Machinery & Energetics. Journal of Rural Production Research. Kyiv. Ukraine. 2021, Vol. 12, No 4, 5-13
ISSN 2663-1334 (print), ISSN 2663-1342 (online), www.journals.nubip.edu.ua/index.php/Tekhnica

http://dx.doi.org/10.31548/machenergy2021.04.005

UDK 621:664: 669.01(075)

CHEMICAL COMPOSITION INFLUENCE ON ELEMENT SEGREGATION AND PROPERTIES OF STEEL STRIP MANUFACTURED BY STRIP CASTING ROUTE

Ye. G. Aftandiliants

National University of Life and Environmental Sciences of Ukraine, Ukraine.

Speciality of article: 131 – applied mechanics.

Corresponding author: aftyev@yahoo.com.

Article History: Received – June 2021, Accepted – November 2021, Published – 17 December 2021.
Bibl. 14, fig. 10, tabl. 6.

Abstract. The article presents the results of the chemical composition influence on element segregation and properties of steel strip manufactured by strip casting route.

It is shown that in the transition from the slab production with a thickness of 220 mm to slabs with a thickness of 1.2 mm, the thickness of the segregated diffusion layer in the case of the continuous strip casting process is 4.1 - 12.4 times less than in the case of traditional continuous casting.

The carbon, nitrogen, copper, tin, phosphorus and sulfur segregation percentage in the continuous strip casting process is 1.7 - 5.1 times less than in traditional continuous casting.

A method is proposed for calculating the element segregation based on the equality of the segregation level in traditional and strip continuous casting.

It has been established that the content of elements in steels during two-roll continuous casting can be increased for impurities such as S, O, N, P, H from a minimum of 3 for P to a maximum of 497% for S. For residual elements such as Pb, Bi, Sn, Cu, Sb, Zn, As minimum increase from 1.1 for Zn to maximum 401% for Pb. The content of such alloying elements as B, Se, Al, Te, Ca, Mg, Ce, C, La, Nb, Ti, Mn, Ni, Si can be increased from a minimum of 1.1 for Si and Mn to a maximum of 675% for B.

The time and rate of cooling of a 20-ton coil of steel strip are calculated, which are, respectively, 13.7 hours and 0.0051 °C/s. Such cooling conditions create the prerequisites for the precipitation of chromium carbides and an increase in the tendency of steel to intergranular corrosion.

It was found that for eliminate this problem, it is necessary to increase the cooling time with water after rolling to a strip temperature from 300 to 400 °C.

Keywords: steel, chemical composition, segregation, properties, yield strength, tensile strength, cooling, strip casting.

Introduction

Continuous casting of steels is one of the promising areas of modern steelmaking [1]. The state of steel continuous casting analysis shows that in recent decades there has been a tendency towards an increase of the casting speed and a decrease of the slab thickness [2]. Such a change of the process parameters is accompanied by a change in the distribution of alloying elements and impurities in the metal during crystallization and, as a consequence, of properties [3]. Therefore, research to determine the patterns of change in the distribution of alloying elements and impurities in steel and their properties with an increase of the casting speed and a decrease of the slab thickness is relevant [4].

Formulation of problem

The research is aimed at determining the quantitative patterns of changes in the segregation of elements with an increase in the pouring rate and their limiting values from the condition of maintaining the level of mechanical properties.

Analysis of recent research results

The transition from the production of 220 mm thick slabs to 1.2 to 1.8 mm thin slabs is accompanied by an increase of casting speed and average speed of crystallization in 30-66 and 34–50 times, accordingly [5]. Total solidification time decreases in 415-922 times (table 1).

In according with table 3 the residence time of steel in the temperature interval of brittleness from 1350 to 1450 °C, for different productive route, is as follow:

- conventional continuous casting (slab thickness – 220 mm) τ = 8.33 s;
- thin slab (slab thickness – 50 mm) τ = 2 s;
- strip casting (thickness – 1.8 mm) τ = 0.121 s;
- strip casting (thickness – 1.2 mm) τ = 0.054 s.

In according with research [2], the diffusion mobility coefficient at 1400 °C will be for different elements as follow:

- carbon - $D_C = 4.53 \cdot 10^{-10}$ m²/s;
- nitrogen - $D_N = 2.43 \cdot 10^{-10}$ m²/s;

- copper - $D_{Cu} = 3.18 \cdot 10^{-12}$ m²/s;
- tin - $D_{Sn} = 2.09 \cdot 10^{-12}$ m²/s;
- phosphor - $D_P = 8.26 \cdot 10^{-13}$ m²/s;
- sulfur - $D_S = 2.55 \cdot 10^{-13}$ m²/s.

Manufacture technological parameters are shown for steel SAE 1006 at the twin rolls casting process in table 3.

Table 1. Steel strip and thick slab manufacturing parameters [1].

Parameter	Strip		Thick slab
Thickness, mm	1.2	1.8	220
Casting speed, m/min	131	59	2
Total solidification time, s	0.116	0.258	107
Average speed of crystallization, mm/s	5.172	3.488	0.103
Average shell cooling rate in mould, °C/s	1853	826	12
Average size of dendrites (x^p), mm	0.6 - 0.7	1.0 - 1.2	12.0 – 20.0
Speed of melt flow (u_∞), m/s	0.2 – 0.50		0.2 – 0.6
Coefficient of diffusion of elements (D), m²/s	$5 \cdot 10^{-9} \div 1 \cdot 10^{-8}$		
Kinematic viscosity of melt, with C = 0.054 %wt., at 1550 °C (ν), m²/s	$10.8 \cdot 10^{-7}$		

Table 2. Effect of increasing content of the residual elements on various properties of steel

N	Property	Element					
		Cu	Ni	Cr	Mo	Sn	Sb
1	Strength and hardness	+	+	+	+	+	+
2	Ductility	-	+	+	-	-	-
3	Strain hardening	-	-	0	-	-	-
4	Strain ratio	+	0	0		0	-
5	Impact resistance	+	+	0	-	0	-
6	Hardenability	+	+	+	+	+	+
7	Weldability	-	-	-	-	-	-
8	Corrosion resistance	+	+	+	+	+	-
9	Temper embrittlement	+	-	+	-	+	+

Reduction of steel solidification time and residence time of steel in temperature interval of brittleness with a decrease of the slab thickness [6], it creates the prerequisites for inhibition of the process of segregation of elements at grain boundaries [7].

