RECENT CONTRIBUTIONS OF THE UNIVERSITY OF BOLOGNA CONCERNING MHD PROCESSING OF MATERIALS

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ABSTRACT

Some new activities started in the Department of Electrical Engineering of the University of Bologna, with the aim to analyze different applications of MHD Sciences and superconducting technologies. Thanks to the cooperation with Kawasaki Steel Corporation, Nippon Steel Corporation, Tokyo Institute of Technology and Nagoya University, numerical and experimental activities have been carried out during the last three years. This paper reports three different topics: the three-dimensional numerical simulation of the molten steel flow in continuous casting mold, the evaluation of the influence of electromagnetic force on the boundary layer of a molten steel pool and the separation of inclusion in a molten metal through magnetization forces. For each activity, measured and calculated results are compared and discussed.

NUMERICAL SIMULATION OF MOLTEN STEEL FLOW

The surface and internal defects in cast slabs are closely related to the fluid flow of the molten steel in the continuous casting mold. The steel flow discharged from the submerged entry nozzle (SEN) penetrates downward along the narrow face of the solidified shell, carrying non-metallic inclusions and gas bubbles. Excessive steel flow velocity at the meniscus entrains molten mold powder into the strand pool. These phenomena became significant at higher casting speeds and deteriorate the surface quality of the final product. Therefore, control of the molten steel surface velocity becomes a key technology for the high product rate.

Kawasaki Steel Corporation has developed a flow control technology for molten steel in the mold called FC Mold (Flow Control), that control the flow pattern in a slab casting mold with two level static magnetic fields. One of the magnetic fields is imposed on the molten steel flow at the meniscus in order to suppress the surface turbulent flow, to eliminate the amount of the mold powder entrainment and to improve the condition of initially solidified shell yield and growth. The other is imposed on the flow below the outlet ports of the SEN in order to decrease the impinging velocity and to achieve a uniform downward stream in the lower half of the mold. Since both the magnetic fields cover the entire width of the slab, the electromagnetic braking force is uniform along the width of the mold (see Fig. 1).

![Fig. 1. - Schematic view of the FC Mold.](image)

In order to encourage mixing, to help prevent nozzle clogging and to promote the flotation of solid inclusion bubbles from the liquid steel, Argon injection is usually employed. It enters the continuous casting mold through the SEN, and eventually escapes from the liquid steel surface through the mold flux powder layer. The injected Argon bubbles influence the flow pattern, which has corresponding effects on grade mixing and inclusion movement. The extent of this effect is intensified by the volume expansion of the gas bubbles in the high temperature of the molten steel, which could increase its ambient-temperature volume up to five times, under typical casting conditions. Therefore, even a small rate of Argon injection could have significant effects on the flow pattern.

The present section describes the three-dimensional numerical simulation of the molten steel flow in continuous casting mold (FC mold) at No. 3 caster at Chiba Works, Kawasaki Steel Corporation. The first objective is to study the influence of the imposed magnetic fields on the flow

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pattern with the injections of Argon bubbles. The second aim is to find a representative diameter of the injected bubbles which can simulate the surface velocity of molten steel flow, by using a customized version of the computational fluid dynamics code FLUENT.

**Numerical simulation**

For the calculation of the dynamic behavior of the metal pool in the presence of a static magnetic field, solution of Maxwell’s equations (coupled with Ohm’s law) for the electromagnetic field, and of the Navier-Stokes and continuity equations for the flow are required. The turbulence is taken into account by using the $k-e$ model. Since interphase flow is to be considered, a source term in the continuous phase equations must be added. Thus, the calculation of the trajectories of the dispersed phase (Argon injection) is needed. In order to predict the turbulent dispersion of bubbles of Argon the Discrete Random Walk (DRW) model was used.

