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INFLUENCE OF THE TECHNOLOGICAL PARAMETERS OF STEEL CASTING AND CRYSTALLIZATION ON QUALITY INDICATORS OF A CONTINUOUSLY CAST BILLET

In order to increase the speed of casting high-carbon liquid steel, technological modes of casting and crystallization of the continuously cast billet have been tested during the research process.

As compared to the billets, which were cast using conventional cooling modes, reduced affection with cracks and central porosity has been achieved.

The conducted research has shown that during production of continuously cast billets, made of high-carbon steels C80D and C86D, the drawing (casting) speed could be increased to 3.2 m / min., which will make it possible to reduce the process time of one heat without sacrificing quality indicators of the billet.

***Key words**: continuously cast billet, casting speed, high-carbon steel, quality indicators of the billet.*

Introduction and state of the problem. Hereditary influence of the quality indicators of a continuously cast billet on hot-rolled products is well-known and described in [1 - 5]. However, liquid steel casting with the use of continuous casting machines (CCM) has a number of features, which determine quality indicators of the cast billet and depend primarily on the production process parameters and design features of the equipment used. In the billet macrostructure there are always defects, which cannot be prevented completely even under rational choice of technological production parameters and which are directly related to liquation processes occurring during crystallization.

As compared to ingots, cast in a mold, crystalline structure of a cast billet has certain peculiarities. This is due to its intensive cooling in a crystallizer and secondary cooling zone (SCZ), which ultimately promotes formation of a more uniform crystalline structure. Unlike ingots, continuously cast billets are characterized by a very slight variation of their chemical composition (complete absence of a zonal and reduction of a microphysical (dendrite) liquation as well as by more uniform properties in both longitudinal and transverse directions [6].

Formation of quality indicators of a continuously cast billet (the size of structural zones, central axial porosity, axial liquation, cracks, etc.) is determined mainly by technological parameters of the liquid steel casting process. Metal temperature in the intermediate bucket and subsequent billet drawing speed have significant influence on the process [1]. Metal overheating above the liquidus temperature during the metal casting process increases the length of columnar crystal zone, which also depends on carbon content in steel [2, 7, 8].

In accordance with the latest world trends, leading metallurgy equipment manufacturers (Danieli, Concast Standard, Siemens VAI and others) implement advanced technological modes of continuous casting of high-carbon steel, which are characterized by increased intensity of the billet water cooling in the first two sections of SCZ. This facilitates metal crystallization process.

While manufacturing high-carbon steel billets, Danieli recommend to perform cooling in SCZ with the water consumption intensity about 1.6 l / kg, while Concast Standard suggests using more intensive water cooling of ~ 2,0 l / kg. It is recommended to use high-speed injectors in the crystallizer, such as those produced by Lechner. According to the first two companies, combination of such cooling modes with the technology of electromagnetic stirring (EMS) of metal in the crystallizer makes it possible to increase steel casting speed, to reduce development of liquation processes and the degree of central porosity in the cast billet.

Taking the above-mentioned into consideration, the paper aims at studying the influence of the technological parameters of casting steels C80D and C86D (according to EN ISO 16120-1:2011) and intensity of their cooling in SCZ on formation of quality indicators of the continuously cast billet with cross-section of 125×125 mm.

Industrial batches of continuously cast billets with cross-section of 125 x 125 mm, made of steel C80D and C86D at OJSC «Moldovan Metallurgical Plant» (Rybnytsia, Moldova) with the application of different liquid steel crystallization rates and water cooling intensity in WCZ, served as **research material**. Studies on the development of defects in the macrostructure of a continuously cast billet, designed for rolled coils production, were conducted in accordance with standard requirements (OCT 14-1-235-9 “Steel. Method for controlling the macrostructure of a continuously cast billet for producing rolled steel products and tubular billets”). Cast billet macrostructure was determined using the method of deep etching in a hot 50% aqueous solution of hydrochloric acid in accordance with the requirements of ГОСТ 10243-75 «Steel. Methods for macrostructure testing and evaluation”. Characteristic defects of the continuously cast billet macrostructure (central axial porosity, axial liquation, etc.) were evaluated by comparing full-size etched templates with standard scales according to OCT 14-1-235-91.

