THE OPTIMUM CONTENT OF BORON IN STEEL

A. A. Azarkevich,[1] L. V. Kovalenko,[1] and V. M. Krasnopolskii[1]

Boron microalloying of steel allows the manufacturer to increase its hardenability or decrease the content of alloying elements. Boron steels have a wide application range, but the optimum boron content that would ensure maximum hardenability of boron steels has not been strictly determined. In this paper, the effect of the boron content (0.000005 – 0.005%) on the hardenability of low-carbon and low-alloy steels is investigated.

The high efficiency of boron microalloying is explained by the fact that boron has a small atomic radius and a very low solubility in iron, which causes it to concentrate mainly on the boundaries of austenite grains, which attract various structure defects. Boron atoms are arranged in regions with defects, decreasing the energy of the boundaries and the probability of generating crystallization centers, which leads to an increase in the hardenability of steels [1]. The dominating presence of boron at the boundaries of austenite grains has been proved experimentally [2]. Only the dissolved boron exerts a favorable effect on the hardenability [3]. As shown in [4], for the hardenability to be increased, the concentration of boron in the solid solution should be at least 0.0008%.

Taking into account that the presence of boron decreases the energy of grain boundaries, we can assume that the greatest amount of boron will be observed in regions with multiple defects, where the formation of ferrite is the most probable. Therefore, in order to attain maximum hardenability in steels with a specified composition in specific hardening conditions, the content of dissolved boron should not exceed that needed for the decrease of the boundaries' energy in regions with ferrite formations.

Since the available published data are contradictory, we investigated low-alloy steels with different weight fractions of boron (from 0.000005 to 0.005%), in order to establish its optimum concentration (Table 1). For example, the optimum boron concentration is determined as 0.001 – 0.006% in [5], 0.0010 – 0.0015% in [6], and 0.0001 – 0.0009% in [7].

Steels were melted in a 200-kg induction furnace. Having obtained the required composition of the principal alloying

elements, we placed into the furnace 100 g of aluminum, up to 400 g of 33% ferrotitanium, and the necessary amount of ferroboron allowing for 70% assimilation of the boron.

The metal was kept for 1.5 min and then 50 kg of the metal was poured into a 50-kg mold. Then the necessary amount of ferroboron was added, and then a new 50-kg por-

TABLE 1

Heat	Weight fractions of elements, %					B	
	C	Mn	Si	Cr	Cu	calculated	actual
1	0.19	0.41	0.13	0.04	0.07	0	–
	0.19	0.42	0.13	0.04	0.07	0.00005	Traces
	0.19	0.39	0.12	0.04	0.07	0.00050	Traces
	0.19	0.40	0.12	0.04	0.07	0.00500	0.0040
2	0.17	0.68	0.27	0.08	0.07	0	–
	0.17	0.60	0.28	0.08	0.07	0.00005	Traces
	0.17	0.60	0.28	0.08	0.07	0.00500	0.0050
3	0.20	0.96	0.64	0.06	0.24	0	–
	0.20	0.98	0.60	0.06	0.24	0.00005	Traces
	0.20	0.98	0.60	0.06	0.24	0.00050	Traces
	0.20	0.98	0.60	0.06	0.24	0.00500	0.0040
4	0.26	0.86	0.59	0.10	0.23	0.00005	Traces
	0.26	0.86	0.59	0.09	0.22	0.00050	Traces
	0.26	0.86	0.59	0.10	0.25	0.00500	0.0050
5	0.26	0.96	0.67	0.56	0.29	0	–
	0.26	0.93	0.64	0.52	0.29	0.000005	Not found
	0.26	0.94	0.64	0.52	0.29	0.000050	Traces
	0.26	0.94	0.64	0.50	0.29	0.000500	< 0.0010
6	0.29	1.66	1.29	0.09	0.20	0	–
	0.29	1.67	1.30	0.09	0.20	0.00005	Traces
	0.29	1.66	1.32	0.09	0.20	0.00050	Traces
	0.28	1.66	1.30	0.09	0.20	0.00500	0.005

Note. Rolled steel contained 0.02 – 0.03% of aluminum and titanium.

