Influence of Joint EMSFN and M-EMS on Fluid Flow in the Mold During Continuous Casting

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Received: 1 June 2018 / Revised: 11 July 2018 / Published online: 5 September 2018
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Abstract

Homogenization of physical properties and the chemical composition through the control of liquid metal flow is essential during the continuous casting production of billets. This work was aimed at obtaining improved finished products via continuous casting that implements two magnetic fields. These fields were realized via two electromagnetic stirring processes implemented in a single process: one in the nozzle and one in the mold. The qualitative effects of applying double electromagnetic stirring (EMS) were verified through numerical simulation of 178 mm × 178 mm square billets exposed to double electromagnetic fields during the continuous casting process. The accuracy of the numerical calculations was verified via physical experiments. In addition, the final simulation results were compared with the intermediate results, to determine the true effects of different EMS on the metal flow in the mold. The results revealed that casting using EMS with different directions of magnetic field in the mold and the nozzle has the best effect on the distribution of the fluid flow and minimal influence on the stability of the meniscus and yields the minimum metal-jet penetration into the mold.

Keywords Continuous casting · Submerged nozzle · Electromagnetic stirring · Microstructure

1 Introduction

The demand for improvements in the quality of metallurgical products is increasing. Therefore, steel plants apply many new technological approaches for improving the quality of billets during the continuous casting (CC) process. An electromagnetic field requires no contact, promotes rapid reactions, and is easily controlled. Hence, these fields are widely used as electromagnetic stirrers [1], electromagnetic stoppers [2], or flow controllers [3] during

the CC process. To obtain the desired result, electromagnetic stirring (EMS) can be used in different parts of the CC process, without significant rebuilding of the main equipment. This process (i.e., EMS) is especially useful when implemented in the submerged nozzle (referred to as electromagnetic swirling flow in nozzle, EMSFN). Rather than placing the blade in the nozzle or changing the shape of the nozzle [4], the equipment will surround each nozzle without incurring any additional expenditure. The EMSFN process uses low power input and leads to an overall change in the flow through small changes, thereby playing an essential role in controlling the metal flow. When suitable EMSFN parameters are employed, the uniformity of the process will increase and, in turn, the physical and mechanical properties in the volume of the billets will improve.

Most studies have focused on the numerical simulation results of EMS used in only the mold or in the nozzle. For example, the CC process of a square billet with stirring in the mold was discussed and a robust numerical simulation was presented [5]. The process of round billet casting with stirring in the nozzle and the effect of different current values of the stirrer have also been investigated. In literature [7], a similar process of casting with literature [6] was

Available online at <http://link.springer.com/journal/40195>

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considered, but the influence of magnetic permeability was also evaluated, thereby highlighting the attributes of electromagnetic stirrer implementation. The imposition of additional forces on the metal flow leads to significant changes in the subsequent flow. Identifying the overall effects and, in turn, the dominant effect associated with the use of double stirring (EMSFN and M-EMS) is therefore extremely difficult. Hence, in addition to the modeling of double stirring, the impact of each process should be separately evaluated for the same given conditions.

Numerical simulations may suffer from drawbacks such as half-model calculations of a symmetric system [8–10]. In previous studies, authors presented half and quarter numerical models, where calculations accounted for the planes of symmetry along the direction of casting. Irregularities in the calculations may increase, owing to non-uniformity of the casting process due to the heterogeneity of the incoming melt [11]. For a symmetric model, the number of admissions will increase, and the convergence of the simulation with the real process will decrease.

For reliable modeling results, the computational grid must be sufficiently dense and appropriate angular grid directions are required. Otherwise, the simulation results will differ significantly from the practical result and will therefore be inadequate as a basis for improving the technology [12]. A systematic investigation of the process requires a robust grid, which will consider any possible deviations of the process [13].

