IMPACT OF CAST SPEED ON THE OCCURRENCE OF THE NON-METALLIC INCLUSIONS IN STEEL

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Abstract
This paper deals with the examination of the impact of steel cast speed on the occurrence of the non-metallic inclusions due to the investigation of the individual samples taken at different steel cast speeds. The aim of this paper was to identify and describe the relation between the non-metallic inclusions occurring in the metal and the cast speed variations at the continuous casting machine. The non-metallic inclusions within this investigation were identified by the method (AES) based on the atomic emission spectroscopy that evaluates the occurrence of the determined elements in the metal. This method applies the principle of the light emitting acquired by the high-voltage spark supply. The investigation of the impact of both the technological production parameters, and the casting on the cleanliness of the given absorption quality of steel leads to their optimization, as well as, to total minimization of occurrence of the non-metallic inclusions in the steel volume were studied.

Keywords: casting, steels, non-metallic inclusions

1 Introduction
The worldwide steel production has proved a continuous increase after the financial crisis. The increase of the steel production requires the provision of high-quality steel. The result of the quality increase of the steel products due to the enlisted professional references can be demonstrated in the lower occurrence of the non-metallic inclusions in the metal and moreover in the most efficient management of the production processes. It is necessary to provide and maintain the high cleanliness of steel mainly in some types of steel which are appropriate for specific applications such as in the foodstuff industry [1, 2]. The development in the field of packaging materials dominantly influences the thin electrolytic tin-coated steel-sheet. This material plays a highly important role in some fields of the packaging sector. The packaging materials can be used in a lot of fields nevertheless due to their wide range of mechanical features, high corrosion resistance and, of course, their health safety enable their application first of all in the foodstuff industry. In this case, the steel purity is defined by the level of occurrence of the non-metallic inclusions in the metal volume [3-5]. The non-metallic inclusions are characterized by the agglomeration into bulk metals, esp. solid products of oxidation resulting from the steel production where their concentration varies. The composition of the agglomerates of the non-metallic inclusions consists mainly of the fine particles of Al_2O_3. In many cases of the occurrence of the non-metallic inclusions in steel products their shapes, quantity and chemical

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composition have to be taken into consideration. In general, it is advisable to prevent the occurrence of large and angular shapes in the non-metallic inclusions in the metal **Fig.1**, because their occurrence will decrease the purity of the produced steel products [6-9]. The main quantity of the non-metallic inclusions arises in the steel paradoxically at purity increase by deoxidation where the quantity of the non-metallic inclusions depends on the cleanliness and quantity of the deoxidating admixture [10-12]. The presence of the non-metallic inclusions in the metal volume comes from the product remains of the deoxidation from different sources including reoxidation, slag dragging into the steel, fire resistant lining, impact of the surrounding atmosphere and chemical reactions [13-15]. When the casting velocity varies there is a higher probability of slag dragging, moreover casting powders and particles from the clogged nozzles could be dragged into the molten metal. From the point of view of clean steel, it is ideal to prevent variations of steel cast speed at the continuous casting machine however in praxis some variations of the cast speeds are necessary [16-17]. The non-metallic inclusions arrive the surface in the form of the surface defects such as cracks or metallurgical slivers which worsen and excessively lengthen the processing period of the produced material and markedly degrade the product utility properties. The range of the defect characterized by the occurrence of the non-metallic inclusions is dependable to a certain extent on the elasticity and strength of the material, its localization under the metal surface, the intensity of the defect oxidation and the processing methods [18-20]. The rise and quantity of the non-metallic inclusions in the metal volume are markedly influenced by the quantity, time and speed of the argon injection at secondary metallurgy steel processing. In this relation we consider those technological operations such as bubbling, purification of steel or dead-melting after the secondary metallurgy processing before the exact casting. From the point of view of cast speed mainly the stability of the casting process belongs to the key factors influencing the final purity of the casted material. The determination of the non-metallic inclusions in the steel plays an important role in the quality improvement of the steel products [3, 21].