[1] Ukrainian Research Institute of Metallurgy, Kharkov, Ukraine.

tion of steel was molded. In this way, we obtained four ingots with different compositions in one heat.

The ingots were rolled into a strip $10 - 30$ mm thick, from which the specimens were cut, rolled, and heat-treated. The connection between the hardenability of the steel and its boron content was determined by measuring the hardness (in the center of a specimen with respect to the thickness), of the hot-rolled and quenched specimens $(10 - 30) \times 60 \times 60$ mm in size, and investigating their microstructure. The fracture toughness was investigated for standard specimens cut from ingots $15 \times 15 \times 120$ mm (radius of cut 1 mm) and hardened from 900°C and tempered at 200°C.

The results are presented in Table 2.

Analysis of the data in Table 2 shows that even a 0.000005% content of boron affects the hardenability, while the boron content ensuring the maximum hardenability decreases with increasing level of alloying and cooling rate. For properly deoxidized low-carbon and low-alloy steels, maximum hardenability can be attained when the total content of boron is equal to 0.00005 – 0.001%.

The positive effect of small (0.000005%) amounts of boron on the hardenability with an increase in the temperature of heating for quenching can be explained by the growth of boron concentration along the boundaries of austenite grains due to the decrease of the area of the boundaries, which accompanies the grain growth. At the same time, for the 16GFR steel containing about $n \times 10^{-3}$% of boron, an increase in the austenization temperature from 920 to 1100°C leads to a substantial decrease in the hardenability [8].

The effects of boron, the rolling parameters, and the post-deformation cooling on the specific toughness were investigated for heat 3, because its carbon, manganese, and silicon contents were close to the average values for all heats. Moreover, the chemical composition of heat 3 was the closest to the 25GSRD steel for which a large set of industrial data on the impact toughness has been collected.

After heating to 1150°C specimens $22 \times 80 \times 120$ mm in size from heat 3 were rolled to a thickness of 11 mm in two passes. The rolling and cooling regimes are presented in Table 3.

TABLE 2

Heat	Quenching regime	h, mm	v_{cool}, °C/sec	HRC of specimens with different contents of boron (%)				
				0	5×10^{-6}	5×10^{-5}	5×10^{-4}	5×10^{-3}
1	950°C, water	10	108	22	–	26	40	39
	950°C, oil	22	49	165 HB	–	174 HB	182 HB	192 HB
2	900°C, water	12	96	33	–	44	–	44
	1100°C, water	12	96	44	–	44	–	44
3	900°C, oil	15	15	21	–	31	30	26
		22	11	187 HB	–	207 HB	212 HB	194 HB
4	900°C, oil	15	15	–	–	44	33	29
5	900°C, oil	22	11	27	27	31	30	–
	1100°C, oil	22	11	29	32	35	35	–
6	Cooling after rolling	30	0.4	223 HB	–	243 HB	243 HB	247 HB
	from 900°C in oil	30	8	48	–	48	48	48

Notation. h) Thickness of a specimen; v_{cool}) rate of cooling from the austenization temperature to 300°C.

The results of the tests for impact toughness in specimens from heat 3 after rolling and cooling show that even very low contents of boron (0.00005%) reduce the impact toughness (Table 4). In boron microalloying, the greatest decrease in the impact toughness was observed at low testing temperatures. An increase in the boron content causes a further decrease in the impact toughness.

The impact toughness of heat 3 $(t_{test} = -60°C)$ after quenching and tempering $(42 - 44$ HRC $)$ was $64 - 85$ J/cm^2 for any boron content.

In specimens with a high boron content (0.0005 – 0.005%) subjected to rapid cooling, we found point formations (see Fig. 1) arranged in chains connected at large angles ($\sim 120°$). The absence of such formations in specimens containing no boron, and the increase in their size with the introduction of growing amounts of boron, allows us to conclude that these chains are borides. Frequently, these chains intersect the boundaries of ferrite grains at right angles, which indicates that the borides do not occur along the boundaries of austenite grains from which the ferrite grains have been formed.