The application of EMS is presented in the current study, and EMS-induced changes in the fluid flow are described. The results of the final numerical simulation will be compared with those of EMSFN and M-EMS under the same conditions. Furthermore, the intensity and direction of EMS will be varied, to determine the effect of EMS on the metal flow.

Our research team has already conducted fundamental research on this issue. The studies of Li et al. [14–16], where the main advantages and disadvantages of the process were considered, were taken as the basis of the present study. The research group, which focuses on EMS implementation, is currently composed of: Tretiak Oleksandr, Xiao-Wei Zhu, and Chun-Lei Wu.

In this work, a CC process with different flow fields was calculated using a numerical simulation method. Results of different stirring methods and their placement in the CC revealed the improvements in fluid flow control. Analysis of the samples revealed that the macro- and microstructure of the billets improved after implementation of the technology. Owing to the complexity of EMS, its effect on the fluid flow and the interaction between the two EMS systems are considered in the intermediate results.

Positive results were obtained when two EMS devices were implemented: in the nozzle and in the mold. In

addition, positive effects were observed when different stirring directions and power were employed.

2 Research Methods

2.1 Numerical Calculation

2.1.1 Calculation Model

The model and relevant sizes are shown in Fig. 1, where the conditions for each simulation in the software are indicated. In terms of boundary conditions, each wall of the mold interfaces was designated as a stationary wall characterized by no-slip shear conditions, and the roughness constant is 0.5. The meniscus surface was considered a stationary wall, which undergoes specified shear conditions when the stress is zero from all directions.

Physical characteristics of the cast steel were taken from the theoretical values, where density: 7020 kg/m³ (theoretical: 6500–7000); viscosity: 0.0062 Pa s (theoretical: 0.005–0.0085); and electrical conductivity: 140 mk Om cm (for Fe).

Scheme of solution methods: SIMPLE; gradient spatial discretization: Green–Gauss cell based; pressure: second order; momentum, turbulence kinetic energy, turbulence dissipation rate, B_x, B_y, and B_z: QUICK. Solution initialization: standard, computed from velocity inlet (top of nozzle), patched in B0_x with value of 0.0001.

Fig. 1 Calculation model (unit: mm)

The simulation ends with the steady-state casting process, when the shape of the incoming flow in the mold remains practically unchanged or changes cyclically (Fig. 2).

2.1.2 Physical Fundamentals

The Coriolis power plays an important role in this process [17, 18]. The effect of this power is manifested even in EMS-free rotation of liquid steel. The power was calculated as part of the total energy, where

$$\frac{\partial(\rho h_{\text{tot}})}{\partial t} - \frac{\partial p}{\partial t} + \nabla(\rho U h_{\text{tot}}) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot (U \cdot \tau) + U \cdot (S_{M,\text{rot}} + S_{M,\text{buoy}}) + S_E, \quad (1)$$

and momentum equations:

$$\frac{\partial(\rho U)}{\partial t} + \nabla \cdot (\rho U \times U) = \nabla p + \nabla \cdot \tau + S_{M,\text{rot}} + S_{M,\text{buoy}}, \quad (2)$$

where $h_{\text{tot}} = h_{\text{stat}} \times U^2/2 - \omega^2 r^2/2$ is full enthalpy in the presence of rotation, ω is angular velocity of the liquid, r is radius vector, λ is thermal conductivity coefficient, ρ is liquid density, p is pressure, U is velocity vector, T is temperature, τ is viscous stress tensor, $S_{M,\text{rot}} = -2\rho\omega \times U - \rho\omega \times (\omega \times r)$ takes the Coriolis force and the centrifugal force into account, $S_{M,\text{buoy}} = \rho_{\text{ref}}\beta(T - T_{\text{ref}})g$ is source of the pulse formed by the buoyancy, β is the coefficient of volume expansion, g is gravitational acceleration vector, and S_E is energy source.

