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SOME ASPECTS OF CONTINUOUS CASTING OF LOW CARBON MICROALLOYED STEELS WITH NIOBIUM AND TITANIUM**WYBRANE ASPEKTY CIĄGŁEGO ODLEWANIA NISKOWĘGLOWYCH STALI Z MIKRODODATKAMI NIOBU I TYTANU**

An analysis of the causes of transverse corner and surface crack formation during continuous casting of low carbon niobium and titanium-containing steel into square billets is presented in this paper. Using X – ray analysis method, the chemical composition of non- metallic phases inside corner cracks was determined. The temperature ranges of the occurrence of nitrides and carbonitrides of Nb, Ti and Al were established using FactSage 6.2., a commercial computer program. The need for the precise selection of cooling conditions during casting of billets both in the mould and in spray cooling regions was pointed out with the aim of obtaining the optimum surface, and particularly corner temperature of the billet before its entrance to the straightening stand.

Keywords: continuous casting of steel, High Strength Low Alloy Steel, corner cracks, non - metallic phases, casting parameters

W referacie przedstawiono na podstawie badań w warunkach przemysłowych, analizę przyczyn powstawania pęknięć na powierzchni i na narożach wlewków ciągłych o przekroju kwadratowym, odlewanych ze stali niskowęglowych z zawartością niobu i tytanu. Przy użyciu metody mikroanalizy rentgenowskiej dokonano oceny składu chemicznego faz niemetalicznych występujących wewnątrz pęknięć. Z wykorzystaniem programu komputerowego FactSage 6.2 wyznaczono zakresy temperatury występowania azotków i węglikoazotków Nb, Ti, Al. Wskazano na konieczność precyzyjnego doboru warunków chłodzenia odlewanych stali w krystalizatorze oraz w strefie chłodzenia natryskowego celem uzyskania optymalnej temperatury wlewka ciągłego w szczególności na narożach przed operacją jego prostowania w klatce walców ciągnąco – prostujących.

1. Introduction

Currently manufactured High Strength Low Alloy (HSLA) constructional steels can be classified into the group of advanced constructional materials. Their successful implementation in production is dated at the 60s of the 20th century, as the next generation of steels to so the called „mild steels” (0.1÷0.25% C, 0.4÷0.7% Mn) with an average yield strength value of about 250 MPa, which turned out to be too low compared to constructors’ requirements [1]. As a result of numerous studies and industrial tests, a constructional material was obtained, for which a far-reaching combination of properties, such as strength, high plastic deformability, ductility, resistance to dynamic loads, etc., is possible. Owing to its universal properties, there is high demand for numerous HSLA steel grades, e.g. for steels with guaranteed impact strength at low temperatures, intended for marine

structures and steels for gas transport pipelines as well as for medium-carbon steels designed for forgings intended for the automotive and machine-building industries [2]. With the advances in continuous steel casting and after developing the thermomechanical rolling (TMR) technology, an increasing number of grades of steels with micro-additions of niobium, titanium and vanadium have been manufactured on a mass scale. However, manufacturing of products from microalloyed steels causes a number of quality problems, whose solving will require the liquid metal quality achieved at the melting and ladle treatment stage to taken into account and, especially, the continuous casting conditions to be precisely selected and adhered to. These problems gain particular importance, when the steel is melted in electric arc furnaces with a large share of steel scrap. These issues constitute the subject of the present study.

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2. Characterization of the defects of microalloyed steels

The transverse cracks are one of the most frequently defects of HSLA steels which can arise during continuous casting or at initial stages of plastic working. These transverse cracks are situated chiefly at the corners or in their immediate vicinity. Cracks of this type occur, when at a specific point on the billet surface the magnitude of stresses formed is higher than the material strength at a given temperature. These stresses may have a thermal or mechanical nature, and their source can also be structural transformations occurring during solidification and formation of the crystalline structure of the material. Transverse cracks are most often generated inside the mould as a result of the concentration of thermal stresses caused by the contraction of the forming continuous cast billet skin and in the case of incorrect mould operation parameters, including the improper interaction of the mould flux layers (solid and liquid) in the gap forming between the skin and the mould wall. Equally often, transverse cracks at the corners forms during straightening of the billets in the straightening stand in the case when this operation is carried out in the range of plasticity loss temperature, being characteristic of a specific chemical composition of steel.

