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MULTI-PHYSICS ANALYSIS FOR ELECTROMAGNETIC PROCESSING IN CONTINUOUS CASTING OF STEEL BY FINITE VOLUME METHOD APPROACH

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ABSTRACT

Aiming at the realization of multi-physics analysis in the application of electromagnetic processing for continuous casting (CC) of steel, coupled analysis among fluid dynamics, electromagnetism, heat transfer including phase change and solid dynamics are discussed by use of finite volume (FVM) approach with some examples.

NOMENCLATURE

$\boldsymbol{A}$	Vector potential
$\boldsymbol{B}$	Magnetic flux density
$\boldsymbol{D}$	Deformation tensor
$\boldsymbol{D_R}$	Rate of deformation tensor
$\boldsymbol{f}$	Volumetric force (Lorentz force)
h	Enthalpy
I	Unit tensor
$\boldsymbol{j}$	Electric current density
K	Bulk modulus
k	Thermal conductivity
p	Pressure
Q_W	Density of spray cooling water
q_V	Volumetric heat
R_V	Momentum sink
S	Surface area
$\boldsymbol{S}$	Surface area vector
t	Time
T	Temperature
T_S,T_F	Deformation tensor
T_W	Water temperature
u	Displacement
z	Distance from meniscus
V	Volume
V_C	Casting speed
$\boldsymbol{v}$	Flow velocity
α	Thermal expansion coefficient
ϕ	Scalar potential
μ	Molecular or effective viscosity of fluid
μ_m	Magnetic permeability
ρ	Density
σ	Electrical conductivity
η,λ	Lame's constants

INTRODUCTION

Applications of electromagnetic processing technology to the steel continuous casting (CC) process have been widely spread for the cast quality improvement and the increase in productivity (Toh, Takeuchi and Matsumiya, 2006). Electromagnetic fields are generally categorized to direct current (DC) field and alternating current (AC) field. DC plasma heating in a ladle and a tundish is used as a clean heating technology in steelmaking. Electromagnetic braking in a CC mold is also the example of the DC field application.

Channel induction heating in the iron reserve tank and in a tundish is the application example of heating function of AC field. In-mold electromagnetic stirring is the example of traveling field application generated by linear motors. Levitation casting is the application of shaping effect by use of pinching force generated by stationary AC magnetic field. As seen in these applications, the functions such as heating, stirring, braking and shaping are widely used in the steelmaking processes and many metallurgical benefits have been obtained. On the numerical analyses in the electromagnetic processing for CC, which have been greatly supporting the development of technology, many researches have been achieved (Takatani, 2005). However, the complex phenomena in steel CC technology itself (Thomas, 1995) and in additional electromagnetic processing of materials (EPM) procedure still demand the further development in this field. So-called multi-physics analysis is suitable for this field, as the EPM in CC contains fluid dynamics, electromagnetism, heat transfer, phase change, multiphase, chemical reaction and etc.

In this paper, electromagnetic analysis and deformation analysis by use of finite volume method (FVM) approach are discussed with some example analyses, aiming at the realization of multi-physics analysis in this field.

MODEL DESCRIPTION

Finite volume formulation for heat and mass transfer and electromagnetism are described as follows (Toh, Maruki, Tanaka, Yamamoto and Takeda, 2005).
Equation of continuity and momentum conservation for fluid flow are described as follows (Teskeredzic, Demerzic and Muzaferija, 2002):

$$\frac{\partial}{\partial t}\iiint_V \rho dV + \iint_S \rho \mathbf{v} \cdot d\mathbf{S} = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\iiint_V \rho \mathbf{v} dV + \iint_S \rho \mathbf{v}\mathbf{v} \cdot d\mathbf{S} = \iint_S \mathbf{T}_F \cdot d\mathbf{S} + \iiint_V \mathbf{f} dV - \iiint_V \mathbf{R}\mathbf{v} dV \tag{2}$$

$$\mathbf{T}_F = 2\mu \mathbf{D}_R - \frac{2}{3}\mu \mathrm{div}\mathbf{v}\mathbf{I} - p\mathbf{I} \tag{3}$$

$$\mathbf{D}_R = \frac{1}{2}[\mathrm{grad}\mathbf{v} + (\mathrm{grad}\mathbf{v})^T] \tag{4}$$

Equation of energy conservation is described as follows:

$$\frac{\partial}{\partial t}\iiint_V \rho h dV + \iint_S \rho h \mathbf{v} \cdot d\mathbf{S} = \iint_S k \operatorname{grad} T \, d\mathbf{S} + \iiint_V \mathbf{T} \operatorname{grad} \mathbf{v} dV + \iiint_V q_V dV \tag{5}$$