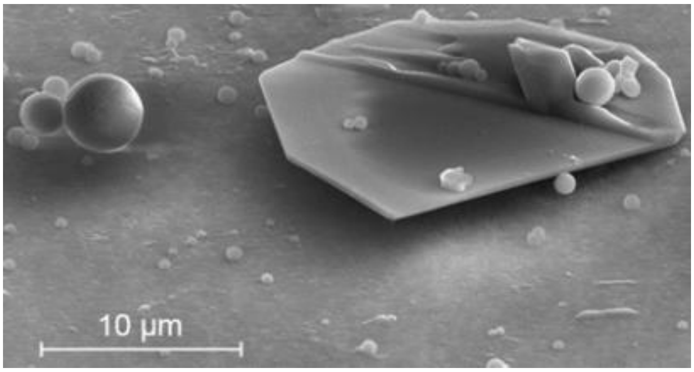

Fig. 1 Sharp-edged lamelliform non-metallic inclusions [3]

2 Experimental materials

During the steel production and processing, the packaging qualities were assessed. In this case, we considered the quality of the casted materials thatwere assigned for the production of the thin electrolytic tin-coated sheets suitable for the foodstuff industry. This material is casted at a standard speed 1.6 m.min^{-1}, which is the maximum cast speed for this type of steel. An

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increased number of cast speed variations is mostly related to the necessary technological operations at the continuous steel casting on the one hand (e.g. replacement of the nozzles), on the other hand, they can be related to the current operating conditions concerning the timely delivery of the cast to the continuous casting machine.

According to the chosen method of solution, the primary aim was to identify the cleanliness of the casted steel during the cast speed variations by steel sampling from the mold. The castspeed variations during the process of the submerged entry nozzle replacement were considered there. During the process of the nozzle replacement, the cast speed of the steel does not change. The first two samples were taken some minutes before the nozzle replacement, the third one right before the replacement, the fourth and fifth samples were taken in the intervals ca. two and four minutes after the replacement of the submerged entry nozzle. In the following **Tables 1-5,** the individual columns signed from the left to the right are demonstrated“S. No“ standing for the sample numbers, “phase of sampling“ characterizes the phase /time of sampling before or after the nozzle replacement - abbreviated as (SENR) at the continuous casting machine. “Time [min]“ shows the time period of sampling according to the nozzle replacement (SENR) was realized in time 0 [min] in relation to the sampling. “v [m.min^{-1}]“ identifies the cast speed of the steel in meters per minute. “Al_{INS} [%]“ identifies the content of the interstitial aluminium in percentage, i.e. the aluminium content in the non-metallic inclusions. ”Al_xO_y [ppm]” considers the concentrations of the identified non-metallic inclusions on the basis of aluminium and oxygen. The non-metallic inclusions on the basis of other elements proved minimum concentrations that were at the boundary identification regarding the machine sensitivity. Each analyzed sample was examined in three points so-called tracks (S_1, S_2, S_3) and further ($S_⌀$) shows the calculated average of three tracks. Those concentrations exceeding ten ppm at the analyzed tracks (S_1, S_2, S_3) were highlighted. This highlighting was necessary because of the occurrence of the increased concentrations of the non-metallic inclusions (>10ppm), which could cause metallurgical surface defects on the basis of the non-metallic inclusions.

Table 1 Analysis of the first cast samples (T1) at the submerged entry nozzle replacement

S. No	Phase of sampling	time [min]	v[m.min^{-1}]	Al_{INS} [%]	Al_xO_y [ppm]			
					S_1	S_2	S_3	$S_⌀$
1	First before SENR	7-10	1.61	<0.002	04	13	02	06
2	Second before SENR	3-5	1.39	<0.001	09	04	03	05
3	Third right before SENR	0.5	1.00	<0.002	00	02	07	03
4	Fourth after SENR	2	1.20	<0.002	01	02	01	01
5	Fifth after SENR	4	1.40	<0.002	07	02	02	04

Table 2 Analysis of the second cast samples (T2) at the submerged entry nozzle replacement

S. No	Phase of sampling	time [min]	v[m.min^{-1}]	Al_{INS} [%]	Al_xO_y [ppm]			
					S_1	S_2	S_3	$S_⌀$
1	First before SENR	7-10	1.60	<0.001	06	09	02	06
2	Second before SENR	3-5	1.40	<0.001	01	00	03	01
3	Third right before SENR	0.5	1.00	<0.001	04	03	03	03
4	Fourth after SENR	2	1.25	<0.002	07	04	05	05
5	Fifth after SENR	4	1.40	<0.002	02	12	00	05

Table 3 Analysis of the third cast samples (T3) at the submerged entry nozzle replacement

