The Effect of Electromagnetic (i.e. Induction) Stirring of the Melt of Concast Billets on the Reduction of their Surface Defects

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Abstract. Electromagnetic stirring (EMS) suppresses the growth of columnar crystals of billets and reduces the tendency to cracking during casting and at low temperatures. A caster was used for the testing of two induction stirrers – one on the actual mould and the other beneath the mould – to determine the effect of EMS on the formation of the structure of non-alloy steel. As part of these tests, certain parts of the billets had been cast without the use of stirrers and other parts underwent alternate switching on and off of the stirrers for as many as nine combinations of modes. Samples were taken from the sections of these billets, fine-ground and etched in order to make the dendritic structure visible. The mode with the highest efficiency was when both stirrers ran simultaneously. The growth of the columnar crystals, which pointed inward, was limited to ¼-to-⅓ of the length of the case when there was no stirring. Experimental research was also confronted with results acquired from the application of the models of the temperature field and chemical heterogeneity and the physical-similarity theory. Statistical monitoring of the quality of concast billets has proven that stirring significantly reduces the occurrence of defects – in this case cracks.

Introduction

Currently, casters use rotating stators of electromagnetic melt-stirring systems. These stators create a rotating magnetic induction field with an induction of B, which induces eddy-current J in a direction perpendicular to B, whose velocity is v. Induction B and current J create an electromagnetic force, which works on every unit of volume of steel and brings about a stirring motion in the melt. The vector product $(v \times B)$ demonstrates a connection between the electromagnetic field and the flow of the melt. The speeds of the liquid steel caused by the EMS is somewhere from 0.1-to-1.0 m/s.

The stirring parameters are within a broad range of values, depending on the construction and technological application of the stirrer. The power output is mostly between 100 and 800 kW, the electric current between 300 and 1000 A, the voltage up to 400 V and with billet casting the frequency from 5 to 50 Hz.

The EMS applied on the steel caster is basically a magneto-hydraulic process together with crystallization processes and solidification of billet steel. The complexity of the entire process is enhanced further by the fact that the temperatures are higher than the casting temperatures of concast steel. The temperature of the billet gradually decreases as it passes through the caster down to a temperature lying far below the solidus temperature. From the viewpoint of physics and chemistry, the course of the process is co-determined by a number of relevant material, physical and thermokinetic characteristics of the concast steel and also electrical and magnetic quantities. There is also a wide range of construction and function parameters pertaining to the caster and EMS as well as parameters relating to their mutual arrangement and synchronization. Numerous works from recent years relate that exact mathematical modelling of EMS on a caster is still unsolvable [1] to [3].

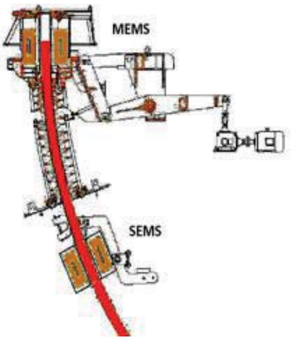

Fig. 1. The positions of the MEMS and SEMS stirrers

The basic EMS experiment was conducted on a CONCAST billet caster where two individual mixers were working as in Fig. 1.
The first stirrer, entitled MEMS (Mould Electromagnetic Stirring), is mounted directly on the mould and the second stirrer, entitled SEMS (Strand Electromagnetic Stirring), is mounted at the beginning of the flow directly after the first cooling zones but in the secondary-cooling zone. Here the outer structure of the billet is already created by a compact layer of crystallites, however, in the centre of the billet there is still a significant amount of melt that is mixed by the SEMS.

The conditions of the experiment

The first stirrer (MEMS) stirs the melt still in the mould while the billet is undergoing crystallization and solidification. The second stirrer (SEMS) works at a time when the melt is already enclosed by a shell of crystallites around the perimeter of the billet and inside the billet there is less melt than above in the active zone of the first stirrer.

When both stirrers were switched off, the crystallization and solidification continued in the normal way, i.e. the solidifying melt did not undergo a forced rotational movement.

Samples were taken throughout the course of the experiment – from parts of the billet cast using the MEMS and SEMS and without and also using either one. The samples were taken in the form of cross-sections (i.e. perpendicular to the billet axis). The samples were fine-ground and etched in order to make visible the dendritic structure which is characteristic for individual variants of the solidification of the billet.