These equations describe fluid flow, and one of the most important relations, i.e., the continuity equation, is given as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0. \quad (3)$$

2.2 Industrial Experimental Conditions

The numerical simulation results were verified via physical experiments conducted at an industrial plant. The experiments were implemented in accordance with the conditions of a steel company. The chemical composition of the metal considered in the experiment is shown in Table 1.

Table 1 Chemical composition of the studied steel (wt%)

C	Si	Mn	P	S	Cr	Ni
0.698	0.201	0.560	0.013	0.013	0.036	0.012

Two positions of the EMS are required for determining the influence of electromagnetic stirrers on the microstructure. This influence is investigated by considering the effect of the magnetic-field-induced rotation and the stirring intensity on the microstructure. Values and properties of the industrial experiment are shown in Table 2. Also there are such parameters as speed rate of casting is 2 m/s, M-EMS current is 200A, frequency is 50 Hz.

3 Results and Discussion

3.1 Simulation Results

Simultaneous stirring in the mold and the nozzle has rarely been studied. Therefore, the simulation results can only be compared with the intermediate results (corresponding to only one electromagnetic stirrer) from the references listed in Sect. 1.

Similarity between the numerical simulation results and the experimental results is essential for understanding the processes occurring stirring. Therefore, similar process parameters, materials, and a qualitative experimental plan must be considered. For that reason, in this work, numerical modeling of factory samples was performed under several conditions. The results of the modeling were then compared (at least qualitatively) with the experimental results.

In addition, numerical calculations provide only a theoretical result, which must then be verified via various test points. For the simulations, the EMS current was selected based on ten intermediate points, and variations in the EMS rotation were considered by including clockwise stirring in the mold. Dubious results have been excluded, and the analysis includes only those deemed reliable.

For qualitative representation of the results, simulations were performed, where electromagnetic field forces of similar magnitude were considered, thereby yielding a qualitative conclusion comparable to the numerical simulation results. Thus, conditions (e) and (f) of Table 2 are excluded, and the results of macrostructural and microstructural analysis will be explained based on the conditions of the numerical modeling results.

The results show that processes of metal flow in the submerged nozzle and the mold can be investigated with the help of known formulas. Subsequently, the influence of different factors on the quality of the billets can be determined.

Numerical modeling results obtained from using EMS systems in the nozzle and the mold can be compared with the results of previous studies [5–7], where fluid flows under EMSFN or M-EMS were described.

Table 2 Industrial experimental conditions

Sample	Direction of EMS in a submerged nozzle	M-EMS	EMSFN current (A)
(a)	–	Counterclockwise	–
(b)	Counterclockwise	–	200
(c)	Counterclockwise	–	400
(d)	Counterclockwise	Counterclockwise	400
(e)	Counterclockwise	Counterclockwise	600
(f)	Clockwise	Counterclockwise	200
(g)	Clockwise	Counterclockwise	400

3.1.1 Results of Numerical Simulation

The influence of stirring in the nozzle on the double mixing process of fluid flow in the nozzle and the mold in CC is investigated. Knowledge of the processes occurring during metal flows is essential for understanding the function of an electromagnetic stirrer. For example, stirring may be performed in only the nozzle, in only the mold or at different values of power and sense of rotation. This understanding is necessary as the distribution of fluid flows inside the mold may change with the parameters of the CC process. When mixing of the stirrer is added, the flow of the liquid changes considerably, and identifying the parameters fundamental to applying the correct method is difficult. Moreover, simulations comparing double mixing and mixing in only one position are essential for verifying the aforementioned influence.

As Fig. 3 shows, the penetration depth of the metal jet decreases significantly from the submerged nozzle to the mold. This results from the fact that, under the action of the

Fig. 2 Simulation of the magnetic field: 1—submerged nozzle, 2—electromagnetic coils, 3—core of the electromagnetic device and its contour

Fig. 3 Distribution of velocities in the mold: **a** without EMS, **b** EMSFN, **c** M-EMS

magnetic field, the flows of liquid metal in the submerged nozzle undergo rotational motion. Therefore, at the outflow of the nozzle, the fluid flows in the gravity-force direction and in the radial direction. The value of the total kinetic energy of the stream ($E_K = \frac{m \cdot v^2}{2}$) remains the same, despite the influence of the field, but the directions associated with this energy will be redistributed. Consequently, the total kinetic energy in the gravity-force direction will decrease.