Each iteration of solution procedure consists of the following steps: the momentum equations are solved in turn using the guessed pressure field; the pressure correction equation (mass balance) is then solved to obtain the necessary correction to the pressure field and corresponding adjustments to the velocity components are also made; the $k-e$ equations are solved using the updated velocity field; Maxwell equations are solved using the previously updated values of other variables; fluid properties are updated; the source terms in the continuous phase equations due to interphase coupling is updated via a dispersed phase trajectory calculation. These steps are continued until the error in each conservation equation within the global domain has decreased to a required value.

The distribution of the three-dimensional external magnetic flux density field was calculated by J-MAG program. Then, in order to simplify the computations, the magnetic field was fitted to only a y-component (the direction of mold thickness), uniform along both the thickness and the width of the mold. In Fig. 2 the distribution of the external field, is shown.

The dimensions of the considered slab are 1600 mm width, 260 mm thickness and 4000 mm length. The submerged nozzle is located at the center of the mold and its immersion depth below the meniscus is 220 mm with two ports inclined at 25 degree downward. The molten steel flows through the SEN into the mold and exits at the bottom where it is solidified. The throughput is 4.7 ton/min, which corresponds to a casting speed of 1.614 m/min. The considered steel is assumed to have a density of $7000 \text{ kg/m}^3$ ($T = 1800 \text{ K}$), a viscosity of $5.5 \times 10^{-3} \text{ kg/m.s}$ and an electrical conductivity equal to $7.14 \times 10^7 \text{ S/m}$.

The calculation were performed using a three-dimensional Cartesian mesh with a grid number of 134160 cells, that is wide face direction 86 through thickness direction 13 and casting direction 120. The Reynolds number, estimated at the nozzle exit, was of the order of $10^4$, which confirms that it is necessary to take into account the effect of turbulence. The boundary at the mold, i.e. solidified shell, is assumed to be electrically insulated, hydrodynamically non-slipped and a reflection boundary for the bubbles. The boundary at the meniscus, i.e. molten steel surface, is assumed to be insulated, slipped and escape boundary for the bubbles. To simulate the Argon bubbles trajectory, 1200 bubbles have been injected from 60 fixed positions at the nozzle exit. The Argon inlet is 13.0 NL/min with a density of 0.2705 kg/m$^3$ ($T = 1800 \text{ K}$). Argon bubbles diameters of 0.5 mm, 1 mm and 2 mm, with and without magnetic Field imposition, have been considered.

Fig. 3 shows the calculated molten steel velocity fields and the bubbles trajectories on the central slab face for bubbles diameter of 0.5 mm, with and without magnetic Field imposition. Figs. 4 and 5 show the velocity distributions along the slab central line on the molten steel surface, for the different diameter of the Argon bubbles injected, respectively in case without and with magnetic field imposition. Fig. 5 shows the measured value obtained by the immersed bar method: a rectangular body of refractory material was immersed in the molten steel in the mold and the dynamic pressure of the steel was measured with a strain gauge.

**Fig. 2.** Distribution of the external magnetic flux density used for numerical simulation.

![Argon bubbles diameter of 0.5 mm; Without B](image)
Argon bubbles diameter of 0.5 mm; With B

Fig. 3 - Comparison of velocity fields and bubbles trajectories on the central slab face for bubbles diameter of 0.5 mm, with and without magnetic Field imposition.

**Influence of Argon injected diameter.**

The simulation confirms what was already reported in the literature: decreasing bubbles diameter intensifies the changes in the flow pattern. The molten steel flow from the submerged entry nozzle impinges on the narrow face of the mold and is divided into the upward flow and downward flow. Larger bubbles of Argon float more easily and leave the mold faster, so that they have less effect on the lower loop, but possibly more effect on the surface turbulence. Smaller bubbles, on the other hand, penetrate deeper into the liquid pool, increasing their probability of entrapment into the solidified shell. The influence of the diameter values is shown in Fig. 4, where the values of the distribution of molten steel surface velocity decrease with the increasing of the diameter of the injected bubbles.

Fig. 4 - Effect of Argon gas injection on molten steel surface velocity distribution along the slab central line, without magnetic field imposition. Velocity is taken positive when directed toward the nozzle.