The verification of the influence of MEMS and SEMS on the macrostructure of the billet was carried out on two melts of almost the same chemical composition (Table 1).

Table 1 Chemical composition of experimental melts [wt.%]

Melt	C	Mn	Si	P	S	Cu	Cr	Ni	Al	Ti
A	0.14	0.31	0.22	0.014	0.009	0.03	0.05	0.02	0.02	0.002
B	0.13	0.32	0.22	0.018	0.012	0.09	0.06	0.04	0.02	0.002

The timing of the concasting process of the billets – without the involvement of the stirrers and with the working of the EMS of individual variants of stirrers (MEMS and SEMS) – is given in Table 2. The speed of the concasting (i.e. the movement, the proceeding of the billet through the mould) of the billet was maintained constant during the experimentation at a value of 2.7 m/min. Table 2 shows that as many as nine concasting variants were verified. The lengths of individual experimental billets – from which samples had been taken – were always a multiple of the metallurgical length. The average superheating of the steel above the liquidus was 32.8 ± 3.1 °C in melt A and 28.0 ± 4.6 °C in melt B, which lies within the standard deviation of the temperature measurements.

Table 2 The billet concasting modes and sampling

Melt	Concasting mode –sampling	Superheating of steel above liquidus [°C]	MEMS stirring [Amperes]	SEMS stirring [Amperes]	Fig.
A	1A	37	210	0	
	2A	31	0	0	Fig. 3
	3A	33	0	29	
	4A	30	210	57	Fig. 4
B	1B	35	210	0	
	2B	30	0	0	
	3B	27	0	57	
	4B	24	210	57	
	5B	24	210	29	

(Note: Detailed records of the experimental verification of the effects of MEMS and SEMS during concasting on the relevant device pertain to Table 2. The data are appended with a time history of the MEMS and SEMS connection and with information relating to the lengths of individual billets and the points from which the actual samples had been taken (i.e. the cross-sections from which the dendritic structures had been created [4]).

Evaluating experiments

Evaluation of all nine variants of concasting (Table 2) indicates that the arrangement of dendrites in the cross-section follow the same tendency in the first phase of crystallization. The structure is created by columnar crystals – dendrites – perpendicular to the walls of the billet (Fig. 2). In the billets that were not stirred the dendrites gradually touch one another on the diagonals of the cross-section. Here their growth either ceases, or the dendrites bend in the directions of the diagonals and their growth continues all the way to the centre of the billet. The columnar dendrites that grow from the middle part of the surface maintain their basic orientation – perpendicular to the surface – almost all the way to the centre of the billet. In the central part of the cross-section there is an obvious hollow on all nine macroscopic images. This is most probably a shrinkage. The above-described mechanism of dendrite growth during concasting without stirring is frequently the subject of interest (Fig. 2).

Inside the billets, when using the MEMS stirrer (or both MEMS and SEMS), the kinetics of solidification and dendrite growth is initially the same as without stirring. This also creates columnar dendrites which touch along the diagonals, however, soon their growth ceases still near the surface. Dendrites, which are called equiaxed dendrites continue to grow – their orientation is more random and only partly directed towards the centre of the billet (Fig. 3).