Force equilibrium equation is shown as follows:

$$\frac{\partial^2}{\partial t^2}\iiint_V \rho \mathbf{u} dV = \iint_S \mathbf{T}_S \cdot d\mathbf{S} + \iiint_V \mathbf{f} dV \tag{6}$$

$$\mathbf{T}_S = 2\eta\mathbf{D} + \lambda \operatorname{div}\mathbf{u}\mathbf{I} - 3K\alpha\Delta T\mathbf{I} \tag{7}$$

$$\mathbf{D} = \frac{1}{2}[\operatorname{grad}\mathbf{u} + (\operatorname{grad}\mathbf{u})^T] \tag{8}$$

Electromagnetic field equations by **A**-ϕ formulation with Coulomb gauge is described as follows:

$$0 = \iint_S \sigma \operatorname{grad} \varphi d\mathbf{S} - \iiint_V \sigma(\mathbf{B} \cdot (\nabla \times \mathbf{v}) - \mathbf{v} \cdot (\nabla \times \mathbf{B}))dV \tag{9}$$

$$\frac{\partial}{\partial t}\iiint_V \mu_m \sigma \mathbf{A} dV = \iint_S \operatorname{grad} \mathbf{A} \cdot d\mathbf{S} + \iiint_V \mu_m \sigma(-\operatorname{grad} \varphi + \mathbf{v} \times \mathbf{B})dV \tag{10}$$

The numerical model is based on the commercial CFD-code FLUENT with additional user defined functions for the calculation of electromagnetic fields and deformations of solid region. Standard k-ε model is chosen as a turbulence model.

ANALYSIS OF ELECTROMAGNETIC BRAKE

Phenomena and Metallurgical Effects

The in-mold electromagnetic braking technique started as a localized MHD application to slow down directly the molten steel stream discharged from the submerged entry nozzle. (Lehman, Tallback, Kollberg and Hackl, 1994) At that time, however, the technique had several problems concerning the stability of braking effect and resultant metallurgical benefits. The new technique of stably controlling the molten steel flow in the mold was developed by applying a level DC magnetic field across the mold width to discover a new function of suppressing mixing in addition to the conventional functions ensuring the slab quality (Ishii, Konno, Okazaki, Uehara, Takeuchi, Harada, Kikuchi and Watanabe, 1996).

Figure 1 shows the schematic view of steel CC mold and a level magnetic field brake (LMF) for the flow control of discharged flow from the submerged entry nozzle, which has two ports. The casting speed of conventional steel CC reaches to more than 2 m/min, so that the flow velocity from the nozzle ports reaches to the level of 1 m/s. The static magnetic field interacts with discharged flow and generates induced current. Then the induced current interacts with static magnetic field, and finally electromagnetic force is generated to slow down the discharged flow.

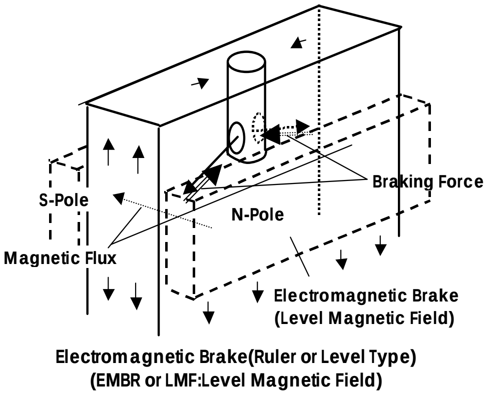

Figure 1: Schematic view of level magnetic field brake

Density		7800 (273K), 7600 (1273K), 7400 (1767K), 7200-0.9T (>1793K) (Linear interpolation by T) kg/m^3
Specific heat		469 (273K), 485 (373K), 519 (473K), 552 (573K), 594 (673K), 661 (773K), 745 (873K), 845 (973K), 1431(1023K), 954(1073K), 644(1173K), 644(1373K), 66 (1473K), 686(1573K), 686(1767K), 750 (>1793K) (Linear interpolation by T) J/kgK
Thermal conductivity		51.8(273K),51.0(373K),48.6(473K), 44.4 (573K), 42.6 (673K), 39.3 (773K), 35.6 (873K), 31.8 (973K), 28.5(1023K), 25.9(1073K), 26.4(1173K), 27.2(1373K), 28.5 (1473K), 29.7(1573K), 29.7(1767K), 41.0(>1793K) (Linear interpolation by T) W/mK
Liquidus temperature		1793 K
Solidus temperature		1767 K
Latent heat		251000 J/kg
Cast size		1200mmW, 250mmT
Nozzle	Inner diameter	100 mm
	Outer diameter	160 mm
	Immersion depth	350 mm
	Port angle	30 degree
Casting speed		2.0 m/min
Heat extraction	Mold	8x10^5(Vc/z)$^{0.35}$ W/m^2
	Strand	5885xQ$_W^{0.451}$ (1-7.5x10^{-3}T$_W$)(T-T$_W$) W/m^2 Tw= 300 K Qw= 150l/min/m^2 (0.8m<z<1.1m) 120 l/min/m^2 (1.1m<z<2.5m) 60 l/min/m^2 (2.5m<z<3.5m) 30 l/min/m^2 (3.5m<z<5m)