Figure 1 represents the relationship of the value of the reduction of area of steel containing 0.09% C; 1.41% Mn; 0.032% Al; 0.028% Nb and 52 ppm N as a function of temperature, as determined experimentally in study [3]. As indicated by the presented relationship, the minimum values of the reduction of area, which can be assumed in this case as the measure of plasticity, are attained by the steel of the specified chemical composition in the temperature range of 800÷870°C (1073÷1143 K). If the temperature at the billet corners reaches values from the determined temperature range during straightening, the stresses that form as a result of stretching undergone by the top surface of the billet (on the side of the smaller radius of CC machine) will cause transverse cracks to occur. The results of numerous research works [5-7] indicate clearly that the concentration of those stresses occurs in hollows on the continuous cast billet surface, which are caused by the oscillatory movement of the mould (the so called oscillation marks). When analyzing the causes of transverse cracks occurring on the surface of low-carbon HSLA steels, it should also be taken into account that, due to their carbon content, they are classified into the group

of peritectic steels ($0.07\% \leq [C] \leq 0.17\%$), in which the occurring transformations of ferrite δ into austenite, followed by the strong growth of primary austenite grains in the sub-surface layer, along with the ferrite “film” forming at their boundaries, particularly intensify the tendency to cracking. In addition, grain boundaries may be weakened by the precipitates of niobium and titanium nitrides and carbonitrides, as well as aluminium nitride. In steels melted in electric arc furnaces based on steel scrap, another factor weakening the grain boundaries can be the precipitates of elements – nonferrous metals and their solutions, and in particular, copper, tin, arsenic, antimony, and others. As can be seen, the number of factors that have a directly or indirectly effect on the formation of cracks in the corner zone during continuous casting of the steels require deeper analysis.

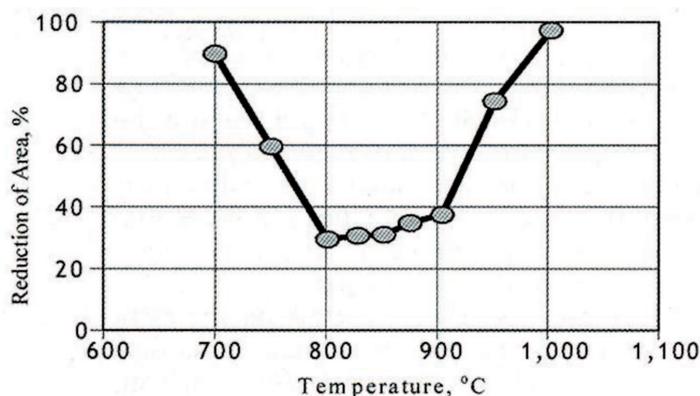


Fig. 1. Variation in the value of the reduction of area as a function of temperature for steel containing 0.028% Nb [3,4]

3. Experimental results

The subject of investigation was the S355J2-NbTi grade steel melted in an electric arc furnace with the use of steel scrap with the addition of pig iron up to 8.0% of metallic charge mass in a solid state. After secondary metallurgy processes carried out in a ladle furnace, the steel was cast using an curved-type Continuous Casting Machine to form 160 mm square cross-section billets. Liquid metal temperature, as measured in the tundish during casting ranged from 1560 to 1565°C, while the average casting rate was 359 kg/min. per strand. Chemical composition of the continuous cast billet, on which transverse cracks were found to have occurred at the corners and in their immediate vicinity, is presented in Table 1.

TABLE 1

Chemical composition of S355J2-NbTi steel grade

Element content, wt. %												
C	Mn	Si	P	S	Cr	Ni	Cu	Al _{total}	Sn	N	Ti	Nb
0.10	1.51	0.22	0.012	0.007	0.04	0.08	0.14	0.017	0.011	0.011	0.017	0.029

As can be seen from the values given in Table 1, low concentrations of detrimental admixtures, i.e. phosphorus and sulphur, have been obtained; similar is also true for nonferrous metals, copper and tin. The relatively high nitrogen content, 110 ppm, is characteristic of steels melted in electric arc furnaces. On the surface of several billets, transverse cracks were found, which extended from the corners to the surface centre, as well as discontinuities along large grain boundaries, stretching over a considerable area along all continuous cast billet planes. A view of the surface is shown in Fig. 2, while a fragment of the corner area with a patterns of cracks visible after etching of the sample is presented in Fig. 3.