The fluid flow in the mold is also affected by the inertia of centrifugal forces, with time- and energy-dependent effects retained by the electromagnetic field. The flows circulate until the viscosity forces stop the active flow of the liquid metal. Unlike electromagnetic rotation in the mold, the rotation in the nozzle yields only a modest effect. The significant influence of this rotation (main influence:

uniform and steady distribution of fluid flows from the submerged nozzle into the mold) will end at the outlet of the nozzle.

3.1.1.1 Comparison of EMS in the Nozzle and EMS in the Mold Figures 3 and 4 show the changes in metal flow after using EMS. As reported in several studies, stirring in the mold has a significant effect on metal flow with a considerable braking effect. However, active stirring of metal initiates ingress of inclusions and bubbles into the mold, leading to the formation of defects in the ingots. Electromagnetic stirring of liquid steel in the nozzle creates a directional braking effect, with a smaller influence on the stable meniscus than the braking effect associated with stirring in the mold. This effect results from changes in the vector direction of the fluid flow after additional rotational movement.

When the rotational component is added, the liquid in the mold undergoes rotational motion in the mixing region and, due to viscosity, is directly influenced by the direction of the gravitational force. The influence of this component depends on the point of EMS application, and, hence, different effects occur after the implementation of various stirrers (in the nozzle or in the mold). Electromagnetic stirring in the mold will lead to upward metal flows, resulting in considerable disturbances in the zone near the submerged nozzle, and in turn, slag penetration of the mold and submerged nozzle will lead to upward metal flows to the meniscus and more complex disturbances in the mold (compared with those induced by stirring in the mold). These disturbances will collapse and undergo time-dependent changes. As a result, disturbances are generated in a different manner and exert a smaller retracting force than that exerted in the mold. Upward flows of metal after stirring in the nozzle create hood-like fluid flows,

characterized by less active circulation than those generated during stirring in the mold. Therefore, some inclusions will remain in the upper part of the mold and then enter the slag.

The distribution of metal flows varies with the type of stirring. After using the nozzle stirrer, the inclusions can float up to the slag with good braking effect. However, compared with the nozzle stirrer, the mold stirrer has a greater effect on mixing (good for solidification and destruction of the columnar crystal layer) and the braking effect. This stirrer also has considerable influence on the meniscus zone.

3.1.1.2 Casting with Stirring Only in the Submerged Nozzle Figure 5 shows the braking effect associated with changing the current of the magnetic field in the nozzle. The effect of the centrifugal force increases with its magnitude. Furthermore, the inlet velocity near the wall of the nozzle differs from the velocity at the center. For a specific value of the current associated with the magnetic field, the velocities in the outlet zone differ considerably from those at the peripheral regions of the nozzle. This is attributed to the magnetic-field-induced rotation of the liquid. In this case, the outer layers undergo more rotation than the inner layers. In addition, the kinetic energy of the outer layers is greater and, hence, these layers move more rapidly than the inner layers, owing to their easier penetration into the mold. As a result, highly complex and correlated flows are formed with a significant level of mixing and braking effect. The stability of the meniscus decreases with increasing magnitude of the current associated with the magnetic field in the nozzle. This decrease involves small upward fluid flows characterized by time-dependent changes in direction, and owing to their instability, the flows from the meniscus into the mold are relatively shallow.

