MACROSCOPIC INVESTIGATIONS OF THE PRIMARY STRUCTURE OF CONTINUOUS CASTING INGOTS

Zdzisław Kudliński[1)], *Krystian Janiszewski*[2)*]
[1)] *Silesian University of Technology, Department of Materials Science and Metallurgy, Institute of Metallurgical Technology Katowice, Poland*
[2)] *Silesian University of Technology*, Department of Materials Science and Metallurgy, *Institute of Metallurgical Technology, Katowice, Poland*

Received: 12.10.2013
Accepted: 18.03.2014

[*]*Corresponding author: e-mail: krystian.janiszewski@polsl.pl, Tel.:+48 32 603 43 53, Department of Metallurgy, Silesian University of Technology, Krasińskiego 8, 40-019 Katowice, Poland.*

Abstract
This paper presents the results of macroscopic investigations of the structure of continuous casting ingots depending on the kinetics of solidification and speed of casting of low carbon steel intended for welding wires. We have determined the L_k length of solidification path of ingots of 140 x 140 mm cross-section. We have also performed macroscopic investigations of the ingot structures together with identification of shrinkage porosity defects and axial porosities. microscopic investigations of axial ingot zones, areas of shrinkage defects and axial porosity, have demonstrated that the non-metallic phase (silicates and aluminates) presented there stands in the way of welding during the process of rolling of continuously cast ingots.

Keywords: analytical electron microscopy, microstructure, continuous casting, solidification, ingot structure

1 Introduction

Defects of the primary structure of continuous casting ingots, including porosity and axial shrinkage defects, occurring concurrently with typical zones of crystallizations, are their important components, which form the non-continuity zones in the material. These defects have especially negative impact in case when continuous casting ingots are intended for production of metallurgical steel products with very small cross-section areas. Such products include welding wires of diameters from 1.5 to 3.0 mm. The occurrence of wire breakage observed in the process of wire drawing from the rolled material produced of the continuous casting ingots, is the result of the shrinkage porosity defects and axial porosity. The reasons why the mentioned macroscopic defects of continuous casting ingots occur, can mainly be looked for in improper selection of parameters for the process of casting of the given steel sort, which parameters determine the ingot solidification kinetics and do not assure proper moment of solidification in the continuous casting machine, in the secondary cooling zone. This especially regards to the radial and curved (arced) pieces of equipment. Liquid steel filtration, broadly described in literature, can be an alternative in the process of elimination observed in axial zone of continuous casting ingots of non-metallic phase [1-11].

DOI 10.12776/ams.v20i2.310 p-ISSN 1335-1532
e-ISSN 1338-1156

2 Estimation of solidification kinetics of 140 x 140 mm continuously cast ingots contributions

Essential part of the estimation of solidification kinetics of the 140 x 140 mm ingot of G3Si1 steel (**Table 1**) is the determination of L_k length of solidification path in relation to the design characteristics of the used CSC machine: L_m metallurgical length of the machine (a distance between steel table level in the crystallizer and the point of ingot cutting) and L_h length of the secondary cooling zone – **Fig. 1**.

Table 1 Chemical composition of G3Si1 steel, %.

	C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Al (c)**	**Ca (m)**	**O_2**	**N_2**
min	0.06	1,30	0,75								
max	0,09	1,55	0,95	0,02	0,02	0,15	0,10	0,02	0,001	0,01	0,01

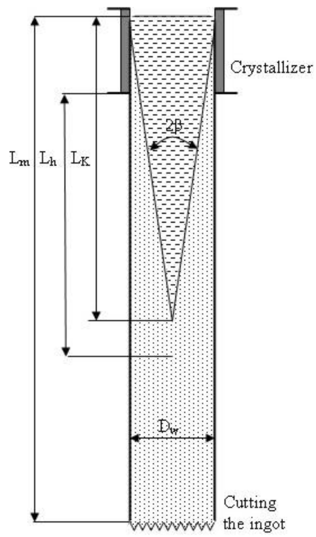

Fig. 1 Illustration of solidification path of continuously cast ingot [12]

In practice the solidification kinetics of continuously cast ingots can be expressed with use of Stefan [13] formula:

$$d_w = K \cdot \sqrt{\tau_K} \qquad (1)$$

where: d_w [cm] – thickness of the solidified layer of the ingot,
K [cm/min^{0,5}] – solidification speed constant,
τ [min] - solidification time.