It has been established in [1] that the concentration of boron along the boundaries of austenite grains decreases with cooling. As mentioned above, point inclusions are formed only in specimens subjected to rapid cooling, which substan-

TABLE 3

Rolling regime	t_{roll}, °C	Cooling after rolling
1	1150 – 1100	In air
2	1150 – 1100	In furnace to 650°C and then in air
3	1000 – 950	In air
4	1000 – 950	In furnace to 650°C and then in air
5	1150 – 1100	In water to 770 – 800°C and then in air
6	1150 – 1100	In water to 770 – 800°C, in furnace to 650°C, and then in air

TABLE 4

Rolling regime	Impact toughness a_1, J/cm^2, in specimens of heat 3 with different boron contents (%)			
	0	5×10^{-5}	5×10^{-4}	5×10^{-3}
1	$51 - 96/43 - 74$	$39 - 79/11 - 12$	$25 - 51/5 - 7$	$37 - 49/7$
2	$61 - 81/58 - 67$	$46 - 48/9 - 10$	$27 - 59/7 - 11$	$15 - 44/7$
3	$67 - 85/39 - 71$	$41 - 90/10 - 27$	$40 - 70/7 - 8$	$34 - 60/9 - 15$
4	$41 - 88/46 - 64$	$46 - 61/7 - 10$	$22 - 79/6 - 9$	$15 - 20/6 - 7$
5	$83 - 103/41 - 43$	$48 - 61/12 - 21$	$41 - 46/6 - 7$	$39 - 48/5 - 17$
6	$85 - 90/35 - 43$	$45 - 61/9 - 27$	$41 - 51/7$	$41 - 55/6 - 16$

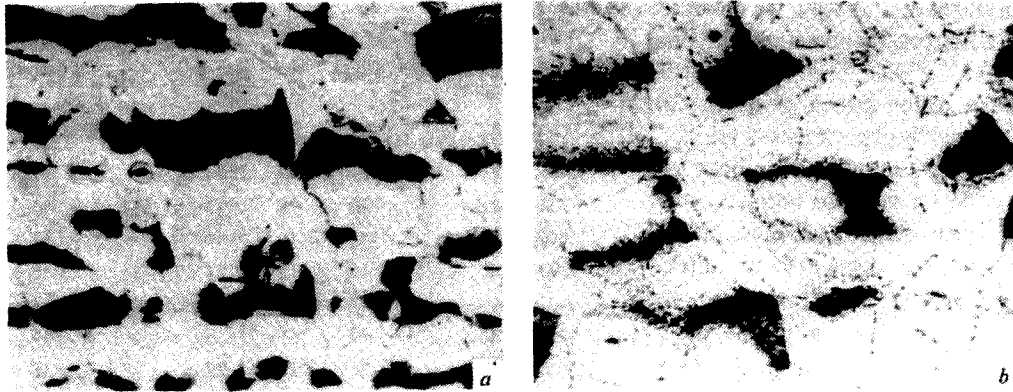**Note.** The numerator gives the impact toughness at $-20°C$, the denominator at $-60°C$.

Fig. 1. Microstructure of heat *3* after rolling and cooling by regime 6 (× 800): *a*) steel containing no boron; *b*) steel with 0.005% of boron.

tially reduces the rate of diffusion processes at high temperatures (800 – 1100°C). The size of these formations in specimens cooled rapidly in a furnace is greater than in specimens cooled in air. Therefore, we can assume that borides have been formed near the boundaries of austenite grains existing before rolling and in the rolling process. Thus, boride formations are possible already at a 0.0005% boron content. This may be the reason behind the decrease in the hardenability of heats *3* and *4* with an increase of the boron content.

CONCLUSIONS

1. The boron content ensuring maximum hardenability is decreased when the alloying level and the cooling rate of steels is increased; for low-carbon and low-alloy steels it is 0.00005 – 0.0005%.

2. If the boron content is below the optimum value, an increase in the austenization temperature increases the hardenability; and if it exceeds the optimum value, the hardenability is decreased.

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