Fig. 4 Distribution of velocities in the meniscus: **a** without EMS, **b** EMSFN, **c** M-EMS

Fig. 5 Distribution of velocities with EMSFN: **a** 200 A, **b** 300 A, **c** 400 A

This effect is revealed by the maximum tangential velocity distribution (Fig. 6) characterizing the upper part of the mold, which lies between the meniscus and the outlet of the nozzle. Analysis of the calculation results shows that the curvatures vary significantly with time and are, therefore, unstable. Furthermore, the presence of constantly growing and shrinking areas or the absence of time-dependent changes in the curvature reveals the stability of flow formation with liquid-jet penetration of the retraction zone.

The results confirm that the formation of the retracting vertex changes significantly during stirring in the nozzle, yielding higher quality billets than those obtained with only stirring in the mold. Similarly, in the absence of stirring, the retracting forces result in retraction of the slag, despite the low velocity in the meniscus zone.

When the direction of the magnetic field is changed, the intensity of the stirring in the mold decreases under the resistance action of the Coriolis forces. Therefore, compared with those corresponding to the prior magnetic field, the time required for stable flow formation increases with the use of a smaller EMS current. This is attributed to the decrease in the energy component of the EMS rotational effect and increase in the influence of the Coriolis force on the flow of the liquid and jet penetration moves closer to the wall at a smaller depth of the melt, the energy of the fluid will decrease, and the fluid moves further under the action of a gravitational force. As a result, the rotation

effect of liquid steel in the mold decreases. This modest effect can be increased if some of the casting parameters are changed, leading to a decrease in the depth of the jet. Figure 7 shows the penetration depths of intense, average, and weak flows, corresponding to the highest, intermediate, and lowest fluid flow rates, respectively, in the mold. In EMSFN, the distribution of the flow in the cross-sectional area of the mold is better than that of other regions; however, destruction of the columnar structure comprising the metal can be reduced, owing to the extremely slow rotation of the metal.

The influence of Coriolis forces on the flow of liquid has been discussed in [17, 18], and an example showing the formation of a billet under the influence of these forces is presented in [19]. The effect of Coriolis forces on the flow of fluid is illustrated in Fig. 8.

If the Coriolis forces are neglected, metal will flow to areas with the lowest stress state. Therefore, a flow pattern is formed, where the fluid flows to the corners of the square mold with upward flow in these zones. Fluids flow into the meniscus zone from a higher stress state too, and the direction of the flow will depend on the energy of the neighboring upward flow. As a result, a pattern of fluctuations forms in the meniscus zone, consisting of upward flows with dominance that eventually change to neighboring upward flows.

In calculations considering the influence of the Coriolis force, the upward flows are affected twice, i.e., when they are formed by the incoming jet, which is influenced by the Coriolis forces, and float into the meniscus zone, and thereby move under the influence of this zone. Taking this double influence and areas with the least stressed states into account, we obtain a new pattern of fluid flow. The meniscus flow is directed to the center, owing to the minimum stress state.

3.1.2 Casting with Stirring in the Submerged Nozzle and the Mold

Using two EMS fields for stirring of the liquid steel has a positive effect on the stability of the flows in the upper part of the mold. In contrast to stirring only in the mold, flow stream penetration in the top part of the mold is modest, thereby increasing the stability of the meniscus (Fig. 9). The flow rate associated with double EMS is two times smaller than that associated with stirring only in the mold. Therefore, in the top part of the mold, the velocity distribution is shown as stirring only in the nozzle, and the flow field in the bottom part of the mold is shown as stirring only in the mold, albeit more stable stirring (Fig. 10).

In addition, the braking effect will change with the direction of the magnetic field (Fig. 11). For example, compared with clockwise stirring, counterclockwise stirring leads to deeper metal-jet injection into the mold. This is attributed to the Coriolis force, which leads to either

Fig. 6 Distribution of the maximum tangential velocities in the upper part of the mold **a** without stirring, and with stirring in the **b** nozzle, **c** mold

Fig. 7 Metal-jet penetration into the mold with: C—clockwise, ConC—counterclockwise

increased or decreased rotation power of the stirrer. Owing to this force, the energy of the flow will increase during stirring in the mold and, hence, the depth will increase. This increase in depth (albeit moderate) results from counterclockwise stirring in the nozzle.