**Representative diameter for the simulation.**

The representative diameter of the injected bubbles, which can simulate the surface velocity of molten steel flow, was found equal to 0.5 mm. Fig. 5 shows that the molten steel surface velocity distribution, for the case with an injected diameter of 0.5 mm, is the nearest to the measured data of 3CC Continuous Casting machine. With the increase of the diameter of the injected Argon bubbles a vortex appears under the meniscus and near the narrow face. As a consequence, the molten steel surface velocity decreases and, in the case of diameter of 2 mm, changes direction (Fig. 5). In the case with 0.5 mm diameter, almost all the bubbles considered are dragged by the molten steel flow, since they reach the impingement point. Then the bubbles float towards the molten steel surface with trajectories passing near the narrow face. This deep circulation was thought to be the reason of the disappearing of the above mentioned vortex in the case with Argon diameter of 0.5 mm.

**Effect of magnetic field imposition.**

The effect on the surface velocity of the magnetic field imposition, in the suitable case of 0.5 mm, is a reduction of 22%, which is very similar to the data that was previously found. For the same case of 0.5 mm diameter injection, it was found out that the maximum vertical velocity, on the slab face at 1.5 m from the molten steel surface, decreases from 0.07 m/s to 0.04 m/s with the imposition of magnetic field.

**Drag coefficient.**

In real caster are observed bubble diameters bigger than 0.5 mm. So we think that the representative value of 0.5 mm is too small if compared with real data. This result suggests a deeper study about the value of the Drag Coefficient used.

**INFLUENCE OF ELECTRO-MAGNETIC STIRRING (EMS) ON THE BOUNDARY LAYER OF A MOLTEN STEEL POOL.**

Over the last ten years the Electromagnetic Stirring (EMS) has been studied in order to improve the steel quality. In particular EMS can remove, by means of electrodynamic forces, the non-metallic inclusions and the gas bubbles, which
are still present in the molten steel after the Refining process. Even if EMS is already a commercial technology for many steel making companies, several phenomena still have to be understood in order to predict the quality of the cast.

The objective of this section is to show how the boundary layer of the molten steel in a mold for billets is affected by EMS. The applied magnetic field leads to an increase of the molten steel velocity gradient at the wall, causing a lift force (Saffman force), which can remove the inclusions from the solidifying shell. The Saffman Force, acting in the direction transversal to the walls, pushes the inclusions toward the center of the pool, where they have higher chances to be eliminated by the action of the surface tension related phenomena.

The Saffman Force can be expressed as:

$$F_s = 1.62 \frac{d_p^3}{u_{p,\|}} \left( \frac{\rho_f}{\mu_f} \frac{\partial u_{p,\|}}{\partial x} \right)^{1/2}$$

where $d_p$ and $u_{p,\|}$ are the diameter and the tangential velocity component of the particle, and $\mu_f$, $\rho_f$ and $u_{p,\|}$ the viscosity, the density, and the tangential velocity component of the molten steel. This force depends on the tangential velocity gradient $(\partial u_{p,\|} / \partial x)$, on the tangential velocity difference between fluid and particle and on the square of the particle diameter. As shown in Fig. 6, for particles having a diameter greater than 100 µm the Saffman force overcomes the Drag Force and the inclusions are removed from the solidifying shell. It is experimentally proved that EMS doesn't have any effect on the particles having smaller dimensions.

![Fig. 6. Forces acting on near-wall particles vs. their dimensions.](image)

**Numerical Simulation**

The flow pattern of the molten steel pool in the mold for billets ($100 \times 100$ mm$^3$) has been analyzed in order to show the influence of the applied EMS. The calculation were carried out considering two different configurations:

A) Without EMS: the flux flow is mechanically driven by a wall having a velocity of 0.4 m/s (value suggested by the continuous casting operating conditions);

B) With EMS: the flux flow is driven by the electromagnetic forces that are applied near the walls.