When parameters of the continuous casting process are taken into account, the formula (1) obtains the following form:

$$d_w = K \cdot \sqrt{\frac{L_K}{v_{odl}}} \qquad (2)$$

where: L_k [cm, m] - length of ingot solidification path,
V_{odl} [m /min] - casting speed.

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If we define the „ingot solidification path length” as a distance between the level of steel table in the crystallizer and the point where the ingot becomes solidified (**Fig. 1**), then its value will be expressed by the formula:

$$L_K = \frac{D_w^2 \cdot v_{odl}}{4 \cdot K^2} \tag{3}$$

where: D_w [m] – dimension of the square ingot side (equal to $2d_w$).

The CSC machine used in casting of the investigated square ingots, have had the following design characteristics [14-17]:

- length of the secondary cooling zone L_h= 9,5 m
- metallurgical length L_m = 29,7 m
- distance of the ingot straightening 13,7 m from steel table in the crystallizer,
- recommended ingot casting speeds for 140x140 mm products, V_{odl}= 3,1- 3,4 m/min.

For this analysis we have assumed the values of K solidification constant and casting speed, which result from the casting technology used worldwide. The results of calculations of the solidification path length are presented in **Table 2**. The obtained results indicate that only in one case (for K =3,0 cm/min ^{0,5} and V_{odl} =2,0 m/min) the ingot becomes solidified in the terminal area of the secondary cooling zone. Each trial to increase casting speed causes the solidification path length to be increased.

Table 2 Path of solidification of 140 mm square ingot

Ingot casting speeds, V_{odl}, m/min	**The decrease in casting speed, K, cm/min^{0,5}**						
	1,8	2,0	2,2	2,4	2,6	2,8	3,0
	Length of ingot solidification path L_K						
2,0	30,25	24,50	20,25	17,01	14,50	12,50	10,88
2,2	32,27	26,95	22,27	18,72	15,95	13,75	11,98
2,4	26,30	29,40	24,30	20,42	17,40	15,00	13,07
2,6	39,32	31,85	26,32	22,12	18,55	16,25	14,15
2,8	42,34	34,30	28,35	23,82	20,29	17,50	15,24
3,0	45,37	36,75	30,37	25,52	21,75	18,75	16,33
3,2	48,39	39,20	32,40	27,22	23,19	20,00	17,42
3,4	51,42	41,65	34,42	28,92	24,65	21,25	18,51
3,6	54,44	44,10	36,45	30,62	26,09	22,50	19,06
3,8	57,42	46,55	38,47	32,33	27,55	23,75	20,69

L_h = 9,5 m, L_m = 29,7 m

When continuously cast ingot with non-solidified internal part passes to its horizontal position then formation of axial porosity and shrinkage porosity defects will always be the result. If macrostructure of continuously cast ingots is the priority, then increasing casting speed can not be deemed as the way to increase the CSC machine performance.

3 Results of macrostructure investigation of 140x140 mm continuous casting ingots

For these investigations we have selected ingots from melts characterized by significant differentiation of product rejections resulting from shrinkage defects and axial porosity occurring during ingot rolling and wire drawing. Selected examples of macrostructure are illustrated in **Fig. 2-6**. Increase of casting speed in each case has negatively affected the product rejection index.