Experimental studies and discussion of the obtained results. Prior to in-depth investigation, research technology of casting high-carbon steel C80D was tested with the average speed of cast billet drawing increased from 2.4 m / min to 3.4 m / min and using the existing SCZ mode. It was determined, that as compared with the existing technology of liquid steel casting (2.4 m / min.), under research mode (3.4 m / min.) the billet macrostructure affection with cracks increased by 1.0 point and central porosity – by 1.4 points on the average (Fig. 1). In addition to the above-mentioned deviations of quality indicators, increased convexity of faces (to 2.8 mm per side) was observed.

Chemical composition of steel C80D of two control heats and parameters of the experimental modes in SCZ during steel casting are presented in Tables 1 and 2 respectively.

Table 1

Chemical composition of steel C80D

Heat number	Chemical composition of steel by mass, %							
	C	Mn	Si	P	S	Cr	Ni	Cu
1	0.79	0.64	0.16	0.010	0.002	0.05	0.04	0.12
2	0.81	0.59	0.15	0.009	0.003	0.04	0.03	0.14

Table 2

Parameters of cooling the continuous cast billet with cross-section of 125×125 mm, made of steel C80D, in SCZ

Mode number	Average casting speed, m / min	Specific water consumption in SCZ, l / kg	Share of the total water consumption in the section			
			Section 1	Section 2	Section 3	Section 4
1	2.4	1.35	0.36	0.36	0.17	0.11
2	3.2	1.70	0.30	0.39	0.18	0.13
3	2.6	1.60	0.30	0.40	0.18	0.12
4	2.8	1.85	0.29	0.39	0.19	0.13

During the steel casting process main parameters and deviations from the technological mode were recorded, billet temperature change (overcooling) was evaluated visually; geometric parameters (curvature, rhombic shape, convexity of the faces) were measured. Templates for studying the macrostructure quality indicators were selected from the billets manufactured in accordance with basic and experimental technological modes.

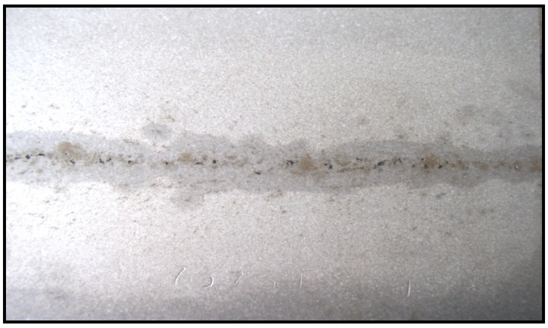


Fig. 1. Macrostructure of the longitudinal continuously cast billet, made of steel C80D (drawing speed 3.4 m / min; specific water consumption in SCZ 1.30 l / kg)

Results of studying the macrostructure of continuously cast billets with cross-section of 125x125 mm in accordance with standard requirements (ОСТ 14-1-235-91), which were manufactured using basic and experimental technological modes, are presented in Table 3.

Table 3

Quality indicators of the continuously cast billet with cross-section of 125×125 mm, made of steel C80D, according to ОСТ 14-1-235-91

Mode number	Average casting speed, m / min	t_{sl}^{1}, °C	Quality indicators of the billet, score					
			CP[2]	AL[3]	Cracks			PBC[4]
					Along the section	angular	axial	
1	2.4	1502	2.1	2.5	1.1	0.2	0.4	0.3
2	3.2	1499	1.6	2.2	0.4	0.2	0.4	0.4
3	2.6	1498	1.9	2.3	1.2	0.1	0.4	0.5
4	2.8	1502	1.7	2.4	0.3	0.3	0.5	0.6
Note: 1 – temperature of the metal in the steel ladle; 2 – central axial porosity; 3 – axial liquation (chemical inhomogeneity); 4 – point boundary contamination								