In order to compare the two different flow patterns, in both cases the same maximum value of the steel velocity (0.14 m/s) has been realized in the middle of the fixed wall $W_1$ (see Fig. 7), so that the hydrodynamic similitude was respected. Near the corners the mean value of the velocity decreases because of the presence of secondary vortices due to the perpendicular wall. The considered steel is assumed to have a density of 7200 kg/m$^3$ and a viscosity of $5.5 \times 10^{-3}$ kg/m·s. The estimated Reynolds number is 48000.

![Fig. 7. Flow patterns in the molten steel: (a) flux flow driven by a moving wall and (b) circulating vortex induced by EMS.](image)

In the case without EMS, the set-up was given by a thin grid ($100 \times 100$ mesh), a velocity wall equal to 0.4 m/s, the turbulence models kε and RNG kε, and the two layer zonal model. For the case with EMS the same grid has been used considering all the walls fixed. An electromagnetic force distribution, with a maximum value of 750 N/mm$^3$, is applied near the walls. The velocity distributions are shown in Figs. 7(a) and 7(b), for cases A (without EMS) and B (with EMS), respectively.
The behavior of the inclusions in the molten steel, largely depends on the velocity gradient, therefore the study of this parameter is useful to predict the steel quality grade which can be achieved through EMS. In the 2D simulation, the velocity gradient near the walls \( W_1 \), \( W_2 \) and \( W_3 \) has been studied (see Fig. 7), considering thirty points, equally spaced, at a distance of 1 mm from each wall.

![Inclination of the tangential velocity component near the wall \( W_2 \).](image)

\[ \theta [^\circ] \]
\[ x_r [\text{mm}] \]

\( \theta \) [\text{]}]
\[ x_r [\text{mm}] \]

Fig. 8. Inclination of the tangential velocity component near the wall \( W_2 \).

![Inclination of the tangential velocity component near the wall \( W_3 \).](image)

\[ \theta [^\circ] \]
\[ x_r [\text{mm}] \]

\( \theta \) [\text{]}]
\[ x_r [\text{mm}] \]

Fig. 9. Inclination of the tangential velocity component near the wall \( W_3 \).

![Inclination of the tangential velocity component near the wall \( W_1 \).](image)

\[ \theta [^\circ] \]
\[ x_r [\text{mm}] \]

\( \theta \) [\text{]}]
\[ x_r [\text{mm}] \]

Fig. 10. Inclination of the tangential velocity component near the wall \( W_1 \).

The direction perpendicular to the wall has been indicated with \( \theta = 0 \), therefore when \( \theta \) is positive the velocity is directed like the main vortex (in an anticlockwise direction) (see the insert in Fig. 8). The change of the sign for \( \theta \) indicates the presence of secondary fluxes that appear near the corners because of the turbulent pattern and the geometry of the problem. The curves shown in Figures 8, 9 and 10 represent the inclination of the tangent to the near-wall velocity profiles in case with and without EMS. It can be seen that for the wall \( W_2 \) and \( W_3 \) the gradient of the velocity increases, and the area within the curves becomes larger. This result clearly appears for the wall \( W_2 \). Anyway, the turbulent effects near the corners, seem not negligible. The turbulent effects in the case of the wall \( W_1 \) appear even prevalent, since it can be noticed that the gradient increases only in the first half part of the wall \( W_1 \).

The benchmark comparison used for the 2D simulation is given by the study of the molten steel pool in case of the continuous casting of a slab (2000 \( \times \) 250 \( \text{mm}^2 \)). Since the molten steel flow circulates from the narrow faces, next to the corners, toward the center of the pool, this flow pattern can be assimilated to a 1D duct flow, having an inlet and an outlet. In this case also both situations have been considered: with and without EMS in order to analyze the influence of the electromagnetic field on the boundary layer. The applied electromagnetic force achieves a maximum value of 3000 \( \text{N/mm}^2 \) and in both cases the maximum value of the velocity is 0.4 m/s. Analyzing the flow pattern near the wall, it is observed that the laminar layer (or viscous sub-layer) increases going from the end (at the narrow face) to the center of the pool. Therefore the attention has been focused on the area, within 3 mm and distant 750 mm from the narrow face. In this region it is supposed to find the most relevant effects of the electromagnetic field. Actually, it can be noticed that, in the described region, EMS modifies the velocity distribution. In particular, the molten steel velocity changes from a pseudo-linear distribution, without EMS, to a parabolic one if EMS is applied\(^2\).

