthanum and yttrium oxides.

CONCLUSIONS

The structure of borated layers formed in melts containing 5, 10, and 20 wt. % of lanthanum, yttrium, and scandium oxides was investigated. The depth of the resulting layers was measured. It was found that additions of lanthanum and yttrium oxides significantly increase the depth of the borated layers, whereas scandium oxide either has no effect or reduces the layer depth.

X-ray phase analysis revealed the formation of low-melting rare-earth borates ($LaBO_3$, YBO_3, $ScBO_3$) in the boriding melts. These phases improve the fluidity of the melt, facilitating more efficient transport of boron atoms to the grain boundaries and enhancing their delivery into the steel. This leads to higher boron concentrations within the grains and plays a key role in forming deeper and more uniform borated layers.

Estimated values of both bulk and grain boundary diffusion coefficients were obtained. The addition of yttrium oxide increased the bulk diffusion coefficient in VKS-5 steel by 280 %. In Kh12MF steel, lanthanum oxide led to an 83 % increase. In 40Kh steel, no increase in the bulk diffusion coefficient was recorded in any of the studied cases. The addition of lanthanum oxide resulted in a 1000 % increase in the grain boundary diffusion coefficient in VKS-5 and Kh12MF steels. The addition of yttrium oxide resulted in a 1000 % increase in grain boundary diffusion in VKS-5 steel, 135 % in Kh12MF, and 87 % in 40Kh. The addition of scandium oxide led to a 160 % increase in grain boundary diffusion in VKS-5.

VKS-5 steel exhibited the strongest response to REO additions, attributed to its fine-grained structure and the dominant role of grain boundary diffusion. In Kh12MF steel, which has a medium grain size, the effect was noticeable but less pronounced. In 40Kh steel, which has a coarser grain structure, REO additions in some cases contribute to an increase in boriding depth, although bulk diffusion remains significant.

The grain boundary diffusion coefficients obtained through modeling were in good agreement with experimental values, confirming the reliability of the calculation methods and their suitability for modeling diffusion processes in steels.

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