From the analysis of the research data (Table 3) on quality indicators of the billets, manufactured according to both current and test technological modes, it follows:

- application of mode № 2 makes it possible to achieve reduction of the average score on central axial porosity by 0.5 points and on the affection with cracks along the section – by 0.7 points;
- application of mode № 3 gives no essential improvements of the billet quality indicators;
- mode № 4 makes it possible to reduce average score on central axial porosity by 0.4 points and on the affection with cracks along the section – by 0.8 points.

Testing of the most intensive cooling mode (№ 4) showed significant overcooling of the billet surfaces in SCZ, which caused their increased curvature. On the whole, geometric dimensions of the continuously cast billets, produced using test water cooling modes (№ 2 – 4), corresponded to the standard requirements (ЗТУ 14-518-2012-0001-2009 “Continuously cast billet of square cross-section for production of long rolled steel products and rods) in 95 % of cases.

During the research process it was established that increased intensity of cooling in SCZ makes it possible to increase average speed of casting high-carbon steel to 3.2 m / min without sacrificing quality indicators of the cast billet.

Application of more intensive water cooling modes in SCZ has not allowed achieving significant reduction of axial liquation development in the billets. However, absence of the proper effect could be due to insufficiently high pressure of the water that cooled the cast billet surface in SCZ. During the investigation process maximal pressure of the water in the first two sections of SCZ was ~ 0.7 MPa. In order to reduce axial liquation development while using the technology of high-intensity water cooling of the billets, made from high-carbon steel, Danieli and Concast recommend, that the pressure of cooling water in SCZ should be at least 1.2 MPA.

Further research was conducted with the application of two control heats of high-carbon steel C86D with chemical composition given in Table 4.

Table 4

Chemical composition of steel C86D

Heat number	Chemical composition of steel, % by mass							
	C	Mn	Si	P	S	Cr	Ni	Cu
1	0.84	0.59	0.18	0.011	0.001	0.04	0.06	0.14
2	0.83	0.61	0.17	0.010	0.002	0.03	0.05	0.13

During the research process longitudinal templates were selected among the billets of the both control heats from the streams №1 and №6 of CCM, where the billet drawing speeds were 2.43 and 3.28 m / min respectively.

Liquid steel casting was performed by the analogy with steel C80D through an intermediate ladle, having magnesia lining, with metal flow being fully protected from secondary oxidation and using the system of metal EMS in the crystallizer.

Average billet drawing speeds for six streams of CCM were as follows:

stream № 1 – 2.41...2.43 m / min, streams № 2 – 5 – 2.38...2.70 m / min, stream № 6 – 3.21...3.28 m / min (Fig. 2).