Thickness of the element segregation layer around the grain boundary (δ_s) can be defined from the following formula [8]

$$\boldsymbol{\delta_s = (2 \cdot D_i \cdot \tau)^{0,5}}, \qquad (1)$$

where D_i the diffusion mobility coefficient of element I at 1400 °C.

In research [9] is shown the influence of residual elements on properties of steel strip (table 2, 4).

The table 2, 4 data show that the residual elements as Cu, Sn, Sb increase strength, hardness, corrosion resistance, hardenability, temper embrittlement and decrease ductility, strain hardening and weldability [10]. But if the increasing of the residual elements as Cu, Sn, Sb is accompanied by decreasing of grain size it will be possible to increase the content of residual elements without decreasing the mechanical properties of strip manufactured by the conventional continuous casting route [11].

For example [12-14], the elongation of steel strip for deep drawing depend on the chemical composition and the grain size according to the next formula [13]:

$$\delta = 1.4 - 2.9 \cdot [C] + 0.2 \cdot [Mn] + 0.16 \cdot [Si] - 2.2 \cdot [S] - 3.9 \cdot [P] - 0.25 \cdot [Sn] + 0.017 \cdot D^{-0.5}, \quad (2)$$

where [C], [Mn], [Si], [S], [P], [Sn] are the content of C, Mn, Si, S, P, Sn in steel (wt. %);

D – is grain size, mm.

Results of research

Segregation. Element segregation to the austenite grain boundary depends of the element diffusion mobility, the residence time of steel in the temperature interval of brittleness from 1350 to 1450 °C and the austenite grain size. Steel strip and thick slab manufacturing parameters are shown in table 3.

Calculated results are presented in figures 1 and 2.

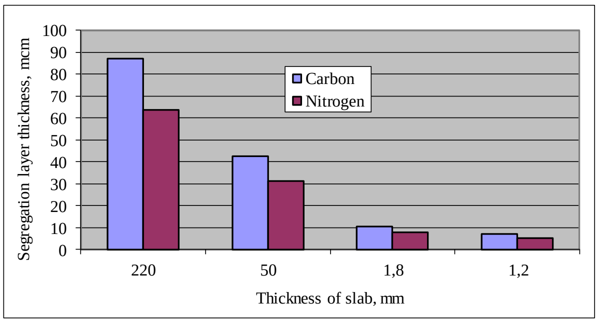

Fig. 1. Dependence of the segregation layer of carbon and nitrogen of slab and strip thickness.

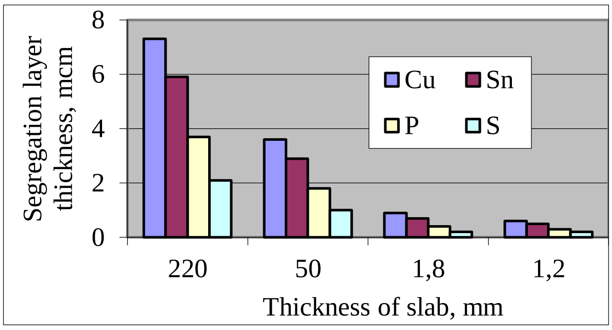

Fig. 2. Dependence of the segregation layer of slab and strip thickness

It could be observed from the fig. 1 and 2 that the thickness of the segregation diffusion layer (δ) in case of the strip casting process is 4.06 to 12.41 times smaller than for the conventional continuous casting.

Table 3. Manufacture technological parameters of steel SAE 1006 at the twin rolls casting process.

Diameters of rolls 600 mm				
Name of parameter	Volume of parameters			
Speed of casting, m/min (m/s)	59 (0.983)	79 (1.317)	105 (1.75)	131 (2.183)
Thickness of strip (δ_{strip}), mm	1.8	1.65	1.4	1.2
Meniscus – Kissing point				
Time of contact since meniscus to kissing point, s	0.258	0.194	0.145	0.116
Surface				
Surface temperature at meniscus, ºC	1508	1508	1510	1515
Surface temperature at kissing point, ºC	1295	1270	1285	1300
Δt, ºC	213	238	225	215
Average cooling rate of surface,ºC/s (ºC/min)	826	1227	1552	1853)
Center (temperature of liquid steel in center, at meniscus equal 1550ºC)				
Centre temperature at kissing point, ºC	1455	1462	1467	1470
Δt, ºC	95	90	83	80
Average cooling rate of centre, ºC/s (ºC/min)	368 (22080)	464 (27840)	572 (34320)	690 (41400)
Kissing point – rolling				
Average temperature at kissing point, ºC	1390	1391	1395	1402
Temperature at rolling, ºC	≈ 1140			
Cooling Time, s	13.53 (13.3/0.983)	10.1 (13.3/1.317)	7.6 (13.3/1.75)	6.09 (13.3/2.183)
Average cooling rate from the kissing point to rolling, ºC/s (ºC/min)	18.48 (1109)	24.85 (1491)	33.55 (2013)	43.02 (2581)
Rolling				
Temperature at rolling, ºC	≈ 1140			
Thickness of strip after rolling,mm	1.6	-	-	0.8
Reduction of area, %	12	-	-	33
Cooling after rolling				
Temperature after rolling, ºC	880 - 900			
Cooling time (since 890 ºC to ≈550 ºC), s	17.29 = 17/0.983	12.91 = 17/1.317	9.71 = 17/1.75	7.79= 17/2.183
Average cooling rate after rolling, ºC/s (ºC/min)	19.66 (1180)	26.34 (1580)	35.02 (2101)	43.65 (2619)
Cooling in coiler. Average speed of cooling of coil from 550 oC to 300 °C ≈ 0.352 ºC/min. Coil weight ≈ 20 ton				

Table 4. Effect of residual elements on Yield Strength (YS) and Tensile Strength (TS).