The coincidence or non-coincidence of EMS rotation forces represents the third effect of double stirring. Coincidence leads to an increase in the energy and depth of injection, whereas the depth will decrease with differing rotations (i.e., non-coincidence), although the differences in coincidence and non-coincidence rotations are only moderate.

Double EMS can yield improved mixing through homogenization (resulting from distribution of the middle layers comprising the liquid in the mold) after using the nozzle stirrer, re-cleaning of the liquid metal, and a more stable meniscus than that achieved via single stirring.

The Coriolis power varies with location in the sample and is therefore an important parameter for controlling the casting process.

Therefore, implementation of double stirring in the nozzle and the mold in the CC process yields the required result. As expected, this stirring affects the distribution of fluid flow by reducing recontamination and the impact on the meniscus. The required levels of mixing intensity and uniformity are met, thereby weakening the effect of centrifugation after the fluid flow direction changes from the center to the wall following mixing in the nozzle.

Fig. 8 Distribution of the main flows in **a** the absence, **b** under the influence of Coriolis forces

Fig. 9 Distribution of velocities in meniscus obtained via double EMS: **a** clockwise EMSFN and clockwise M-EMS, **b** counterclockwise EMSFN and clockwise M-EMS, **c** counterclockwise EMSFN and counterclockwise M-EMS, **d** clockwise EMSFN and counterclockwise M-EMS

3.2 Experimental Results

3.2.1 Microstructure Analysis of Samples

The influence of each parameter was considered for 35 of the samples. The quality of the final product is determined by the structure of the materials composing the billets, which can be obtained via EMS. From the viewpoint of mechanical properties, the quality of a billet can be improved by controlling the pearlite structure. Excluding

the effect of metal forming, the dispersion of this structure has the most significant effect on the mechanical properties of the final products [20]. Figure 12 shows the microstructural analysis results of the pearlite dispersion homogeneity in samples exposed to different magnetic stirrers. The maximum and minimum deviations from the average value of the pearlite dispersion are shown in the figure. Conclusions regarding EMS-induced homogenization of the microstructure can be drawn based on the differences between these values. The melt homogenization

Fig. 10 Distribution of velocities in mold obtained via double EMS: **a** clockwise EMSFN and clockwise M-EMS, **b** counterclockwise EMSFN and clockwise M-EMS, **c** counterclockwise EMSFN and counterclockwise M-EMS, **d** clockwise EMSFN and counterclockwise M-EMS

Fig. 11 Dependence of jet penetration on the casting direction: **a** clockwise M-EMS, **b** counterclockwise M-EMS, **c** clockwise EMSFN and clockwise M-EMS, **d** counterclockwise EMSFN and clockwise M-EMS, **e** counterclockwise EMSFN and counterclockwise M-EMS, **f** clockwise EMSFN and counterclockwise M-EMS

can be described in terms of the absolute differences between the maximum and minimum fluctuations from the average values of the dispersions (Fig. 12). The values (i.e., the differences), which were taken from the points shown in Fig. 13, decrease with increasing homogenization of the melt. Implementation of two EMS systems yields better results than the use of a single system. This is especially true at large values of the EMS current and non-coincidence of EMS rotation.

Fig. 12 Deviation of pearlite dispersion in cross-sectional area from the average dispersion (for conditions shown in Table 2)

3.2.2 Chemical Composition Analysis of Samples

Using an electromagnetic field, superheating of the liquid in the middle region of a billet can be eliminated or minimized, the flow required for achieving uniform distribution throughout the volume of the melt can be realized, and inclusion contamination of the melt can be reduced, thereby improving the cleanliness [21] and, in turn, the chemical composition homogenization of the steel. Based on the X-ray diffraction measurement results, investigation of the chemical composition homogenization focused mainly on the Fe_{19}Mn phase.