Fig. 2. Cracks on the surface of an S355J2-NbTi steel continuous cast billet

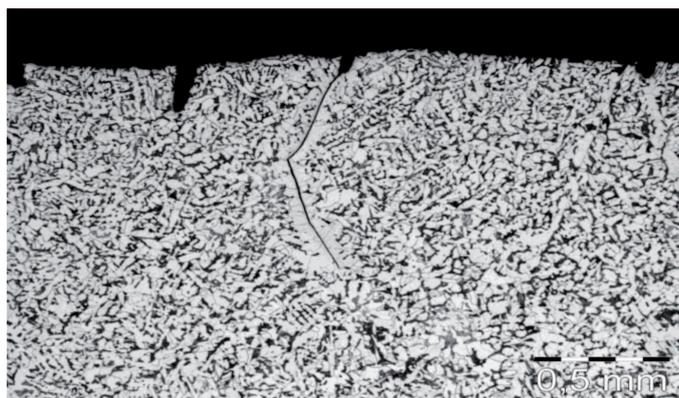


Fig. 3. Arrangement of cracks in the corner area; the sample after etching (with Nital)

Figure 2 clearly indicates that the cracks located at the billet corners and extending into the material have their origin in the locations of oscillation marks.

It should also be noted that the oscillation marks deflect distinctly with increasing distance from the edge, assuming a curvilinear shape. Such a shape of these traces is indicative of clear disturbances of the steel level position in the mould. Metal turbulences at the meniscus level and a variable metal level in the mould, which cause the state as seen in Fig. 2, are an impermissible irregularity in the continuous casting technology. Some of the cracks visible in Fig. 3 are up to 5 millimetres deep, so their removal by grinding of the billet surface is not fully possible.

To identify the phase composition immediately around and inside the cracks, observations of metallographic sections were made using a light microscope and a scanning electron microscope. The contents of elements in selected micro-areas were determined by the X-ray microanalysis method using an energy dispersion spectrometer (EDS) on an Inspekt F scanning electron microscope with an EDAX microanalysis attachment. Examinations of the scanning microscope were made at an accelerating voltage of 15kV. The position of a randomly selected cracks at the billet edge is shown in Fig. 4, while Fig. 5 shows the magnification of the lower crack part, with the locations, for which the determinations of chemical composition of the phases present there were made, being marked with numerals.

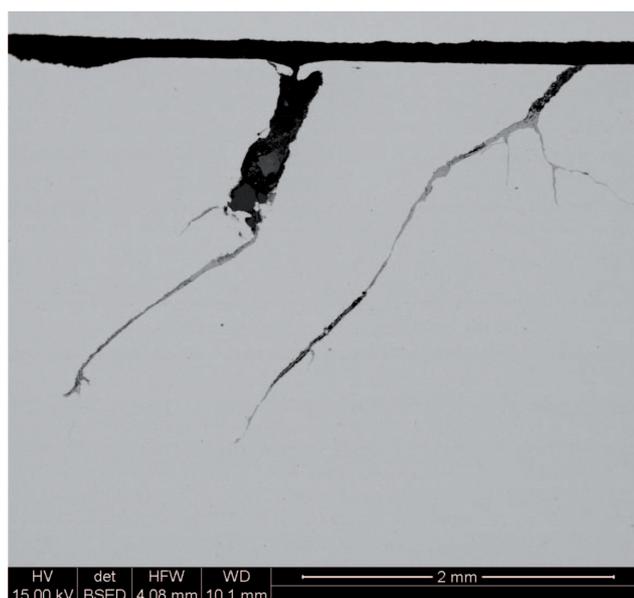


Fig. 4. Corner position of the transverse crack chosen for analysis

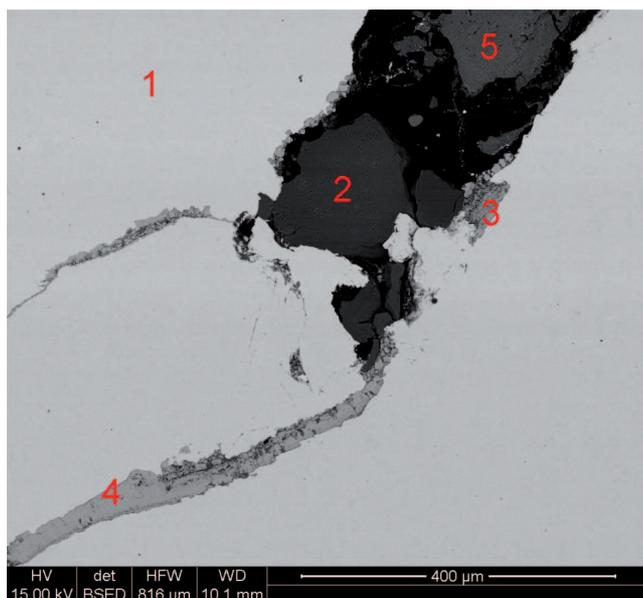


Fig. 5. Positions of the areas (marked with Arabic numerals) selected for analysis, in which chemical composition determination was made

The chemical composition of phases, as determined at particular points, is given in Table 2.