N	Type of steel and heat treatment	Strength increment (MPa per 1 wt. %)									
		Cu		Ni		Cr		Mo		Sn	
		YS	TS	YS	TS	YS	TS	YS	TS	YS	TS
1	0.3% C steel normalized	83	62	55	35	62	90	13	69	-	-
2	0.2% C steel as rolled	-	-	55	69	90	131	-	-	-	-
3	Low-C steel normalized or annealed	41	13	0	13	-28	-41	13	55	124	-
4	Low-C steel normalized	41	13	0	13	-28	-35	13	55	131	-
5	Decarburized iron annealed	-	-	-	76	0	-	35	-	-	-
6	Decarburized steel annealed	62	76	35	48	6.9	0	48	138	-	-
7	Ti –gettered iron annealed	-	-	41	-	6.9	-	-	-	-	-
8	0.005C – Fe quenched	-	-	41	-	-	-	-	-	-	-
9	Very pure iron annealed	-	-	-	-	6.9	-	-	-	-	-
10	High-C steel normalized	-	-	-	-	62	-	-	-	173	-
11	Low-C steel normalized	76	55	41	35	55	69	-	-	-	-
12	Various steels, various trtmts	-	-	-	-	-	-	-	-	110	138
13	Various steels, various trtmts	-	-	-	-	-	-	-	-	110	131
14	High-C steel as rolled	-	-	-	-	131	138	-	-	-	-
15	High-C steel as rolled	35	48	90	69	173	200	6.9	48	-	-
16	Low-C iron annealed	-	-	-	41	-	13	-	41	-	-
17	Low-C iron annealed	-	-	-	35	-	-13	-	41	-	-

The carbon, nitrogen, copper, tin, phosphorus, sulphur segregation compared to the grain volume is shown in figures 3 and 4.

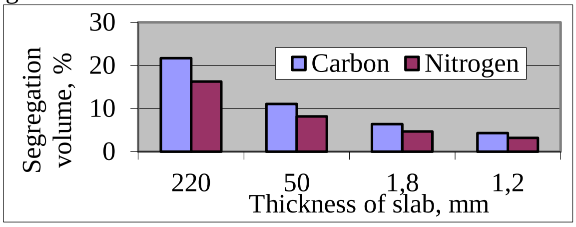

Fig. 3. Dependence of carbon and nitrogen segregation of slab and strip thickness.

The percentage of the segregation volume in case of the strip casting process is from 1.74 to 5.06 times smaller than for the conventional continuous casting process (fig 3, 4).

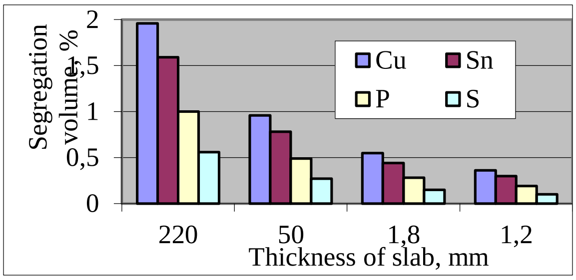

Fig. 4. Dependence of copper, tin, phosphorus and sulphur segregation of slab and strip thickness.

In according with research [6], the element distribution in diffusion layer could be calculated as follow:

$$(C_{bi} + C_{oi})/(C_{bi} - C_{oi}) = (4 \cdot D_i \cdot \tau)/x^2, \quad (3)$$

where C_{oi} and C_{bi} – are respectively the content of element i on the grain boundary before diffusion time and after diffusion time τ (see figure 5),

x – thickness of the boundary segregation layer.

After transformation, the formula 3 will have the follow form:

$$\mathbf{C_{bi} = C_{oi} \cdot (4 \cdot D_i \cdot \tau + x^2)/(4 \cdot D_i \cdot \tau - x^2)}, \quad (4)$$

From formula (2) and (4) could be observed that the minimum concentration of element i in the boundary segregation layer will be $C_{bi} = C_{oi}$, at x = 0. The maximum concentration of element i in the boundary segregation layer will be $C_{bi} = 3 \cdot C_{oi}$ at x = δ. Distribution of element i in boundary segregation layer is shown on fig. 5.

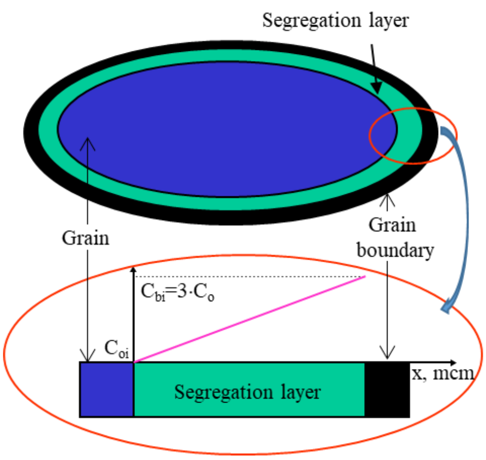

Fig. 5. Distribution of element i in boundary segregation layer.

If it is considered the average content of element I in the segregation layer equal to $2 \cdot C_{oi}$, it can be calculated the segregation Index I_{segr} as:

$$I_{segr} = W_{segr(I)}/V_{grain} = \mathbf{= 12 \cdot V_{sl(i)} \cdot \rho \cdot C_{oi}/(100 \cdot \pi \cdot D^3)}, \quad (5)$$

where $W_{segr(I)}$ – the segregation weight of element I; V_{grain} – grain volume; $V_{sl(i)}$ – segregation volume of element I; ρ - segregation density; D – grain size.

In case of considering an equal segregation for the conventional continuous casting process (ICCC) and for the strip casting process (ISC) the formula presents the relationship of content of the element I in steel for the strip casting (Co(i)str) and for the conventional continuous casting (Co(i)ccc) is

$$C_{o(i)str} = (D^3_{str}/D^3_{ccc}) \cdot (V_{sl(i)ccc}/V_{sl(i)str}) \cdot C_{o(i)ccc}, \quad (6)$$

where Dstr and Dccc – are respectively the grain sizes for the strip and conventional continuous casting processes;

Vsl(i)ccc and Vsl(i)str – are respectively the segregation volume of the element I for the conventional continuous casting and strip casting processes.