S. No	Phase of sampling	time [min]	v[m.min^{-1}]	Al_{INS} [%]	Al_xO_y [ppm]			
					S_1	S_2	S_3	S_{∞}
1	First before SENR	7-10	1.62	<0.001	03	06	02	04
2	Second before SENR	3-5	1.37	<0.001	02	01	03	02
3	Third right before SENR	0.5	1.00	<0.001	00	01	01	01
4	Fourth after SENR	2	1.31	<0.002	04	03	04	04
5	Fifth after SENR	4	1.55	<0.002	03	02	02	02

Table 4 Analysis of the fourth cast samples ($T4_{L1}$) at the submerged entry nozzle replacement from the casting flow No.1

S. No	Phase of sampling	time [min]	v[m.min^{-1}]	Al_{INS} [%]	Al_xO_y [ppm]			
					S_1	S_2	S_3	S_{∞}
1	First before SENR	7-10	1.61	<0.002	06	03	09	06
2	Second before SENR	3-5	1.61	<0.002	01	02	15	06
3	Third right before SENR	0.5	1.03	<0.001	01	01	00	01
4	Fourth after SENR	2	1.15	<0.001	01	03	02	02
5	Fifth after SENR	4	1.25	<0.002	03	02	03	03

Table 5 Analysis of the fourth cast samples ($T4_{L2}$) at the submerged entry nozzle replacement from the casting flow No.2

S. No	Phase of sampling	time [min]	v[m.min^{-1}]	Al_{INS} [%]	Al_xO_y [ppm]			
					S_1	S_2	S_3	S_{∞}
1	First before SENR	7-10	1.62	<0.001	02	01	00	01
2	Second before SENR	3-5	1.28	<0.002	05	01	01	02
3	Third right before SENR	0.5	1.01	<0.001	03	02	00	01
4	Fourth after SENR	2	1.25	<0.001	03	01	01	02
5	Fifth after SENR	4	1.35	<0.002	07	00	01	03

Cast speed variations of steel were observed during the process of the submerged entry nozzle replacement. **Fig. 2**, before the replacement the cast speed of the steel (v [m.min^{-1}]) decreased from the maximum cast speed (1.6 m.min^{-1}) to the value 1 m.min^{-1}. After the replacement of the

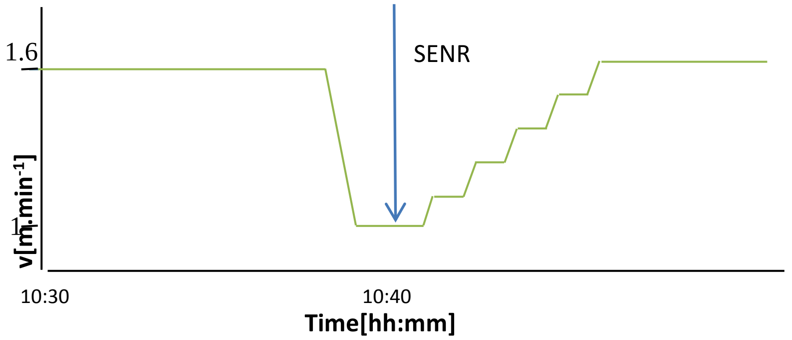

Fig. 2 Steel cast speed during the replacement of the submerged entry nozzle at the cast $T4_{L1}$

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submerged entry nozzle, an increase of the cast speed of the steel up to the maximum cast speed of this type of steel could be observed.

3 Results and discussion

The analyses results of the examined samples showed the occurrence of the non-metallic inclusions on the basis of aluminium in an increased concentration (>10ppm) in three examples. One of these three examples approved the increased occurrence of the non-metallic inclusions during the steel cast speed variations, in two examples an increased occurrence of the non-metallic inclusions during the casting at the maximum speed determined for this quality was observed. The internal quality assessment system confirmed the occurrence of the non-metallic inclusions in the basic material except for the assessed analyses and also approved the identification of the surface defects at the coils in the final processing phases of the examined samples **Table 6**. The identified surface defects were metallurgical slivers and holes on the basis of Al_xO_y at the final processing. In this case at the identification of the steel cast speed variation in combination with the flotation of the contaminants from the submerged entry nozzle (SEN), the formation of the surface defects occurs.