When analyzing the chemical composition of the material filling the crack and its neighbourhood it can be noticed that at point "2" there is an agglomeration of aluminium oxide, which can either be the product of steel deoxidation with aluminium or be a component of the protective flux added to the mould. Point "3" corresponds to the mixture of the oxides of iron, silicon and manganese, whereas point "4", the oxides of manganese and iron. At points "3", "4" and "5", considerable

concentrations of oxygen and iron occur, which suggests the oxidation of the inner surface of the cracks. It can also state with a high probability that, in this region of the crack, the oxides filling it up come to some extent from the flux material, which contained among other 1.0÷2.5% Fe₂O₃, 2.5÷4.0% MnO and up to 5.5% Al₂O₃. Since it is hard to explain their origin by the incomplete modification of the composition of oxide non-metallic inclusions in the liquid steel at the ladle furnace process stage, considering the 0.017% Al content of the steel and its modification with a Ca-Si alloy (with a finished steel Ca content of 26 ppm). The confirmation of this observation is the chemical composition of the non-metallic phase represented by point "5". The presence of carbon, sodium and chlorine in this zone indicates that the source of these elements are chemical compounds being components of the granular flux added to the mould. The relatively high concentrations of chromium and nickel, found in the region where point "5" lies, also require explanation. These elements come from the protective coat applied on the inner plane of the mould's copper tube walls. This coat consists of chromium and nickel, among others. This means that this coat might have been partially damaged as the continuous cast billet skin moved along the mould walls.

To make sure that the composition of the non-metallic phases present inside transverse cracks, as determined by X-ray microanalysis, has not the nature of an isolated case, a crack situated in another area (Fig. 6) was randomly chosen and subjected to similar analysis, whose results are given in Table 3.

TABLE 2

Chemical composition of the phases present in cracks on the S355J2-NbTi steel billet

Point number	Element content, wt. %											
	C	O	Na	Al	Si	S	Cl	Ca	Cr	Mn	Fe	Ni
2		50.5		49.5								
3		26.5			0.3					0.7	72.5	
4		24.9								0.8	74.3	
5	8.3	24.4	0.2	2.0	0.5	1.0	1.0	1.2	2.3	0.5	55.0	3.6

Note: The chemical composition of the metal at point 1, which is similar to the chemical composition of the examined steel, given in Table 1, has been omitted in Table 2.

TABLE 3

Chemical composition of phases present within a crack on a continuous cast billet of steel S355J2-NbTi (analysis at point 1, Fig. 6)

Element content, wt. %												
C	O	Na	Al	Si	S	Cl	Ca	Cr	Mn	Fe	Ni	
4.0	20.9	0.4	0.9	0.4	0.5	0.5	1.4	1.2	0.6	67.0	2.3	



Fig. 6. Distribution of non-metallic phases inside the transverse crack situated near the corners of a 160×160 mm billet

By comparing the chemical composition of non-metallic phases, determined at point "1" (Fig. 6), with the composition determined for cracks in another area (Table 2), great similarity can be found to exist between them. The differences between the contents of particular elements not being large enough to allow the observation that their source is the mould protective flux, what it was earlier affirmed. It is also characteristic that, in the case analyzed, chromium and nickel also occur inside the crack, whose source is an internal Cr+Ni alloy protective coat that is applied on the mould's copper surface. On the basis of the obtained analysis results, a decision was made on the need for changing the chemical composition of the mould flux so as to achieve its lower viscosity in the temperature range of 1200÷1500°C.