Results of calculation, according the formula 6, are presented in figure 6.

The thickness of the segregation diffusion layer for the strip casting is 4.06 – 12.41 times smaller than for the continuous casting process.

It is possible to increase element content in steel for the strip casting process respect to the conventional continuous casting as presented below (table 5):

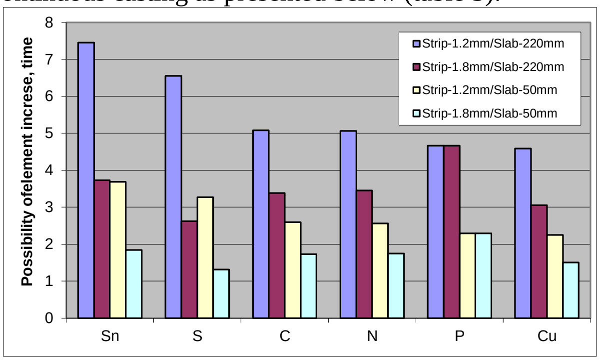

Fig. 6. Possibility of increasing the element content in steel for the strip casting process respect to the conventional continuous casting process.

Table 5. Possible of element content increasing in steel for the strip casting process respect to the conventional continuous casting

Element	Thickness of strip casting			
	1.8 mm	1.2 mm	1.8 mm	1.2 mm
	Compare to slab thickness			
	220 mm		50 mm	
P	4.7	4.7	2.3	2.3
Sn	3.7	7.4	1.8	3.7
N	3.5	5.0	1.7	2.5
C	3.4	5.1	1.6	2.6
Cu	3.1	4.6	1.5	2.2
S	2.6	6.5	1.3	3.3

Properties. It is possible to calculate the increasing of the element content in steel for the strip casting process by considering the same elongation for both manufacturing routes: strip casting and conventional casting.

Calculation of increasing limit content for Sn ($[Sn]_{str} = \Delta Sn + [Sn]_{ccc}$) for strip casting.

$$\delta_{str} = \delta_{ccc} - 0.25 \cdot [Sn]_{str} + 0.017 \cdot D_{ccc}^{-0.5} =$$

$$= -\ 0.25 \cdot [Sn]_{ccc} + 0.017 \cdot D_{ccc}^{-0.5}, \quad (7)$$

$$[Sn]_{str} - [Sn]_{ccc} = 0.068 \cdot (D_{str}^{-0.5} \cdot D_{ccc}^{-0.5}), \quad (8)$$

$$[Sn]_{ccc} + \Delta Sn - [Sn]_{ccc} = 0.068 \cdot (D_{str}^{-0.5} \cdot D_{ccc}^{-0.5}), \quad (9)$$

$$\Delta Sn = 0.068 \cdot (D_{str}^{-0.5} \cdot D_{ccc}^{-0.5}), \quad (10)$$

In according with work [7] for thin slab of size 50 mm, the increasing limit content for Sn is next:

$$\Delta Sn_{max} = 0.068 \cdot (0.0202^{-0.5} - 0.0381^{-0.5}) =$$

$$= 0.068 \cdot 1.91 = 0.13\%, \quad (11)$$

$$Sn_{strmax} = [Sn]_{ccc} + 0.13\%, \quad (12)$$

$$\Delta Sn_{min} = 0.068 \cdot (0.0227^{-0.5} - 0.0284^{-0.5}) = 0.068 \cdot 0.703 = 0.05\%, \quad (13)$$

$$\Delta Sn_{strmin} = [Sn]_{ccc} + 0.05\%, \quad (14)$$

Calculation of increasing limit content for S ($[S]_{str} = \Delta S + [S]_{ccc}$) for strip casting.

$$-\ 2.2 \cdot [S]_{str} + 0.017 \cdot D_{str}^{-0.5} = -\ 2.2 \cdot [S]_{ccc} +$$

$$+0.017 \cdot D_{ccc}^{-0.5}, \quad (14a)$$

$$[S]_{str} - [S]_{ccc} = 0.00773 \cdot (D_{str}^{-0.5} -\cdot D_{ccc}^{-0.5}), \quad (15)$$

$$[S]_{str} + \Delta S - [S]_{ccc} = 0.00773 \cdot (D_{str}^{-0.5} -\cdot D_{ccc}^{-0.5}), \quad (15a)$$

$$\Delta S = 0.00773 \cdot (D_{str}^{-0.5} -\cdot D_{ccc}^{-0.5}), \quad (16)$$

$$\Delta S_{max} = 0.00773 \cdot (0.0202^{-0.5} - 0.0381^{-0.5}) =$$

$$= 0.00773 \cdot 1.91 = 0.015\%, \quad (17)$$

$$[S]_{strmax} = [S]_{ccc} + 0.015\%, \quad (18)$$

$$\Delta S_{min} = 0.00773 \cdot (0.0227^{-0.5} - 0.0284^{-0.5}) = 0.00773 \cdot 0.703 = 0.0054\%, \quad (19)$$

$$[S]_{strmin} = [S]_{ccc} + 0.0054\%, \quad (20)$$

Calculation of increasing limit content for P ($[P]_{str} = \Delta P + [P]_{ccc}$) for strip casting.