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e-ISSN 1338-1156

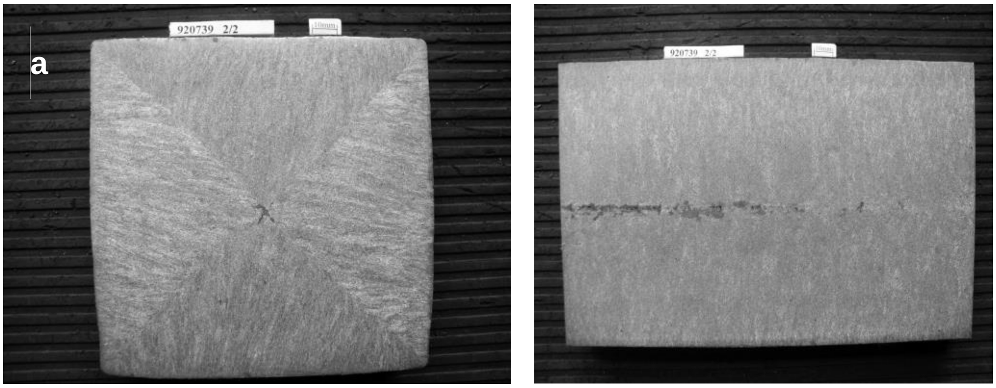

Fig. 2 Macrostructure of the crosswise (a) and lengthwise (b) sections of continuously cast ingots (2/2). Melt 739, V_{odl} = 2,8 m · min^{-1}, ΔT_p = 34ºC, level of rejections of steel per melt 3,88 %.

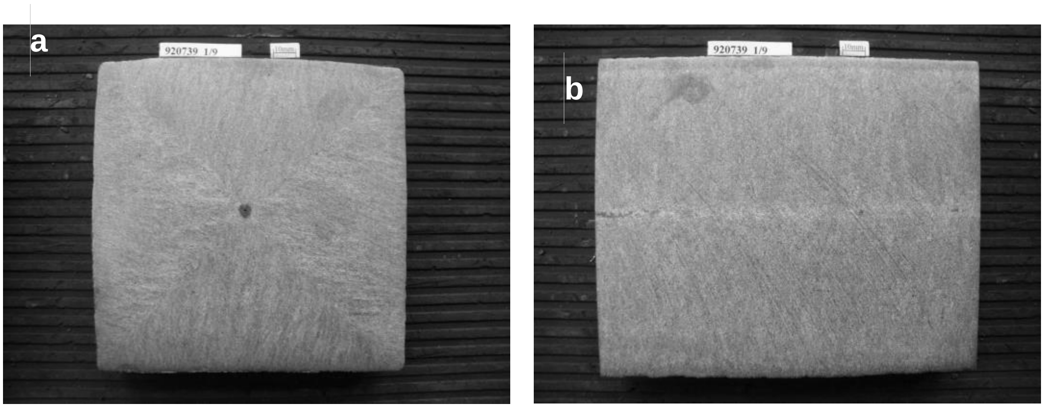

Fig. 3 Macrostructure of the crosswise (a) and lengthwise (b) sections of continuously cast ingots (1/9). Melt 739, V_{odl} = 2,8 m · min^{-1}, ΔT_p = 34ºC, level of rejections of steel per melt 3,88 %.

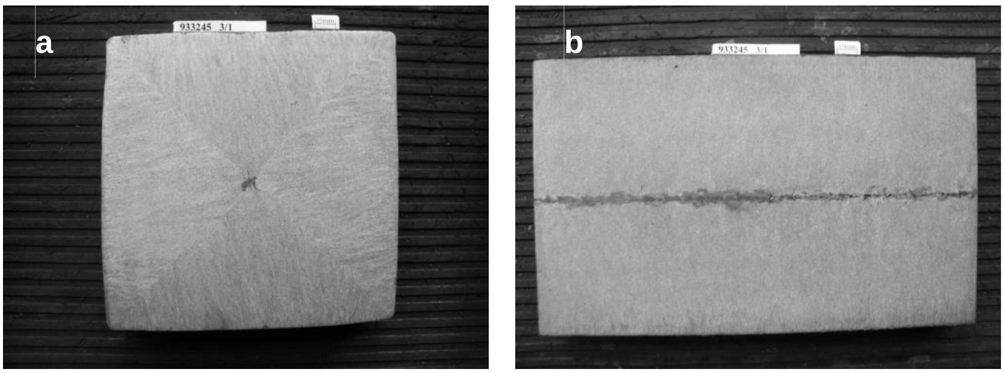

Fig. 4 Macrostructure of the crosswise (a) and lengthwise (b) sections of continuously cast ingots (3/1). Melt 245, V_{odl} = 3,0 m · min^{-1}, ΔT_p = 35ºC, level of rejections of steel per melt 11,04 %.