The 2D study shows that near the wall \( W_2 \) located after the moving wall, the turbulent effects disturb a regular increase of the viscous sub-layer so that it is not possible to notice any effect of EMS. Instead, near the walls \( W_2 \) and \( W_3 \), where the turbulent effects become lower, an increase of the velocity gradient is obtained also in the 2D problem. Thus, the 2D flow pattern presents several differences with respect to the 1D case, due to the boundary effects. Actually in the 1D study the turbulent effects are avoided considering an area placed far enough from the pool corner, whereas in the 2D case this is not possible because of the mold geometry. Therefore in the 2D flow pattern the turbulence effects caused by the presence of the wall corners are not negligible. Anyway when this effect is not predominant, an increase of the molten steel gradient that can generate a positive effect is noticed.

**REMOVAL OF INCLUSIONS USING MAGNETIZATION FORCE**

Material processing may benefit of magnetic field gradient through magnetization forces. The magnetization effects related to the magnetic property of the material have a wide range of developing applications in biology, chemistry and metal-
lurgy. Material processes using such effect are in large development, either offering better efficiency to known processes or introducing new ways of acting on the material. The continuous advance of SC magnet technology leads to the production of high field and steep field gradient large enough to concern materials and processes at an industrial scale. The most valuable interest is that magnetic field gradients are able to produce forces whose magnitude and direction can be controlled by the user to enhance, suppress or counteract gravity-related phenomena.

This section deals with the separation of nonmetallic inclusions, i.e., SiC, from molten Aluminium, when immersed in the 12 T magnetic flux density field produced by a SC magnet with a field gradient up to 20 T/m in the central region. The inclusions present in a stressed metal highly influence its static and dynamic behavior, being crack starting points. Therefore, to increase the homogeneity of the mechanical properties, e.g., workability, of the cast products it’s necessary to remove inclusions from the molten metal as much as possible. The analysis of particles trajectories shows that the magnetization force acting on paramagnetic inclusions has a predominant axial component which aims upwards and opposite to the force of gravity. To neglect the effects of gravitational and buoyancy forces on the inclusions, the density of medium was made equal to the density of the particles adding Copper to the Aluminium bath. Due to the particle susceptibility, the axial component of the magnetization force causes a motion of the particles in vertical upward direction. This effect was utilized to confirm the feasibility of a magnetic separator.

**Mathematical Model**

The magnetic force density, which depends on the winding geometry and on the operating current and is a non-uniform function of the position, in the central region of an axis-symmetric magnet systems, has a dominant axial component that can be expressed as:

\[
f \equiv \frac{\chi_p - \chi_r}{\mu_0} B_z \frac{dB_z}{dz}
\]

where \( B_z \) is the axial component of the flux density field, \( \mu_0 \) is the permeability of the free space, and \( \chi_p \) and \( \chi_r \) are the susceptibilities of the particle and of the surrounding medium, respectively.

Mathematical modeling of the individual particle trajectory in a one-dimensional non-uniform force field is based on the solution of the Newton motion equation using a linear quadratic approximation for the drag force. Assuming that the magnetization force exceeds several times the gravitational forces, the velocity of the particles once the dynamic equilibrium has been reached is:

\[
u = \frac{d^2}{18 \eta} \left[ f + \left( \rho_f - \rho_p \right) g \right]
\]

where \( d \) is the particle diameter, \( \eta \) and \( \rho_f \) are the dynamic viscosity and the density of the medium, respectively, \( \rho_p \) is the density of the particle and \( g \) is the magnitude of the gravitational acceleration.