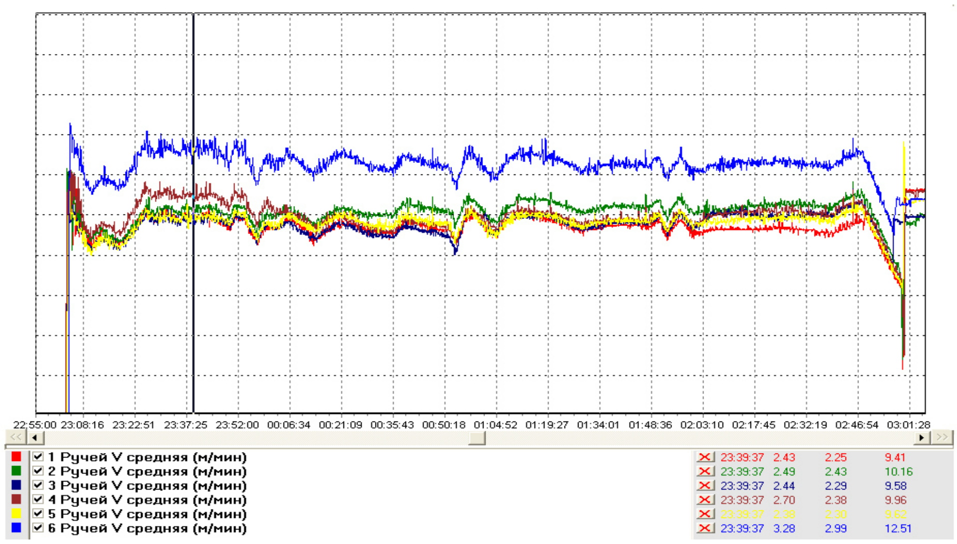


Fig. 2. Average speeds of drawing of the continuously cast billet with cross-section of 125×125 mm, made of steel C86D, using six-stream CCM (according to the data of APCS of OJSC «MMP»)

Parameters of the experimental modes of the billet cooling in SCZ are presented in Table 5.

Table 5

Parameters of cooling the continuously cast billet with cross-section of 125×125 mm, made of steel C86D, in SCZ

Number of CCM streams	Specific water consumption in SCZ, 1 / kg^2	Fraction from the general water consumption in the section			
		Section 1	Section 2	Section 3	Section 4
1	1.60	0.31	0.38	0.18	0.13
2…5	1.65	0.29	0.39	0.17	0.15
6	1.75	030	0.40	0.18	0.12

Results of studying the macro- and crystalline structures of continuously cast billets of control heats, made of steel C86D, are presented in Tables 6 and 7 respectively.

Table 6

Quality indicators of the continuously cast billet with cross-section of 125×125 mm, made of steel C86D

Heat number / stream number in CCM	**Evaluation of the billet macrostructure according to OCT 14-1-235-91, score**					
	CP*	AL*	Cracks			PBC*
			Along cross-section	angular	axial	
1 / 1	2.0	2.4	0	0.3	0.5	0.3
1 / 6	1.8	2.2	0	0.3	0.4	0.4
2 / 1	1.9	2.5	0	0.2	0.5	0.5
2 / 6	1.7	2.3	0	0.3	0.5	0.5
Note: * – see note to Table 3						

Table 7

Results of studying crystalline structure of the continuously cast billet with cross-section of 125×125 mm, made of steel C86D

The number of CCM stream	Dimensions of the structural zones of the billets under study [1], mm		
	Cortical zone	Columnar steel crystals	Aquiaxial crystals
1	$\frac{3…11}{7.5}$	$\frac{11…17}{1.4}$	$\frac{30…35}{32.8}$
6	$\frac{4…10}{7.1}$	$\frac{13…18}{14.8}$	$\frac{31…36}{33.1}$
Note: 1 – averaged maximal and minimal values are given in the numerator and average value – in the denominator			

Analysis of the data, presented in Tables 6 and 7, shows that there are no essential differences in the indicators of macro- and crystalline structures of the billets, which were cast during control heats at the average speeds of 2.43 and 3. 28 m / min.

In order to evaluate development of defects in the axial zone of the billets, which were cast at different drawing speeds, templates with the length of about 1m, cut along the central line, were selected and grinded. Results of estimation of the affection with defects (central porosity), developed in the central zone of the billets, are presented in Table 8.

Table 8

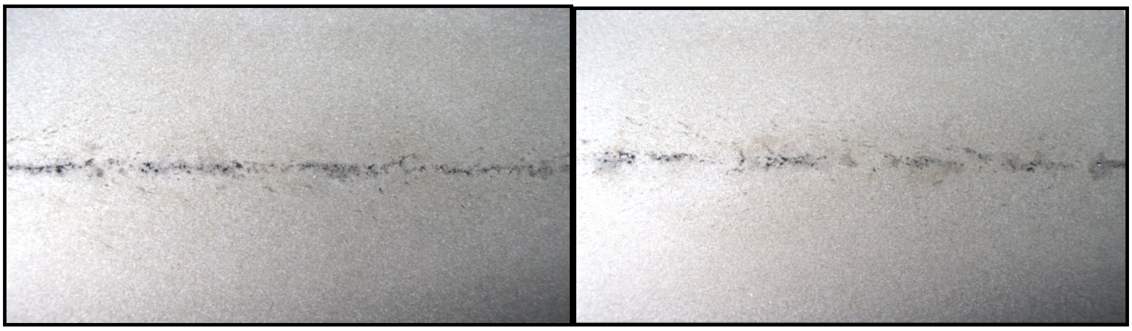
Results of estimation of central porosity in the continuously cast billets with cross-section of 125×125 mm, made of steel C86D