Table 6 Quality Assessment System

Cast No.	Internal quality assessment system	Identified defect
T1	Cast speed variation, flotation of contaminants from SEN	2x metallurgical sliver
T2	Cast speed variation, flotation of contaminants from SEN	5x metallurgical sliver
T3	Cast speed variation, flotation of contaminants from SEN	2x hole
T4	Cast speed variation, flotation of contaminants from SEN	1x metallurgical sliver

In the following graphs **Fig. 3, Fig. 4 and Fig. 5** the final average values from the **Tables 7-9** according to the individual phases of the examined samples are demonstrated. These final values were averagedto achieve provable conclusions. The average value of the interstitial aluminium**Table 7, Fig. 3** was at the value of <0.0014%. From three to ten minutes before the replacement of the submerged entry nozzle, right before the replacement it was (0.5 min. before SENR), at the phase of the replacement the value of ⌀ Al_{INS} was at the level of <0.0012%. After the replacement of the submerged entry nozzle ca. after two minutes the average value of the interstitial aluminium increased to<0.0016%. The last sampling ca. after four minutes shows an increase of the values to <0.002%. These values present a certain relation between the values of the interstitial aluminium in the metal volume and the steel cast speed at the continuous casting machine according to the increasing values of the interstitial aluminium contemporaneously with the increase of the steel cast speed.

Table 7 Values of the interstitial aluminium of the examined casts

	S.No.1 [%]	S.No.2 [%]	S.No.3 [%]	S.No.4 [%]	S.No.5 [%]
T1	<0.002	<0.001	<0.002	<0.002	<0.002
T2	<0.001	<0.001	<0.001	<0.002	<0.002
T3	<0.001	<0.001	<0.001	<0.002	<0.002
$T4_{L1}$	<0.002	<0.002	<0.001	<0.001	<0.002
$T4_{L2}$	<0.001	<0.002	<0.001	<0.001	<0.002
⌀ Al_{INS}	<0.0014	<0.0014	<0.0012	<0.0016	<0.002

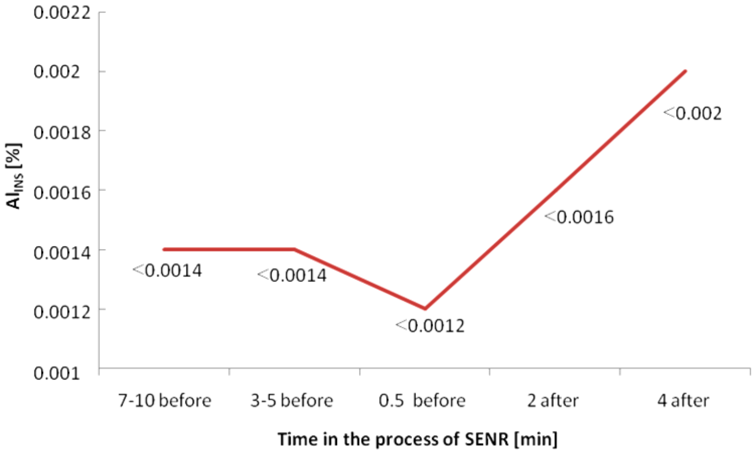

Fig. 3 Average value of the interstitial aluminium from all examined samples

In the graph of the non-metallic dependency on the basis of Al_xO_y and the cast speed in time (the process of the submerged entry nozzle replacement) **Fig. 4** there are demonstrated two curves. The first red curve is connecting the average concentrations of the non-metallic inclusions on the basis of Al_xO_y with the axis on the left side in the same red colour. The second blue curve is connecting the average steel cast speeds with the axis on the right side in blue colour. The average concentration of the non-metallic inclusions in the form of Al_xO_y in the examined samples **Table 8, Fig. 4** and the average steel cast speed **Table 9, Fig. 4** showed variations in different time periods regarding the process of the submerged entry nozzle replacement. At the maximum steel cast speed before the replacement of the submerged entry nozzle, the samples proved the highest average concentrations of the non-metallic inclusions in the form of Al_xO_y. As the steel cast speed began to decrease, a decreasing concentration of the non-metallic inclusions was observed. Right before the replacement of the submerged entry nozzle at the speed ca. one meter per minute the average concentration of the Al_xO_y showed the lowest values. After the replacement of the submerged entry nozzle, the average concentrations of the Al_xO_y demonstrated an increasing tendency together with the average steel cast speed.