**Experimental Results**

In order to verify the assumption of a uniform distribution of equal spherical particles, two geometrical parameters have been defined. Utilizing the measured values of the maximum and minimum dimensions of the inclusions, indicated as \( d_{\text{max}} \) and \( d_{\text{min}} \) respectively, the mean value of the particles diameter (d) and the factor \( C \), defined as the ratio \( d_{\text{av}}/d_{\text{min}} \), have been calculated. Fig. 11 shows a non-treated sample in 1:25 scale. The micrographic observations, made using an optical microscope lead to determine \( d = 16 \pm 5 \) \( \mu \)m and \( C \approx 0.693 \pm 0.072 \). Thus the approximation in assuming the spherical shape of the particles is about 32%. In the following, the particles are assumed to be spherical having all the same diameter \( d = 16 \mu \)m. For what concerns the assumption of a uniform distribution of the inclusions, Fig. 11 shows that the non-uniformities have a scale length of the order of the particles dimensions.

![Fig. 11. Uniform distribution of the inclusions in a non-treated sample (base length 4.2 mm)](image_url)

Ten cylindrical samples of 10 mm diameter and different lengths (40 mm, 50 mm and 65 mm) have been obtained by melting an Aluminium-Copper alloy and inserting SiC inclusions. The medium density has been equalized to the particles density in order to neglect the effect of the gravitational force on the separation. Table 1 shows the bath composition and the density and magnetic suscep-
tility of the components. Five samples of different lengths have been completely melted at 700 °C (ramp rate 10 °C/min), kept for 1 hour at this temperature and then cooled to room temperature (ramp rate 10 °C/min). The whole thermal treatment has been performed in presence of the magnetization force. The time duration of the treatment was established considering that from eq. (3) the migration length for a single particle moving in the liquid for one hour is 25.2 ± 12.6 mm. A statistical variation of 50% has been assumed on the susceptibilities in order to consider that the magnetic properties highly depend on purity.

Table 1. Composition of the samples and properties of the components.

<table>
<thead>
<tr>
<th>Material</th>
<th>Al</th>
<th>Cu</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [g]</td>
<td>529</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Density [kg/dm³]</td>
<td>2.71</td>
<td>8.82</td>
<td>3.17</td>
</tr>
<tr>
<td>Susceptibility (×10⁻⁶)</td>
<td>1.22</td>
<td>0.86</td>
<td>-1.07</td>
</tr>
<tr>
<td>Viscosity [kg/ms]</td>
<td>0.80</td>
<td>0.08</td>
<td>-</td>
</tr>
<tr>
<td>Composition [%]</td>
<td>81.52</td>
<td>7.70</td>
<td>10.78</td>
</tr>
</tbody>
</table>

The experimental apparatus consists of a SC magnet (Toshiba Co., TM-12VH10) in the bore of which the sample was placed, inside an Al₂O₃ reaction tube. The warm bore of the magnet is 100 mm. In the central region the SC magnet produces a 12 T magnetic flux density field with a field gradient up to 20 T/m. The maximum value of the BdB/dz product is 490 T/m. To prevent the oxidation of the samples, i.e., the production of Al₂O₃ inclusions, the separation process was performed in an Argon atmosphere at 0.15 MPa. The temperature control was obtained through a thermocouple acting on the heating source (an AC resistance).

At the end of the separation process a zone from which the inclusions have been removed appears at the bottom of the sample and the inclusions are confined in the upper part. The boundary line between these two zones is defined as the horizontal line over which 99% of the particles lay. To describe the effectiveness of the process, three parameters have been defined:

1. the number of inclusions per unit of surface (n);
2. the ratio (s) between the average distance of the particles below the boundary line from it and the length of the boundary line in the examined area (4.2 mm for all the samples);
3. the ratio (h) between the distance of the boundary line from the bottom of the sample and the length of the sample.