$$-\ 3.9 \cdot [P]_{str} + 0.017 \cdot D_{str}^{-0.5} =$$

$$-\ 3.9 \cdot [P]_{ccc} + 0.017 \cdot D_{ccc}^{-0.5}, \quad (21)$$

$$[P]_{str} - [P]_{ccc} = 0.00436 \cdot (D_{str}^{-0.5} -\cdot D_{ccc}^{-0.5}) \quad (22)$$

$$[P]_{str} + \Delta P - [P]_{ccc} = 0.00436 \cdot (D_{str}^{-0.5} -\cdot D_{ccc}^{-0.5}), \quad (23)$$

$$\Delta P = 0.00436 \cdot (D_{str}^{-0.5} -\cdot D_{ccc}^{-0.5}), \quad (24)$$

$$\Delta P_{max} = 0.00436 \cdot (0.0202^{-0.5} - 0.0381^{-0.5}) =$$

$$= 0.00436 \cdot 1.91 = 0.0083\%, \quad (25)$$

$$[P]_{strmax} = [P]_{ccc} + 0.0083\%, \quad (26)$$

$$\Delta P_{min} = 0.00436 \cdot (0.0227^{-0.5} - 0.0284^{-0.5}) =$$

$$= 0.00436 \cdot 0.703 = 0.0031\%, \quad (27)$$

$$[P]_{strmin} = [P]_{ccc} + 0.0031\%, \quad (28)$$

Increasing of the limit of elements in steel grades for manufacture technological parameters of the twin rolls casting process according with table 3 is as presented in the table

Table 6. Increasing of the limit of elements in steel grades for manufacture technological parameters of the twin rolls casting process according with table 3.

Element	Dendrite segregation at crystallization in		Boundary microsegregation in solid steel	Elongation	Minimum increasing at crystallization in	
	δ phase	γ phase			δ phase	in γ phase
Impurities						
S	4.97	1.16	1.30	1.005	1.05	1.05
O	1.80	1.19	-	-	1.80	1.19
N	1.22	1.04	1.70	-	1.22	1.04
P	1.16	1.07	2.30	1.03	1.03	1.03
H	1.09	1.07	-	-	1.09	1.07
Residual elements						
Pb	4.01	1.04	-	-	4.01	1.04
Bi	1.47	1.05	-	-	1.47	1.05
Sn	1.18	1.06	1.80	1.05	1.18	1.05
As	1.10	1.02	-	-	1.10	1.02
Zn	1.07	1.01	-	-	1.07	1.01
Sb	1.07	1.09	-	-	1.07	1.09
Cu	1.04	1.76	1.50	-	1.04	1.76
Alloying elements						
B	67.5	1.01	-	-	67.5	1.01
Se	4.16	1.03	-	-	4.16	1.03
Al	1.80	1.19	-	-	1.80	1.19
Te	1.58	1.98	-	-	1.58	1.98
Ca	1.47	2.23	-	-	1.47	2.23
Mg	1.45	1.07	-	-	1.45	1.07
Ce	1.44	1.04	-	-	1.44	1.04
C	1.26	1.06	1.60	-	1.26	1.06
La	1.26	1.05	-	-	1.26	1.05
Nb	1.18	1.04	-	-	1.18	1.04
Ti	1.04	1.13	-	-	1.04	1.13
Mn	1.02	1.01	-	-	1.02	1.01
Ni	1.02	1.03	-	-	1.02	1.03
Si	1.02	1.01	-	-	1.02	1.01

The data in table 6 show that the element limits in steel grades for twin rolls casting process can be increasing for impurities S, O, N, P, H minimum from 3 for P to maximum 497% for S. For residual elements Pb, Bi, Sn, Cu, Sb, Zn, As minimum from 1,1 for Zn to maximum 401% for Pb. Alloying elements (B, Se, Al, Te, Ca, Mg, Ce, C, La, Nb, Ti, Mn, Ni, Si) can to increase minimum from 1,1 for Si and Mn to maximum 675% for B.

Cooling. Manufacture of steels strip by the twin rolls casting process has good base because for all steps of process, from the casting till the coiling, the forming macrostructure and the mechanical properties will be very good due to the high cooling rate of steel, but some problems can be verified during the cooling, because in this step it will be a low cooling rate.

In according with [8] the cooling time of steel pieces can be calculated by next formula:

$$\tau_{cool} = \left(2.3 \cdot G \cdot \frac{c}{F \cdot \alpha}\right) \cdot \lg\left(\frac{t_{env} - t_{stcoil}}{t_{env} - t_{fincoil}}\right), \qquad (29)$$

where τ_{cool} – cooling time of coil from t_{stcoil} (°C) to $t_{fincoil}$ (°C), hours; G – weight, kg; c - heat capacity, kJ/(kg·°C); F –surface area of coil, m^2 (D = 1.8 m, d = 0.6 m, H = 1.5 m), F = 15.8279 m^2; α = coefficient of heat transfer to the environment (α = 41.9 kJ/(m^2·h·°C) for calm air at 25 °C), kJ/(m^2·h·°C); t_{env} – temperature of the environment (°C).

The cooling time for a coiler of weight 20 ton, that has to be cooled from 550 °C to 300 °C, is τ_{cool} = (20000·0.704·2.3/(41.9·15.8279)) ·lg(25 - 550/(25 - 300)) = 13.71 hours.

Cooling rate in the above interval will be 250/13.71 = 18.23°C/h=0.304 °C/min = 0.0051 °C/s. The cooling rate is very slowly and if impurities and residual elements saturate the solid solution it is danger that in the above temperature interval the impurities and the residual elements will precipitate from the solid solution to grain boundary (fig. 7).

In according to figure 7 the content of P on the grain boundary for low alloying steel, due to cooled segregation, could be increased till 2.5 times relative to the content in grain [9].

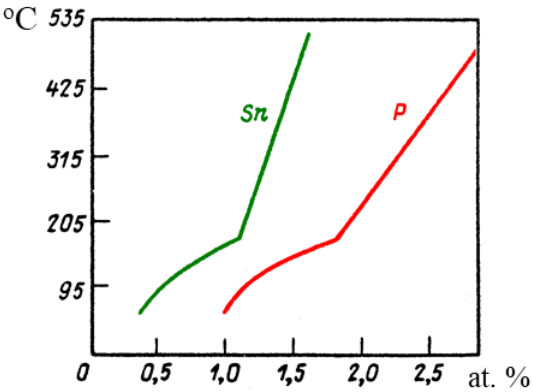

Fig. 7. Concentration of Sn and P on the grain boundaries [8].

In case of austenite steel, for example stainless steel grade, for example AISI 304, it is possible the precipitation of chromium carbides, increasing the sensitiveness the steel to inter crystallite corrosion (fig. 8).