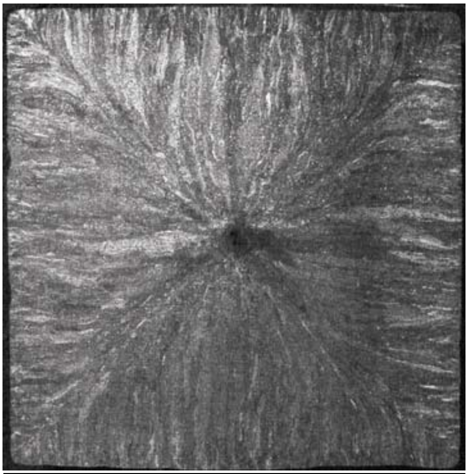

Fig. 2 Dendrite growth in the concasting structure without EMS – mode 2A

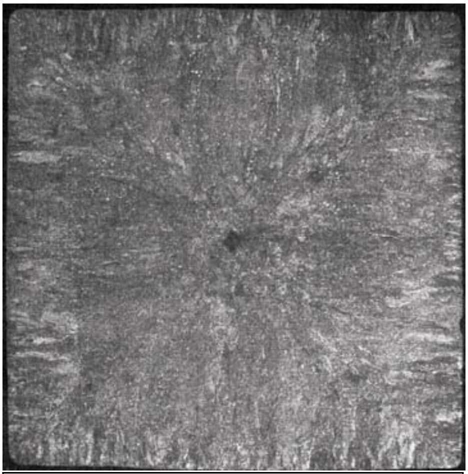

Fig. 3 The growth of dendrites in the billet structure using the MEMS and SEMS – mode 4A (Table 2)

Inside the billets, when using the MEMS stirrer (or both MEMS and SEMS), the kinetics of solidification and dendrite growth is initially the same as without stirring. This also creates columnar dendrites which touch along the diagonals, however, soon their growth ceases still near the surface. Dendrites, which are called equiaxed dendrites continue to grow – their orientation is more random and only partly directed towards the centre of the billet (Fig. 3).

It appears that this dendrite growth mechanism manifests itself most when both stirrers are working simultaneously (Table 2: 4A, 4B and 5B). If MEMS and SEMS are working simultaneously, the stirring effect significantly destroys the formation of columnar crystals. If only MEMS is working and SEMS is switched off (1A and 1B), then the desctruction of columnar crystals is less evident. The working mode of SEMS alone (modes 3A and 3B) cannot be clearly differentiated from the changes in the dendritic structure in relation to the structure formed without stirring (2A and 2B).

The effect of the stirring (using only SEMS) on the destruction of the columnar dendrite band is almost negligible.

Fig. 4 (the macro-ground dendritic structure) shows the depth of the columnar band of dendrites in the direction away from the surface of the billet (Fig. 5 – see arrows) and its value, which (with the simultaneous stirring of MEMS and SEMS) is 23.4±1.8 mm. The same qualified guess was made for ordinary billet casting (i.e. without stirring). Here, the depth of the dendrites can be estimated almost all the way to the central shrinkage at 70 mm (Fig. 6 – see arrows). It is known that additives and impurities during solidification are often concentrated in points of contact of the growing dendrites, where the maximum of segregated additives and impurities and the greatest probability of technological defects occur.

In the given case, this undesirable effect can be expected along the diagonals which have a length of up to 100-to-103 mm towards the central shrinkage. This point of contact of the dendrites during the simultaneous working of SEMS and MEMS is only 29.8±1.9 mm, i.e. 3.4× less. The central area of the billet containing a hollow as a result of a shrinkage is then filled with dendrites growing into a vacuum (i.e. underpressure) (Fig. 6).