TABLE 4

Values of temperature on the surface of a 160 mm square cross-section S355J2 – NbTi steel billet

Place of measurement	Temperature, °C				
	Number of measurement				
	1	2	3	4	5
1	960	975	965	950	965
2	1060	1080	1075	1090	1085
3	820	790	870	890	785

To obtain additional information on the location of occurring transverse cracks, using an optical pyrometer, a measurement of the temperature of their surface and corners was taken immediately after the material had exited the straightener (about 0.6 m beyond the stand). The areas in the billet surface, where the temperature

was measured, are denoted with the numerals 1÷3 and shown in Fig. 7.

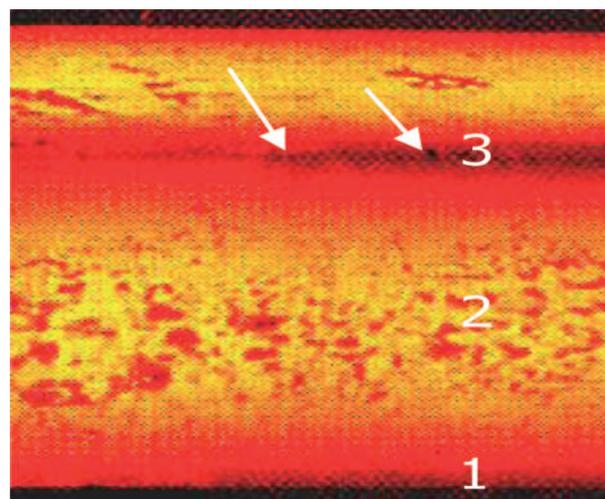


Fig. 7. Locations of temperature measurements on the surface of a continuous cast slab (1÷3) of steel S355J2 – NbTi (cracks at the corners are marked with the arrows)

Points 1 and 3 correspond to the temperatures of the upper and lower corners, whereas point 2 was situated approximately in the middle of the lateral plane. The cracks at the billet corners, visible to the naked eye, situated on the upper plane side (smaller radius of CC machine), are marked with the arrows. The obtained temperature values are given in Table 4. As the temperature measurement was also taken at the exit from the straightening stand, it can be assumed that the measured temperature of the surface and the corners corresponds to the temperature, at which the cast billet deformation caused by straightening took place. As indicated by the values shown in Table 4, the temperature of the upper corner (3) assumed values from the range, in which steels with a niobium content of 0.028% exhibit a distinct loss of plastic properties, as follows from Fig. 1. The clearly lower temperature of corner (3) compared to corner (1) was indicative of a higher intensity of cooling this area of the continuous cast billet. As turned out, the cause of this situation was an excess of water, which, in an uncontrolled manner, dripped down one of the spray cooling zone segments onto that fragment of the billet surface. The material deformation (tensile stresses on the upper billet plane) caused by straightening of the material at too low a temperature was probably one of the causes of transverse cracks occurring at the corners.

The material weakening state could have been additionally aggravated by precipitates of nitrides (e.g. of niobium, titanium) or carbides and carbonitrides of niobium at primary austenite grain boundaries. The relatively low concentrations of copper and tin in the examined steel (Table 1) may, in this case, not to be taken into

account as the additional cause of the low plasticity of material during deformation. Considering the chemical composition of the S355J2-NbTi steel under examination, and adopting the criterion for the occurrence of cracks caused the contents of copper and tin in the following form [7]:

$$Cu_{equ.} = [\%Cu] + 10 [\%Sn] - -[\%Ni] < 0.20 \quad (1)$$

it can be calculated that in the case at hand, $Cu_{equ.} = 0.17$.

As has been demonstrated by computations made using the FactSageTM software program (Fig. 8), for the set chemical composition of the steel investigated (Table 1), the formation and occurrence of nitrides and carbides in a broad temperature range is possible. From the point of view of the influence of those precipitates on the plastic

properties of the material within the temperature range, in which straightening of the continuous cast billet takes place, it is essential to know, at which temperature value these compounds may dissolve in the austenite. Such information is also very important for establishing the necessary temperature of heating the steel grade under examination prior to its rolling.

Using relevant literature data determined for γ iron, the equilibrium temperature of decomposition of nitrides of Al, Nb and Ti, carbides of Nb and Ti, and carbonitride of niobium for the steel composition shown in Table 1. It should be noted that the literature provides different numerical values of the stoichiometric coefficients n , m , defining the carbon and nitrogen fractions of the $Nb(C_nN_m)$ molecule.

The results are given in Table 5.