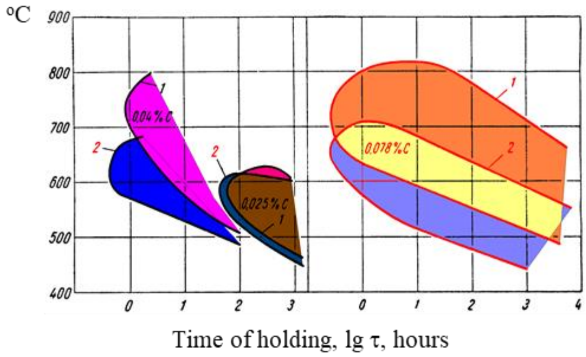

Fig. 8. Influence of temperature and time of the holding on development of the sensitiveness of stainless steel (grade AISI 304) to inter crystallite corrosion [10].

1-as – cast; 2- cold rolling on 30%

Results of research [11] show that the increasing of the cooling temperature will be accompanied with the decreasing of mechanical properties (fig. 9).

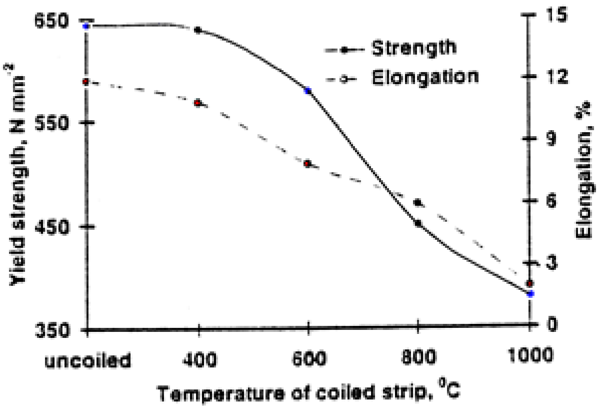

Fig. 9. Dependence of mechanical properties of strip with the coiling temperature.

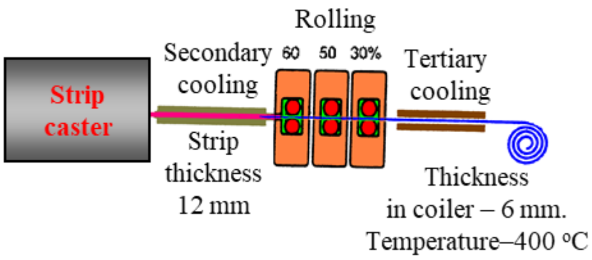

Fig. 10. Direct strip casting process.

The technological parametrs for the case presented in above figure are as follow:

- Chemical composition (% wt.):

C < 0.007, Si = 4.5, P < 0.01, Ni < 0.07, Ti < 0.02, Co < 0.02, Al < 0.01.

- Superheat – 30 °C. Diameter of rolls – 300-400 mm. Length – 150 mm.

- Casting speed – 6 m/s. Thickness of the as – cast strip – 0.1 – 0.3 mm.

- Separation force per unit length of the roll ranged from 0.2 to 2.0 kN/mm.

- Strip tension between the twin – roll and caster and the coiler ranged from 11 to 44 N/mm^2.

To avoid this problem it is necessary to increase the water cooling time after rolling till the strip temperature reaches 300 to 400 ^{o}C and afterwards the coiling has to be done, for example, as it is made in company Thyssen Krupp Stahl AG & Mannesman Demag AG Metallurgie [12] (fig. 10).

Conclusions

1. Theoretical research on the element microsegregation has shown that for the strip casting process the elements content in steel could be increased too much compared to the conventional slab casting process, maintaing the same level of micro segregation.

2. Residual elements as Cu, Sn, Sb increase strength, hardness, corrosion resistance, hardenability, temper embrittlement and decrease ductility, strain hardening and weldability. It is possible to increase the content of residual elements in steel for strip casting manufactury the same level of properties of strip manufactured by conventional casting route.

3. The element limits in steel grades for twin rolls casting process can be increasing for impurities S, O, N, P, H minimum from 3 for P to maximum 497 % for S. For residual elements Pb, Bi, Sn, Cu, Sb, Zn, As minimum from 1 for Zn to maximum 401 % for Pb. Alloying elements (B, Se, Al, Te, Ca, Mg, Ce, C, La, Nb, Ti, Mn, Ni, Si) can to increase minimum from 1 for Si and Mn to maximum 675 % for B.

4. To receive strip with good quality, for the stainless steel grades, it is necessary to decrease the coiling temperature to 300–400 ^{o}C.

Список літератури

1. *Zhi-ling Peng, Chun-gui Zhou*. Research on modeling of nonlinear vibration isolation system based on Bouc-Wen model. Defence Technology. 2014. Vol. 10. P. 371-374.

2. *Semenov M. E., Meleshenko P. A., Solovyov A. M., Semenov A. M.* Hysteretic nonlinearity in inverted pendulum problem. Springer Proceedings in Physics. 2015. Vol. 168. P. 463-507.

3. *Bernyk I., Nazarenko I., Luhovskyi O.* Effect of rheological properties of materials on their treatment with ultrasonic cavitation. Materials and technology. 2018. Vol. 4 (52). P. 465-468.

4. *Veklich A., Tmenova T., Zazimko O., Trach V., Lopatko K., Titova L., Boretskij V., Aftandiliants Y., Lopatko S., Rogovskiy I.* Regulation of biological processes with complexions of metals produced by underwater spark discharge. 2020. Springer Proceedings in Physics. Book series Nanomaterials and Nanocomposites, Nanostructure Surfaces and Their Applications. Vol. 247. P. 283-306.

5. *Nazarenko I., Dedov O., Bernyk I., Rogovskii I., Bondarenko A., Zapryvoda A., Titova L.* Study of stability of modes and parameters of motion of vibrating machines for technological purpose. Eastern-European Journal of Enterprise Technologies. 2020. Vol. 6 (7-108). P. 71-79. doi: 10.15587/1729-4061.2020.217747.