Table 1: Calculation Conditions

The metallurgical effects of LMF are to minimize the penetration of oxide inclusions into the cast and to stabilize the steel flow in the mold so as to prevent the entrainment of liquid flux (lubricant) into the cast. Another application of this technology is to minimize the transition region at the ladle change by imposing the level magnetic field during the sequential casting. This leads to the increase in productivity of continuous casting machine.

The direct effect of braking is that the strong discharged flow from the submerged entry nozzle is suppressed, which increases the uniformity of solidifying shell and the stability of solidification.

Numerical Evaluation of the Phenomena

In the application of electromagnetic brake in CC, it is nowadays well known that the existence of solidifying shell, which is electrically conductive wall with finite thickness, is important to evaluate the actual braking efficiency. In the numerical simulation, therefore, the existence of shell should be taken into account so that the solidification phenomena is tried to solve simultaneously with fluid flow analysis and MHD analysis. Moreover, the heat transfer in the mold is affected by the mold shell gap and its thermal state, which is largely affected by the electromagnetic field application. As a first step in this paper, the coupled analysis between ordinary MHD model and thermo-elastic deformation model with FVM is employed. Table.1 shows the calculation conditions. The result of deformation is counted for the gap change between the mold and the solidifying shell, which changes the total heat transfer coefficient between cooling water and solidifying shell.

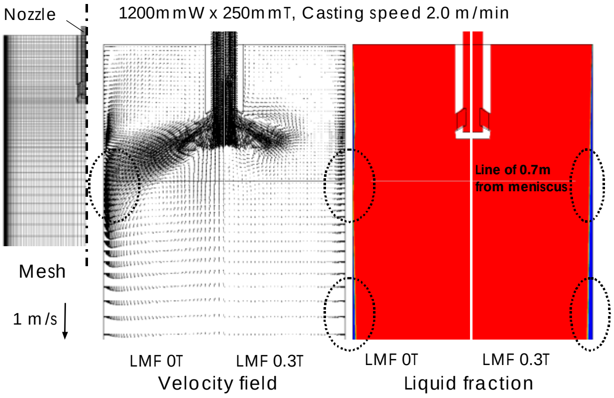

Figure 2: Change in velocity field and solidification state without and with level magnetic field braking (LMF).

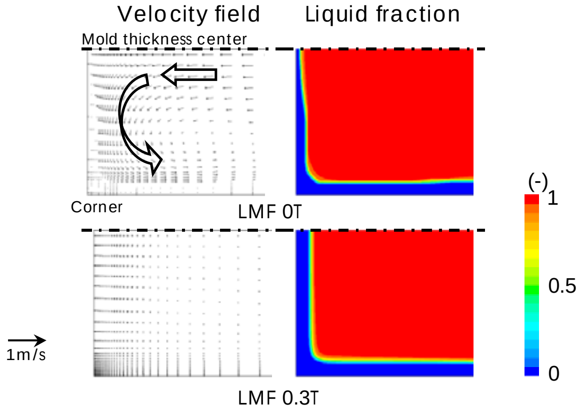

Figure 3: Change in solidification state near cast corner with LMF.

Figure 2 shows the fluid flow and solidification front shape without and with level magnetic field braking (LMF) (0.3T) applied in the CC (1.2m in width 0.25m in thickness and casting speed 2 m/min case).

Figure 3 and 4 shows the change in solidifying shell shape near the corner of the cast and in the deformation of the shell without and with LMF. The decrease in jet velocity from submerged entry nozzle with barking largely affects the solidification state near the narrow face of cast, which is preferable for uniform and stable solidification in the mold.