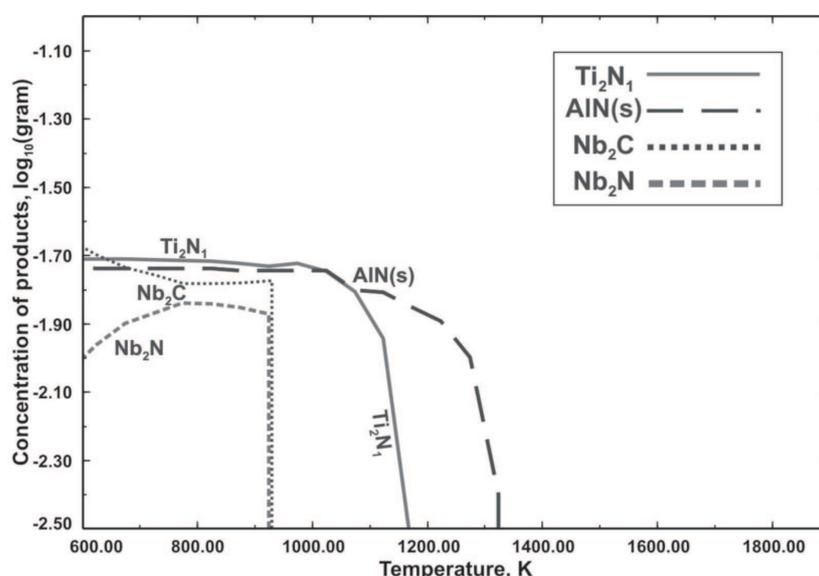


Fig. 8. Relationship of nitride and carbide formation reaction product mass as a function of temperature in steel S355J2 – NbTi of chemical composition, as given in Table 1, computed using the FactSageTM program

TABLE 5

The computed values of the decomposition temperature of some nitrides and carbides for the contents of elements, as per Table 1

Type of component	Solubility product	$\lg K_{Fe-\gamma} =$	Decomposition temperature, °C	Ref.
AlN	$[\%Al] \cdot [\%N]$	$- 6770/T + 1.03$	1149.8	[8]
NbN	$[\%Nb] \cdot [\%N]$	$- 10150/T + 3.79$	1120.0	[8]
TiN	$[\%Ti] \cdot [\%N]$	$- 15790/T + 5.40$	1456.8	[8]
$NbC_{0.87}$	$[\%Nb] \cdot [\%C]^{0.87}$	$- 7020/T + 2.81$	1072.4	[8]
NbC	$[\%Nb] \cdot [\%C]$	$- 6661/T + 2.54$	1311.8	[8]
TiC	$[\%Ti] \cdot [\%C]$	$- 7000/T + 2.75$	995.2	[8]
$Nb(C_{0.7}N_{0.2})$	$[\%Nb] \cdot [\%C]^{0.7} [\%N]^{0.2}$	$- 9450/T + 4.12$	1127.1	[8]
$Nb(C_{0.83}N_{0.14})$	$[\%Nb] \cdot [\%C]^{0.83} [\%N]^{0.14}$	$- 9800/T + 4.46$	1106.9	[9]
$Nb(C_{0.9}N_{0.1})$	$[\%Nb] \cdot [\%C]^{0.9} [\%N]^{0.1}$	$- 6770/T + 2.26$	1110.5	[10]

As indicated by the computed values presented in Table 5, only titanium nitride, TiN, shows a decomposition temperature which is higher than the upper limit of the temperature range of γ iron occurrence, and the majority of the above-mentioned compounds may decompose, when the billet temperature reaches a value of approx. 1150°C.

The location of transverse cracks at the billet corners, as shown in Figs. 2 and 3 clearly indicates that they lie along the oscillation marks. The depth of those marks and the distance between them resulting from the mould travel, as well as the position relative to the billet surface, will therefore indirectly influence the mechanism of formation and the size and frequency of occurrence of corner cracks. This finding is confirmed by the results of numerous studies [11-14]. On these grounds, it was fully justifiable to adjust the continuous casting parameters being in use, which determine the formation oscillation marks. The main parameters characterizing the mould operation include: instantaneous mould speed, average mould speed, complete cycle time, oscillation frequency, stroke length, and negative strip time, t_{NS} . For the sinusoidal form of oscillatory mould movement, t_{NS} is defined as the time, in which, as the mould moves down, its displacement velocity is higher than the casting speed, and is defined from the relationship:

$$t_{NS} = \frac{60}{\pi \cdot f} \arccos \left(\frac{1000 \cdot V_{cos}}{\pi \cdot s \cdot f} \right), \quad [s] \quad (2)$$

where V_{cos} – continuous casting speed, $m \cdot min^{-1}$
 f – oscillation frequency, 1/min,
 s – overall stroke of mould, mm

The distance between adjacent oscillation marks can be calculated from the approximate relationship:

$$l_{so} = \frac{2s}{1 + t_{NS}}, \quad [mm] \quad (3)$$

Selected values of the above parameters as a function of casting speed are shown in Table 6.