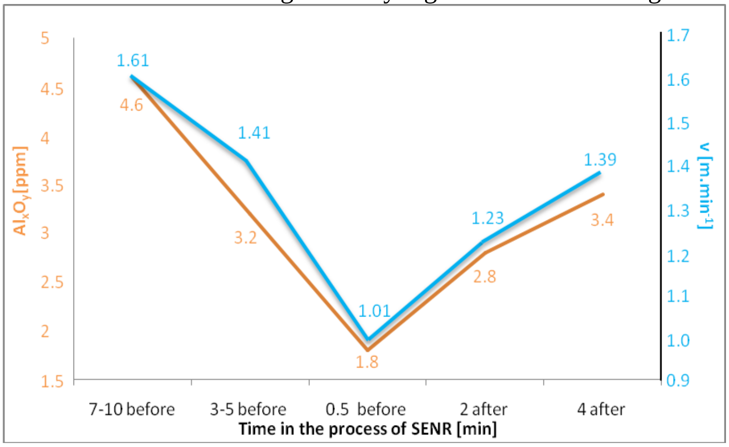

Fig. 1 Dependency of Al_xO_y and steel cast speed in the process of SENR

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Table 8 Concentrations of Al_xO_y from the examined casts

	S. No.1	S. No.2	S. No.3	S. No.4	S.No.5
	[ppm]				
T1	6	5	3	1	4
T2	6	1	3	5	5
T3	4	2	1	4	2
$T4_{L1}$	6	6	1	2	3
$T4_{L2}$	1	2	1	2	3
Ø Al_xO_y	4.6	3.2	1.8	2.8	3.4

Table 9 Steel cast speed at sampling

	S.No.1	S.No.2	S.No.3	S.No.4	S.No.5
	[m.min^{-1}]				
T1	1.61	1.39	1.00	1.20	1.40
T2	1.60	1.40	1.00	1.25	1.40
T3	1.62	1.37	1.00	1.31	1.55
$T4_{L1}$	1.61	1.61	1.03	1.15	1.25
$T4_{L2}$	1.62	1.28	1.01	1.25	1.35
Ø v	1.61	1.41	1.01	1,23	1.39

The graphical mutual dependency between the present non-metallic inclusions in the metal volume and the steel cast speed **Fig. 5** demonstrates the existing impact of the cast speed variations on the occurrence of the non-metallic inclusions in the metal volume. As the cast speed increases, and there is a variation of the cast speed, an increase of the concentrations of the non-metallic inclusions on the basis of Al_xO_y in the metal volume occurs.

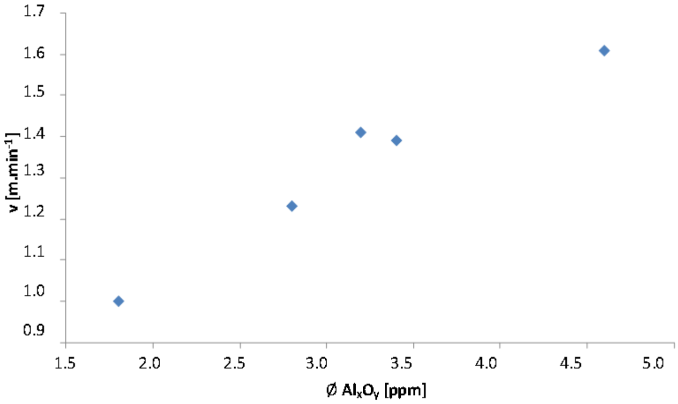

Fig. 2 Graphical dependency between the present non-metallic inclusions and the steel cast speed

In the technical bibliography [22-26] the authors analyse a very similar topic but they deal with different quality types of steel, and the chemical composition of the non-metallic inclusions differs as well, nevertheless the basic principle is the same. In the given specific literature, the

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authors underlined the increase of the non-metallic inclusions content that occurred after the increase of the steel cast speed Fig.6. After the stabilization of the steel cast speed,a decrease of the non-metallic inclusions content was observed, and it led to their stabilization. The results of these studies prove the fact that the steel cast speed variations have a certain impact on the occurrence of the non-metallic inclusions in the metal volume as the steel cast speed varies.