Heat number	CCM stream number	Average steel casting speed, m / min.	Number of pores along the template length	Size of the pores, mm	Pores location zone
1	1	2.43	80	0.5…1.0 (max. – 2.1)	Area with the length of ~ 5.0 mm
	6	3.28	127	0.5…1.0 (max. – 2.8)	Area with the length of ~ 5.0 mm
2	1	2.41	78	0.5…1.0 (max. – 2.2)	Area with the length of ~ 5.0 mm
	6	3.21	114	0.5…1.0 (max. – 3.0)	Area with the length of ~ 5.0 mm

Continuously cast billets of both heats, cast at higher drawing speeds (3.21 – 3.28 m / min), are characterized by increased number and maximal size of pores in the axial zone as compared to the billets, cast at speeds of 2.41 – 2.43 m / min.

Billets of the both control heats, produced with the application of different modes of steel casting and crystallization, were rolled into coil rod with the diameter of 11.0 mm at the wire mill. No discontinuities and deviations as to the quality of the coil rod surface were found. Therefore, defects in the central zone of the billets, cast at the average speed in the range of 2.41 – 3.28 m / min, were rolled up during hot deformation process.

Fig. 3 presents the macrostructure of longitudinal templates of the control heats under study.



a b

a – average billet drawing speed of 2.43 m / min;
b – average drawing speed of 3,28 m / min

Fig. 3. Macrostructure of longitudinal templates of the continuously cast billet, made of steel C86D, at different casting speeds

Central porosity is strongly developed in the billets of small cross-section and the degree of affection with defects of this type increases with the growth of steel casting speed.

Application of the metal EMS in CCM did not make it possible to significantly influence the central porosity level in the cast billet because of the longitudinal liquid metal pool in the crystallizer. More efficient method for central porosity score reduction is application of complex EMS not only in the crystallizer, but also in SCZ, with water cooling intensity being increased simultaneously.

Yet, impact of the above cast billet defect on the finished rolled product quality should be viewed as limited. The most important thing is to limit development of this defect in the continuously cast billet during production of high-carbon steel for cord purposes in order to prevent lamination of the high-strength wire during its drawing to the diameter below 0.50 mm as in this case the defect of the "dimple-cone" type could emerge.

Development of the central axial porosity in a continuously cast billet can be limited by ensuring stable casting speed as well as more intensive and uniform cooling in SCZ.

Conclusions

1. In order to increase the speed of casting liquid high-carbon steel, technological modes of casting and crystallization of a continuously cast billet have been tested. The most optimal results as to the billet quality have been achieved with specific water consumption in SCZ being 1.55 – 1.75 l / kg of steel.

2. As compared to the billets, cast using the conventional cooling mode, reduction of the billet affection with cracks and central porosity has been achieved. Geometric parameters of the billets, produced with the application of more intensive water cooling modes, demonstrated their full correspondence to standard requirements (ЗТУ 14-518-2012-0001-2009). When experimental mode with maximal specific water consumption 1.85 l / kg of metal was tested, considerable overcooling of the surface of billets and increased distortion of their shape were observed.

3. The conducted research has shown that continuously cast billets, made of high-carbon steels C80D and C806D, could be produced with the drawing speed increased to 3. 2 m / min. This will make it possible to reduce technological time of producing one melt without sacrificing quality indicators of the billet.

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