The depth of forming oscillation marks decreases with decreasing value of the negative strip time, increasing oscillation frequency and decreasing length of stroke. Taking into account these considerations and not neglecting the influence of the above-mentioned parameters on the trouble-free continuous casting process (elimination of skin breaks and metal leaks), the shaded field of Table 6 shows the recommended values of the examined parameters. It should be noted that, by comparing the computed values with those currently used under industrial conditions under examination, differences were found, which were large enough to be regarded as additional factors contributing to the formation of cracks at the continuous cast billet corners.

TABLE 6

Selected values of mould operation parameters during casting 160x160 mm cross-section billets as a function of casting speed

Casting speed, $m \cdot min^{-1}$	1,8	1,9	2,0	2,1	2,2	2,3	2,4
Oscillation frequency, cycle/min.	155	163	172	181	189	197	206
Negative Strip Time, s	0,193	0,186	0,181	0,175	0,168	0,161	0,154
Negative Strip, %	17,4						
Stroke length, mm	7 (3,5)						
Distance between oscillation marks, mm	11,7						

Note: shaded field – the recommended values

4. Summary

The high prevalence of transverse cracks in the corner area of 160 mm-square cross-section continuous cast billets from S355J2 – NbTi grade steel being classified into the group of subperitectic steels with the micro-additions of niobium and titanium, justified the need for undertaking the analysis of the causes of the occurrence of this defect that had a substantial effect of reducing the yield of the full-value material. The metallographic analysis of the crack zone on samples taken from the commercial melt with the use optical microscopy and X-ray microanalysis methods using an energy dispersion spectrometer (EDS) on an Inspekt F scanning electron microscope showed that the crack interior was filled with non-metallic phases of diverse chemical composition. In the composition of those phases, compounds were identified, which might be either deoxidation products (e.g. Al_2O_3 , SiO_2 and MnO) or elements typical of the flux added to the mould, such as carbon, sodium and chlorine. Moreover, chromium and nickel were also found to be present within the cracks, which might have come from the internal mould wall protective coat. These observations indicated the need for changing the flux properties (viscosity at a temperature of 1300°C), and thus the change of the conditions of the flux layers interacting between the mould wall and the forming billet skin.

The performed measurements of continuous cast billet surface temperature immediately after the straightener, using an optical pyrometer, showed that the temperature in the upper corner zone reached values in the range of 785÷890°C. According to the results of a literature review, in the temperature range of 800÷900°C steels with 0.028% of niobium are characterized the lowest values of the reduction of area. It was found that billet

straightening was conducted at too low temperatures. It should also be noted that distinct differences in temperature between individual corners were found. With the aim of correcting this irregularity, efforts were undertaken to eliminate the uncontrolled water streams in the spray cooling zone.

The negative influence of the total amount of copper and tin in this type of steels in the form of precipitates at the austenite grain boundaries, as confirmed by the results of numerous studies, could be omitted in the case of the examined chemical composition of the steel, due to the fact that the calculated value of the so called equivalent copper content factor was $Cu_{equ.} = 0.17$, against the recommended value of 0.20.

The possibility of precipitation of nitrides, carbides and carbonitrides of alloying elements (Nb, Ti) and Al in the steel of the analyzed chemical composition, as confirmed by calculations, while considering the potential for their precipitation at grain boundaries, indicates that the proposition to limit the concentration of nitrogen in steel melted in an electric arc furnace is legitimate. The amount of precipitated nitrides will be in that case proportionally smaller.

Observations of the surface of cast billets revealed irregularities in formation of oscillation marks, which, as has been found, make the location for transverse crack initiation. The correction made to the main mould operation parameters associated with the oscillatory mould movement showed that the optimal casting speed values for these steels were contained in the range of $2.0 \div 2.2 \text{ m}\cdot\text{min}^{-1}$, with stroke length of mould of 7.0 mm and an oscillation frequency value in the range of $172 \div 189$ cycles/minute, depending on the casting speed.

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