Fig. 12 shows the boundary line between the zone from which the inclusions have been removed at the end of the separation process (bottom part of the sample) and the zone where the inclusions are confined (upper part). The number of inclusions per unit of surface (n) has been evaluated for all of the samples. The micrographic observation was conducted between axial sections, similar to that of Fig. 12, in the bottom area (low n zone) and in the upper area (high n zone). In the non-treated samples n has been found to be equal to 41 ± 9 inclusions/mm². In the treated samples a number of inclusions per unit of surface equal to 5 ± 4 inclusions/mm² (bottom area) and 51 ± 4 inclusions/mm² (upper area) has been found. Fig. 13 shows the comparison between treated and non-treated samples.

Fig. 12. Boundary line between the two zones at high and low number of inclusions (base length 4.2 mm).

Fig. 13. Comparison between treated and non-treated samples.

The particles distance from the boundary line and the distance of the boundary line from the bottom of the sample have been measured in the treated samples and the parameters s and h have been evaluated. The mean value for s results to be 12 ± 3 %. Since s has been evaluated with reference to the length of the boundary line in the examined area (4.2 mm for all the samples) this result means that between the upper part and the
bottom part of the samples a narrow boundary zone of thickness 0.50 ± 0.13 mm exists.

For what concerns \( h \), its mean value is 20 ± 3 %, Thus, the distance of the boundary line from the bottom of the sample is roughly proportional to the sample length. This result is due to the conservation of the total number of inclusions. In fact, the balance equation for the number of inclusions can be written as:

\[
S L n_{\text{n.t.}} = S (L - H) n_{\text{s.z.}}
\]

(4)

where \( n_{\text{n.t.}} \) and \( n_{\text{s.z.}} \) are the densities of inclusions in the non-treated samples and in the segregated zone of the treated ones, \( H \) is the distance of the boundary line from the bottom of the sample and \( S \) and \( L \) are the area of the sample cross section and the sample length, respectively. Thus, simplifying and taking into account that the inclusions can stick together during the separation process, the following result is obtained:

\[
h = 1 - \frac{n_{\text{h.t.}}}{n_{\text{s.z.}}}
\]

(5)

Eq. (5) is satisfied by the experimental data with a mean error of 10 %. This discrepancy is probably due to the interactions between the inclusions (in contrast with the assumption of collisionless regime), with a resulting braking effect.

Finally, the dependence of the separation effect on the treatment time (30 ± 45 min), the treating temperature (700 ± 750 °C) and the magnitude of the applied flux density field (8 ± 12 T) has been investigated on eighteen samples. As shown in Fig. 14 the separation effect strongly depends on the magnitude of the applied field, especially above a 10 T value, regarding both \( s \) and \( h \), while the influence of the temperature and the exposure time is small. The reference value (\( h_0 \)) corresponds to the value of \( h \) measured in the 700 °C, 30 min case.

For what concerns the density of inclusions \( n \), its dependence on the treatment time, the treating temperature and the applied flux density field confirms that the separation effect is mainly due to the magnitude of the applied flux density field. In fact, a strong decrease on \( n \) in the bottom part of the samples (up to 73 %) has been found for an applied field of 8 T with respect to the 10 T, 700 °C, 30 min conditions, while its variations for an applied field of 12 T are negligible. The treating time and temperature effects on \( n \), for a given field magnitude, can also be neglected.

![Graph showing the dependence of parameters \( h \) and \( s \) on flux density field magnitude, time and temperature of treatment.](image)

**CONCLUSIONS**

The objective of the researches performed is the development of some MHD technologies applied in the industrial field [12, 16-18]. A considerable part of the research is devoted to obtain a better knowledge of the MHD interaction, using commercial and self-developed codes. Moreover, some new activities which started in the Department of Electrical Engineering of the University of Bologna, with the aim to analyze different electric power applications of MHD Sciences and superconducting technologies, are referenced [19-22].

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