6. *Hrynkiv A., Rogovskii I., Aulin V., Lysenko S., Titova L., Zagurskiy O., Kolosok I.* Development of a system for determining the informativeness of the diagnosing parameters of the cylinder-piston group of the diesel engines in operation. Eastern-European Journal of Enterprise Technologies. 2020. Vol. 3(105). P. 19-29.

7. *Tmenova T., Valensi F., Veklich A., Cressault Y., Boretskij V., Lopatko K., Aftandilyant Y.* Etude d'un arc impulsionnel immergé à l'aide de deux dispositifs expérimentaux. Journal International de Technologie, de l'Innovation, de la Physique, de l'Energie et de l'Environnement. 2017. Vol. 3. No 1. P. 2428-8500. doi: 10.18145/jitipee.v3i1.159.

8. *Loveikin V., Romasevych Y., Shymko L., Ohiienko M., Duczmal W., Potwora W., Titova L., Rogovskii I.* Agrotronics and optimal control of cranes and hoisting machines: monograph. Opole: The Academy of Management and Administration in Opole. 2020. 164 p.

9. *Boretskij V. F., Veklich A. N., Tmenova T. A., Cressault Y., Valensi F., Lopatko K. G., Aftandilyants Y. G.* Plasma of underwater electric discharges with metal vapors. Problems of atomic science and technology. 2019. № 1. Series: Plasma Physics (25). P. 127-130.

10. *Nazarenko I., Mishchuk Y., Mishchuk D., Ruchynskyi M., Rogovskii I., Mikhailova L., Titova L., Berezovyi M., Shatrov R*. Determiantion of energy characteristics of material destruction in the crushing chamber of the vibration crusher. Eastern-European Journal of Enterprise Technologies. 2021. Vol. 4. Issue 7(112). P. 41-49. https://doi.org/10.15587/1729-4061.2021.239292.

11. *Aftandiliants Ye. G.* Thickness influence on element segregation in continuously cast steel slabs. Machinery & Energetics. Journal of Rural Production Research. Kyiv. Ukraine. 2021. Vol. 12. No 2. P. 15-22. http://dx.doi.org/10.31548/machenergy2021.02.015.

12. *Palamarchuk I., Rogogvskii I., Titova L., Omelyanov O.* Experimental evaluation of energy parameters of volumetric vibroseparation of bulk feed from grain. Engineering for Rural Development. 2021. Vol. 20. P. 1761-1767. doi: 10.22616/ERDev.2021.20. TF386.

13. *Rogovskii I. L., Titova L. L., Gumenyuk Yu. O., Nadtochiy O. V.* Technological effectiveness of formation of planting furrow by working body of passive type of orchard planting machine. IOP Conference Series: Earth and Environmental Science. 2021. Vol. 839. P. 052055. doi:10.1088/1755-1315/839/5/052055.

14. *Rogovskii I.L., Titova L.L., Trokhaniak V.I., Borak K.V., Lavrinenko O.T., Bannyi O.O*. Research on a grain cultiseeder for subsoil-broadcast sowing. INMATEH. Agricultural Engineering. 2021. Bucharest. Vol. 63. No 1. P. 385-396. DOI: 10.35633/INMATEH-63-39.

References

1. *Zhi-ling Peng, Chun-gui Zhou*. (2014). Research on modeling of nonlinear vibration isolation system based on Bouc-Wen model. Defence Technology. 10. 371-374.

2. *Semenov M. E., Meleshenko P. A., Solovyov A. M., Semenov A. M.* (2015). Hysteretic nonlinearity in inverted pendulum problem. Springer Proceedings in Physics. 168. 463-507.

3. *Bernyk I., Nazarenko I., Luhovskyi O.* (2018). Effect of rheological properties of materials on their treatment with ultrasonic cavitation. Materials and technology. 4 (52). 465-468.

4. *Veklich A., Tmenova T., Zazimko O., Trach V., Lopatko K., Titova L., Boretskij V., Aftandiliants Y., Lopatko S., Rogovskiy I.* (2020). Regulation of biological processes with complexions of metals produced by underwater spark discharge. Springer Proceedings in Physics. Book series Nanomaterials and Nanocomposites, Nanostructure Surfaces and Their Applications. 247. 283-306.

5. *Nazarenko I., Dedov O., Bernyk I., Rogovskii I., Bondarenko A., Zapryvoda A., Titova L.* (2020). Study of stability of modes and parameters of motion of vibrating machines for technological purpose. Eastern-European Journal of Enterprise Technologies. 6 (7-108). 71-79. doi: 10.15587/1729-4061.2020.217747.

6. *Hrynkiv A., Rogovskii I., Aulin V., Lysenko S., Titova L., Zagurskiy O., Kolosok I.* (2020). Development of a system for determining the informativeness of the diagnosing parameters of the cylinder-piston group of the diesel engines in operation. Eastern-European Journal of Enterprise Technologies. 3(105). 19-29.

7. *Tmenova T., Valensi F., Veklich A., Cressault Y., Boretskij V., Lopatko K., Aftandilyant Y.* (2017). Etude d'un arc impulsionnel immergé à l'aide de deux dispositifs expérimentaux. Journal International de Technologie, de l'Innovation, de la Physique, de l'Energie et de l'Environnement. 3(1). 2428-8500. doi: 10.18145/jitipee. v3i1.159.

8. *Loveikin V., Romasevych Y., Shymko L., Ohiienko M., Duczmal W., Potwora W., Titova L., Rogovskii I.* (2020). Agrotronics and optimal control of cranes and hoisting machines: monograph. Opole: The Academy of Management and Administration in Opole. 164.

9. *Boretskij V. F., Veklich A. N., Tmenova T. A., Cressault Y., Valensi F., Lopatko K. G., Aftandilyants Y. G.* (2019). Plasma of underwater electric discharges with metal vapors. Problems of atomic science and technology. 1. Series: Plasma Physics (25). 127-130.

10. *Nazarenko I., Mishchuk Y., Mishchuk D., Ruchynskyi M., Rogovskii I., Mikhailova L., Titova L., Berezovyi M., Shatrov R.* (2021). Determiantion of energy characteristics of material destruction in the crushing chamber of the vibration crusher. Eastern-European Journal of Enterprise Technologies. 4(7(112). 41-49. https://doi.org/10.15587/1729-4061.2021.239292.