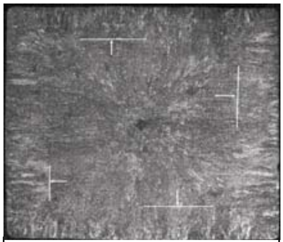

Fig. 4 MEMS+SEMS

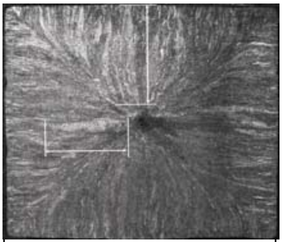

Fig. 5 without stirring

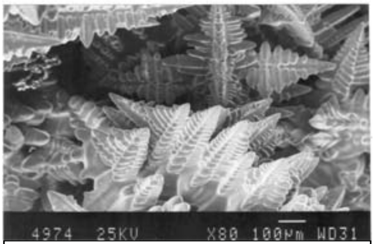

Fig. 6 Dendrites in the centre of the billet

Discussion

Under the assumption that the maximum of defects (i.e. vacancies, impurities, additives and micro-shrinkages) are formed along the diagonals it is possible to expect that in the areas of the corners – specifically on the edges – the nucleation of cracks will be higher than on the walls of the billet. If the first approximation of the fracture toughness of the relevant billet made from low-carbon steel is *KIC* ~ 75.0 MPa.m1/2, then in the ordinary concasting process it can be assumed that the length of the contact of columnar dendrites along the diagonal will be approximately $\Delta l_{normal} \approx 101.5$ mm (Fig. 6). On the other hand, if both electromagnetic stirrers (MEMS and SEMS) are engaged simultaneously, the contact length of the columnar dendrites along the diagonal decreases to $\Delta l_{el.magn.} \approx 29.8$ mm (Fig. 5). Along these lengths (i.e. the areas) it could be expected that during concasting the concentration of the primary defects will increase where according to the mechanical fracture theory the following equations should apply for the preservation of the continuity of the surface: $K_{IC} \geq \sigma_{normal}\sqrt{\pi \Delta l_{normal}}\,\varphi(\Delta l_{normal}/w)$, $K_{IC} \geq \sigma_{el.magn.}\sqrt{\pi \Delta l_{el.magn.}}\,\varphi(\Delta l_{el.magn.}/w)$. The first equation applies to normal concasting without EMS and the second to billet casting with both MEMS and SEMS engaged simultaneously. The component $\varphi(\Delta l / w)$ is the shape factor, which in the first approximation could be the same in both equations thus making it possible to estimate the stress and strain at the peaks of the dendrites touching each other along the diagonals.

This gradually becomes

$$\sigma_{normal} \leq \frac{K_{IC}}{\sqrt{\pi \Delta l_{normal}}} = \frac{75}{\sqrt{\pi 0.0298}} = 245.1 \text{ MPa,} \tag{1}$$

which is the limit stress and strain for normal concast billets without EMS, i.e.

$$\sigma_{el.magn.} \leq \frac{K_{IC}}{\sqrt{\pi \Delta l_{el.magn.}}} = \frac{75}{\sqrt{\pi 0.1015}} = 132.8 \text{ MPa,} \tag{2}$$

which is the limit stress and strain in the area of the edges of the billets during concasting if both MEMS and SEMS stirrers are engaged. A comparison of both limit stresses and strains indicates that the billets (otherwise cast under the same conditions) cast without stirring are almost twice as susceptible to cracking along the edges as billets cast using both stirrers.

A similar assumption can be made even in the case of assessing the effect of columnar dendrites in the central part of the surface of the billet where, without stirring, their length grows from the surface of the wall all the way to the central shrinkage (Fig. 6), while with the stirrers the dendrites are significantly shorter. The boundaries of the dendrites are however much less damaged by technological defects (vacancies, etc.) than the areas of their touching – of the peaks along the diagonals.

Long-term statistical monitoring of the quality of 150×150 mm billets and the chemical composition has proven that the application of EMS has significantly reduced the occurrence of defects (in this case cracks) [4].

Conclusions

This paper introduces the results of a very demanding experimental verification of the effect of EMS on the dendritic structure of steel during the concasting of billets. As many as nine different variants of concasting were verified on the mould in the following combinations:

- Ordinary concasting without EMS;
- Concasting with EMS using MEMS mounted on the mould;
- Concasting with EMS using SEMS mounted beneath the mould;
- Concasting using both MEMS and SEMS.

The method of application of these combinations is characterised in detail in Table 2 together with the corresponding current.

Macroscopic grinding was conducted on samples taken from cross-sections of individual billets in order to make the dendritic structure visible and evaluate it.

In mode 2A and 2B, columnar dendrites form throughout the entire cross-section and oriented perpendicular to each wall of the billet. The growth of these columnar dendrites ceases upon the touching of the other dendrites along the diagonals of the cross-section. Only those dendrites growing in the centres of the walls reach the centre of the cross-section (Fig. 3).

The greatest effect of the EMS was experimentally observed during the mixing using both MEMS and SEMS simultaneously. The area of the columnar dendrites oriented perpendicular to the surfaces of the walls has a thickness limited to ¼-to-⅓ of the billet thickness. In the remaining central part of billets stirred in this way the structure which dominates is the equiaxed dendrite structure.

Based on fracture mechanics, it can be assumed that with the application of MEMS and SEMS technologies, and otherwise under the same conditions, the critical stress leading to the initiation cracks is almost double (1.85×) compared to ordinary casting (i.e. without stirring).

Long-term statistical monitoring of the quality of 150×150 mm billets and the chemical composition given in Table 1 has proven that the application of EMS reduces the occurrence of defects (i.e. cracks) [4].

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