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e-ISSN 1338-1156

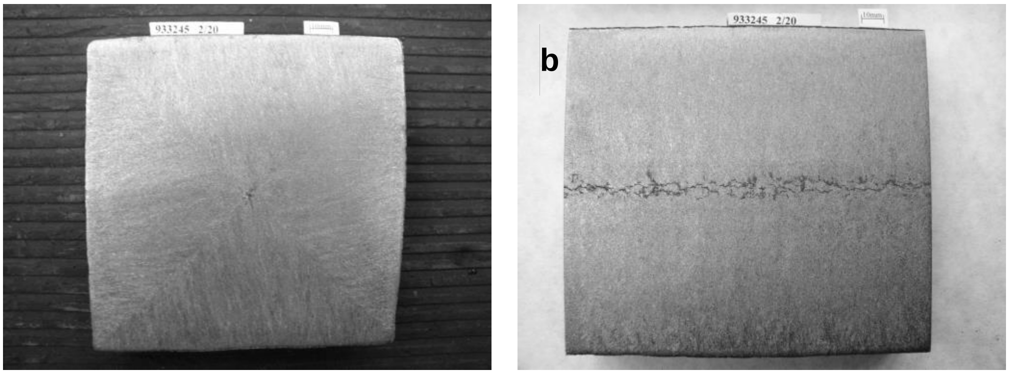

Fig. 5 Macrostructure of the crosswise (a) and lengthwise (b) sections of continuously cast ingots (2/20). Melt 245, V_{odl} = 3,0 m · min^{-1}, ΔT_p = 34ºC, level of rejections of steel per melt 11,04 %.

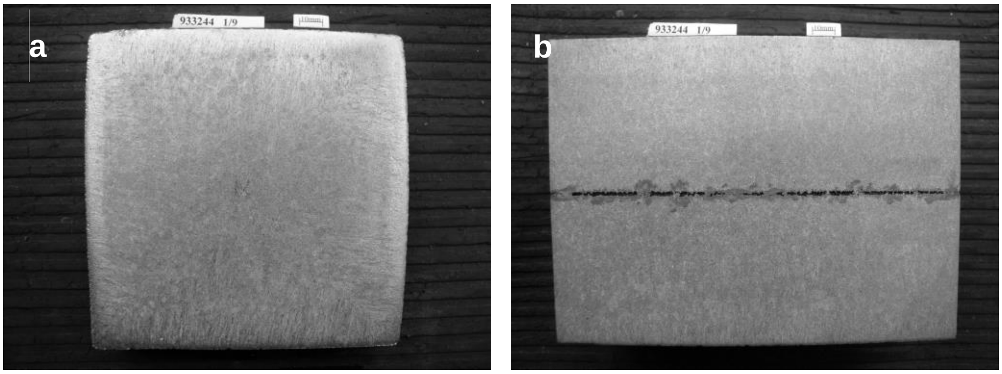

Fig. 6 Macrostructure of the crosswise (a) and lengthwise (b) sections of continuously cast ingots (1/9). Melt 244, V_{odl} = 3,3 m · min^{-1}, ΔT_p = 23ºC, level of rejections of steel per melt 14,35 %.

4 Conclusions

Following conclusions can be drawn on the basis of the performed investigations:

- the significant level of rejections in rolled steel wires 5.5 mm in diameter and drawn wires has been caused by shrinkage defects and axial porosity of continuously cast ingots,
- the decrease in casting speed from 3.3 to 2.8 m/min has positively influenced the level of rejections of steel products.

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DOI 10.12776/ams.v20i2.310 p-ISSN 1335-1532
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