11. *Aftandiliants Ye. G.* (2021). Thickness influence on element segregation in continuously cast steel slabs. Machinery & Energetics. Journal of Rural Production Research. Kyiv. Ukraine. 12(2). 15-22. http://dx.doi.org/10.31548/machenergy2021.02.015.

12. *Palamarchuk I., Rogogvskii I., Titova L., Omelyanov O.* (2021). Experimental evaluation of energy parameters of volumetric vibroseparation of bulk feed from grain. Engineering for Rural Development. 20. 1761-1767. doi: 10.22616/ERDev.2021.20.TF386.

13. *Rogovskii I. L., Titova L. L., Gumenyuk Yu. O., Nadtochiy O. V.* (2021). Technological effectiveness of formation of planting furrow by working body of passive type of orchard planting machine. IOP Conference Series: Earth and Environmental Science. 839. 052055. doi:10.1088/1755-1315/839/5/052055.

14. *Rogovskii I.L., Titova L.L., Trokhaniak V.I., Borak K.V., Lavrinenko O.T., Bannyi O.O.* (2021). Research on a grain cultiseeder for subsoil-broadcast sowing. INMATEH. Agricultural Engineering. Bucharest. 63(1). 385-396. doi: 10.35633/INMATEH-63-39.

ВЛИЯНИЕ ХИМИЧЕСКОГО СОСТАВА НА СЕГРЕГАЦИЮ ЭЛЕМЕНТОВ И СВОЙСТВА СТАЛЬНОЙ ЛЕНТЫ, ИЗГОТОВЛЕННОЙ МЕТОДОМ ЛЕНТОЧНОГО ЛИТЬЯ

Е. Г. Афтандилянц

Аннотация. В статье представлены результаты исследования влияния химического состава на сегрегацию элементов и свойства стальной ленты изготовленной непрерывной разливкой.

Показано, что при переходе от производства слябов толщиною 220 мм до слябов толщиной 1,2 мм толщина сегрегационного диффузионного слоя в случае процесса ленточного непрерывного литья в 4,1-12,4 раза меньше, чем при традиционном непрерывном литье.

Процент сегрегации углерода, азота, меди, олова, фосфора и серы в случае процесса ленточного непрерывного литья в 1,7-5,1 раза меньше, чем при традиционном непрерывном литье.

Предложен метод расчета сегрегации элементов, исходя из равенства уровня сегрегации при традиционном и ленточном непрерывном литье.

Установлено, что содержание элементов в сталях при двухвалковом непрерывном литье может быть увеличено для таких примесей как S, O, N, P, H минимально от 3 для P до максимально 497 % для S. Для таких остаточных элементов как Pb, Bi, Sn, Cu, Sb, Zn, As минимальное увеличение от 1,1 для Zn до максимального 401 % для Pb. Содержание таких легирующих элементов как B, Se, Al, Te, Ca, Mg, Ce, C, La, Nb, Ti, Mn, Ni, Si может быть увеличено минимально от 1,1 для Si и Mn до максимального 675 % для B.

Рассчитаны время и скорость охлаждения 20 тонной бухты стальной ленты в, которые составляют, соответственно, 13,7 часа и 0.0051 °C/s. Такие условия охлаждения создают предпосылки для выделения карбидов хрома и увеличению склонности стали к межкристаллитной коррозии.

Установлено, что для устранения этой проблемы необходимо увеличить время охлаждения водой после прокатки до температуры ленты 300-400 °C

Ключевые слова: сталь, химический состав, сегрегация, свойства, предел текучести, предел прочности, ленточное литье.

ВПЛИВ ХІМІЧНОГО СКЛАДУ НА СЕГРЕГАЦІЮ ЕЛЕМЕНТІВ І ВЛАСТИВОСТІ СТАЛЕВОЇ СТРІЧКИ, ЩО ВИГОТОВЛЕНА МЕТОДОМ СТРІЧКОВОГО ЛИТТЯ

Є. Г. Афтанділянц

Анотація. У статті представлені результати дослідження впливу хімічного складу на сегрегацію елементів і властивості сталевої стрічки виготовленої безперервним литтям.

Показано, що при переході від виробництва слябів товщиною 220 мм до слябів товщиною 1,2 мм ширина сегрегаційного дифузійного шару в разі процесу стрічкового безперервного лиття в 4,1-12,4 рази менше, ніж при традиційному безперервному литті.

Відсоток сегрегації вуглецю, азоту, міді, олова, фосфору і сірки в разі процесу стрічкового безперервного лиття в 1,7-5,1 рази менше, ніж при традиційному безперервному литті.

Запропоновано метод розрахунку сегрегації елементів, виходячи з однакового рівня сегрегації при традиційному і стрічковому безперервному литті.

Встановлено, що вміст елементів в сталях при двохвалковому безперервному литті може бути збільшено для таких домішок як S, O, N, P, H мінімально від 3 для P до максимально 497% для S. Для таких залишкових елементів як Pb, Bi, Sn, Cu, Sb, Zn, As мінімальне збільшення від 1,1 для Zn до максимального 401% для Pb. Вміст таких легуючих елементів як B, Se, Al, Te, Ca, Mg, Ce, C, La, Nb, Ti, Mn, Ni, Si може бути збільшено мінімально від 1,1 для Si і Mn до максимального 675% для B .

Розраховані час і швидкість охолодження 20 тонної бухти сталевої стрічки, які становлять, відповідно, 13,7 години і 0.0051 ^{o}C/s. Такі умови охолодження створюють передумови для виділення карбідів хрому і збільшення схильності стали до міжкристалічної корозії.

Встановлено, що для усунення цієї проблеми необхідно збільшити час охолодження водою після прокатки до температури стрічки 300-400 ^{o}C.

Ключові слова: сталь, хімічний склад, сегрегація, властивості, межа текучості, межа міцності, стрічкове лиття.

Є. Г. Афтанділянц ORCID 0000-0001-5864-9855.