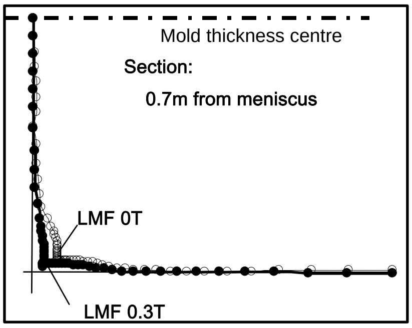

Figure 4: Change in deformation of solidified shell with LMF.

Analysis of DC Plasma Applied to Surface Treatment of Cast Steel

Phenomena and Metallurgical Effects

DC thermal plasma is widely used for the heating and welding in metals processing because of high thermal efficiency and stability compared to other plasmas such as inductive plasma. In steel industry, many applications other than welding are utilized such as tundish plasma heating in steelmaking process. On the other hand, DC plasma shape-controlled by AC magnetic field is one way to get a wide area thermal treatment of materials, which opens the application of DC plasmas to processing other than welding. One of the authors recently tried to develop surface refining and alloying of CC casts in order to develop a process of surface treatment without yield loss and of novel material production

Figure 5 shows the schematic illustration of experimental apparatus and the sequential procedure. This apparatus is composed of induction coil for preheating, DC plasma torch with W-2wt%ThO_2 cathode, steel sample as anode, two turns AC coil for plasma oscillation, argon atmosphere chamber and video camera for the observation. The experiments are sequentially carried out. In order to simulate a hot steel slab just after the continuous casting process, induction preheating has been employed before plasma treatment. Firstly, a steel sample (0.2m x 0.125m x 0.025m) is preheated up above about 1300K by an induction coil. A loop type induction coil is applied to the surface rather than a solenoid type coil. Subsequently a sample moves at the constant rate and it is treated with DC plasma arc. The DC plasma arc is driven by AC magnetic field imposed perpendicular to the plasma axis and the direction of a sample motion. That is to say, the direction of a sample motion is perpendicular to the direction of arc oscillation. The plasma arc behaviour is observed by using two video cameras. The evaluated parameters in the experiments are the nozzle diameter, argon gas flow rate, plasma arc current, magnetic flux density and sample speed of treatment. After experiments, the relations between these parameters and the width and the depth of the melted zone at the surface of the steel sample are investigated in detail. Experimental conditions are described in Table 2.

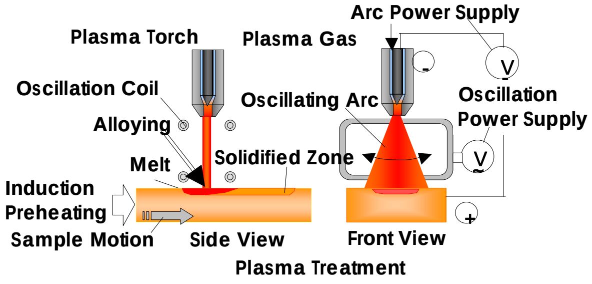

Figure 5: Experimental apparatus for the surface treatment of the casts by use of plasma arc.

Figure 6 shows the typical snapshot of the DC plasma arc under sinusoidal AC magnetic field. Stable fan-shaped arc is obtained as a time-averaged image of plasma arc oscillated by a magnetic field.

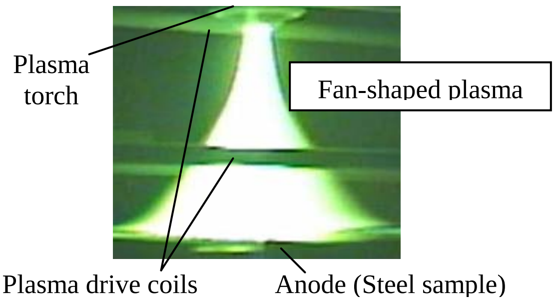

Figure 6: Fan-shaped DC plasma with AC magnetic field.

Figure 7 shows the surface of treated sample. The left-hand side shows the plasma treated cast sample just after the treatment. The right-hand side shows the sample after descaling. Steel sample was moved perpendicular to the direction of DC plasma driven by AC magnetic field so as to enable to fuse widely. The surface of the melted specimen was very smooth. The length of the melted zone was about 150mm. The melted zone depth was about 4mm.

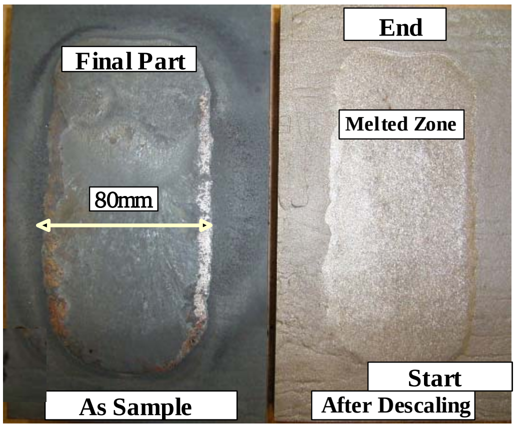

Figure 7: Surface appearance of plasma treated cast.