Fig. 13 Placement position and nomination of samples

Figure 14 shows the Fe_{19}Mn percentage of each sample. For the convenience of comparison, slice types (a) and (g), corresponding to samples (a) and (g), respectively, were taken as Table 2. These samples were chosen as they represent the typical manufacturing process and the proposed upgraded process, respectively. The results reveal that use of a new EMS system leads to an increase in chemical composition homogenization and, hence, a decrease in compositional variations over the cross section of the billet. The homogenization of the melt will be discussed from the viewpoints of reductions in the central porosity of the billet and the distribution of defects in the plane.

From the viewpoint of chemical composition homogenization, the microstructure exerts the greatest levels of influence on the mechanical properties of the material. The steel with a thin-plate pearlite structure has high strength

Fig. 14 Elemental distribution of samples shown in Fig. 13 and Table 2

and hardness as well as good wear resistance and stability [20]. In this case, the strength index increases with increasing dispersion of the pearlite.

Sample (b) has the lowest hardness, owing to the fact that EMSFN is ineffective in achieving structural homogenization. A comparison of the samples revealed that the best homogenization and most significant influence of microstructure on the physical properties are realized for sample (g).

3.2.3 Macrostructure Analysis of Samples

The influence of microstructure on the physical properties was verified via experiments (see results in Table 3). To reduce the errors in the experimental results, the smallest and the largest values [in this case, corresponding to (c) and (f)] were excluded from Table 3.

The hardness tests were performed in accordance with GB/T230, 1-2004 [22]. Macroscopic analysis included the evaluation of central defect samples (see Fig. 15).

The samples considered in these experiments are affected mainly by central porosity, i.e., a macroscopic and classical defect occurring in billets obtained via the CC process. Samples (a)–(c) exhibit pronounced central porosity, resulting from shrinkage of the sample and inhomogeneity of the chemical composition. The inhomogeneous structures are caused by different crystallization temperatures. In samples (d)–(g), the defects (i.e., pores) in the central zone are less pronounced than those in samples (a)–(c), and the defect density decreases with increasing homogeneity of the ingots. Samples (e) and (g), shown in Fig. 14, are more homogeneous than the other samples, and as shown in Fig. 15, have better macrostructures. These images show the top and the front sides of the middle region comprising samples (a)–(g) (sample diameter and height: 10 mm and 20 mm, respectively).

The size of the central equiaxial crystal zone increases with increasing chemical homogenization. Owing to this homogenization, samples (d)–(g) obtained via metal forming are almost defect free.

Table 3 Results of hardness measurements

Number	Value of hardness (HRA)					Average
	1	2	3	4	5	
(a)	65	63	58	63	64	62.6
(b)	58	61	66	65	60.5	62.1
(d)	65	63	61	62	63	62.8
(e)	67.5	63	63	63	60	63.3
(g)	62	65	61	66	66.5	64.1

Fig. 15 Images of different samples taken from the central zone (point 5 in Fig. 13, condition Table 2)

4 Conclusions

1. Stirring in the submerged nozzle has a positive effect on controlling the CC process of steel. This effect is achieved through the addition of a centrifugal force to the resultant vector of the forces associated with fluid flow of the metal from the submerged nozzle.
2. The rotation stirrer caused by the magnetic field and the rotation caused by the Earth yield a total effect, which is strengthened at coincidence of the fields or weakened otherwise.
3. Compared with the individual stirring processes, stirring in the submerged nozzle and stirring in the mold yield greater improvement in the quality of the CC process.
4. The pearlite distribution of the samples improves and becomes increasingly compact with increasing intensity of EMS (current of EMS stirrers or using stirrers in both places). This distribution has a significant effect on the quality of the metal.

Acknowledgements Authors are grateful to the financial support from the National Natural Science Foundation of China (Nos. U1560207 and U51504057), the National Key R&D Program of China: Upgrading and Industrialization of Key Basic Material Technology (No. 2017YFB0304400).

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