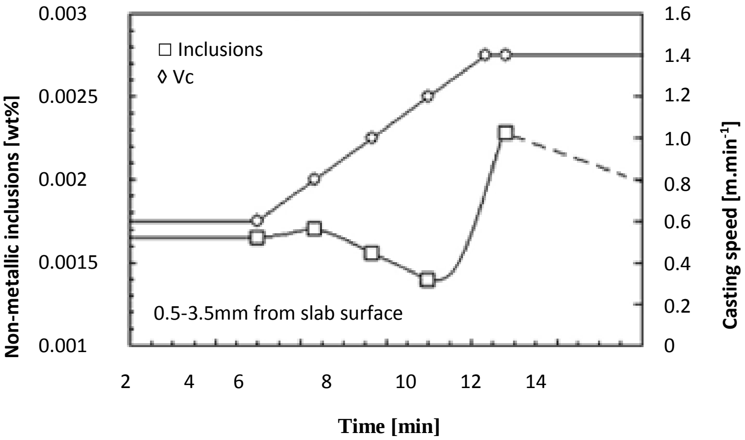

Fig. 3 Occurrence of the non-metallic inclusions in the metal volume at the steel cast speed variations

During the steel cast speed variations at the continuous casting machine, probable infiltrations of the non-metallic inclusions into the metal volume can be observed. According to the individual analyses of the examined samples **Tables 1, 2, 3, 4** and **5,** in three examples the occurrence of the non-metallic inclusions was identified.**Tables 1, 2** and **4** which could influence the steel purity due to their concentration and consequently it can probably lead to the rise of the surface defects during the steel processing in the other operational units of the plant. At assessing the interstitial aluminium **Fig.3,** it is requirable to underline the fact identifying the lowest value right before the replacement of the submerged entry nozzle at the lowest stated steel cast speed. Some minutes before the replacement of the submerged entry nozzle the value of the interstitial aluminium was at a moderately higher level. After the replacement of the submerged entry nozzle, a continuous increase of the value of the interstitial aluminium was observed. The further analysis of the average concentrations of the non-metallic inclusions in the form of Al_xO_y together with the analysis of the average steel cast speeds **Fig.4** demonstrate the decrease of the non-metallic inclusions together with the steel cast speed. Consequently after the replacement of the submerged entry nozzle an increase of both the steel cast speed and the average concentration of the non-metallic inclusions in the form of Al_xO_y in the metal volume was observed. Due to the graphical dependency it can be shown that the steel cast speed variations have a certain impact on the occurrence of the non-metallic inclusions in the form of Al_xO_y, as the final average results connected into lines prove a similar trajectory. In this case we could highlight the probable relation to the flotation of the non-metallic inclusions after the replacement of the submerged entry nozzle in the mold by releasing the non-metallic inclusions from the stopper plug, resp. from the tundish nozzle at speed increase that causes probably dragging of the non-metallic inclusions. It is important to underline the fact that this situation occurs at the cast speed variations, respectively under turbulent conditionsthatare later stabilized.

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The last graphical dependency of the existing non-metallic inclusions in the metal volume and at the steel cast speed **Fig. 5** approves the relation between the occurring non-metallic inclusions and the steel cast speed variations at the continuous casting machine as the increasing speed brings about the rise of the concentration of the non-metallic inclusions on the basis ofAl_xO_y.

Conclusions

The impact of the steel cast speed variations on the occurrence of the non-metallic inclusions in the metal volume can be entirely proved due to the introduced analyses of the examined samples. The examined samples showed the lowest values of the interstitial aluminium and the lowest average concentrations of the non-metallic inclusions on the basis of aluminium at the lowest identified steel cast speed. As the steel cast speed decreases at the continuous casting machine as a consequence there were observed lower values of the interstitial aluminium and lower concentrations of the non-metallic inclusions on the basis of aluminium were observed but in the contrary as the cast speed increases it brings about increased values of the interstitial aluminium and moreover the concentrations of the non-metallic inclusions on the basis of aluminium are higher as well. In the following phases of the processing, metallurgical surface defects on the basis of the non-metallic inclusions were identified. The results of this study are also influenced by the other factors concerning the steel flow in the mold, the design of the applied submerged entry nozzle (inclination angle), depth profile etc. Therefore it could be appropriate to focus on this issue in the future and consider the improvement of the coordination of a smoother transition to the lower respectively to the higher steel cast speeds in a time period. In spite of the rise of the individual surface defects, it is necessary to notice that this kind of the material is transmitted to the adjusting technology, and later the clients obtain them without any defects and at the best quality.

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