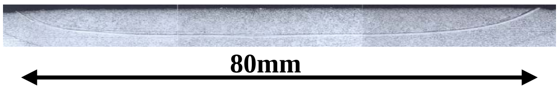

Figure 8: Cross section of plasma treated cast.

Numerical Evaluation of the Phenomena

A-ϕ method is used for the calculation of DC plasma arc motion under AC magnetic field and the time-averaged heat transfer from the arc to the steel sample is calculated. Then the temperature field in the steel sample is calculated by taking into account with melting and solidification. Fluid flow in the melt is also calculated by introducing the effects of drag force caused by the gas motion and buoyancy force. Here, the effects of electromagnetic force and Marangoni force are neglected. Figure 9 shows the composition of numerical simulations for the model.

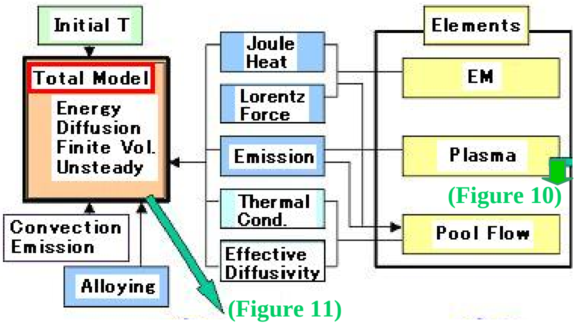

Figure 9: Composition of numerical simulations.

Table 2 describes the conditions of experiments and numerical simulation.

Cathode	Diameter	6 mm
	Tip angle	60 degree
	Nozzle diameter	8 mm
	Argon flow rate	15 l/min
	Plasma DC current	300A
Anode	Material	Steel
	Density	7200-0.9T kg/m^3
	Specific heat	750 J/kgK
	Thermal conductivity	41 W/mK
	Liquidus temperature	1793 K
	Solidus temperature	1767 K
	Latent heat	251000 J/kg
	Treatment speed	0.75 mm/s
Treatment atmosphere		10^5 Pa Argon
Plasma arc length		100 mm
Plasma drive magnetic flux density and frequency		3 mT, 50 Hz
Heat transfer coefficient		20 W/m^{2}K
Emissivity		0.5

Table 2: Conditions of experiment and calculation

Figure 10 shows the example result of plasma arc behaviour simulation. The contour line shows the temperature distribution. Figure 11 shows the temperature field and liquid fraction distribution of the steel sample during plasma treatment. The shape of the liquid zone is affected by the fluid flow in the pool.

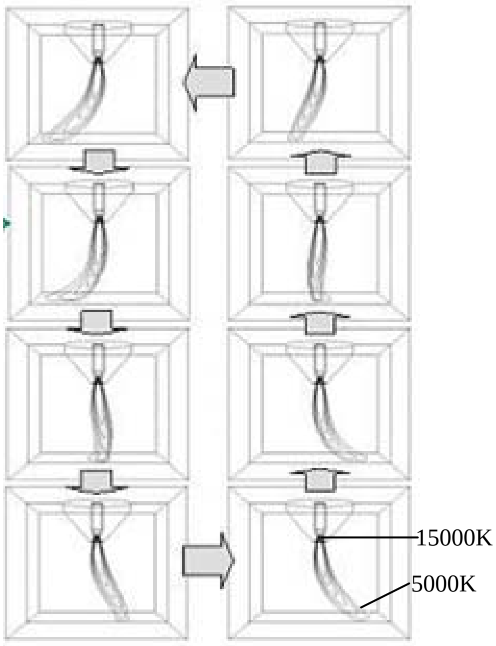

Figure 10: Plasma arc behaviour (one cycle motion).

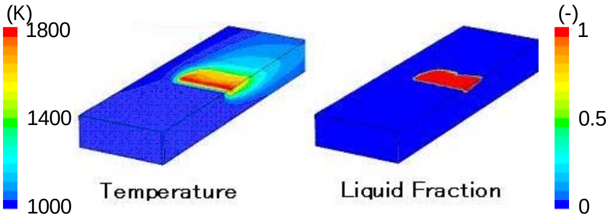

Figure 11: Temperature and liquid fraction distribution during plasma treatment.

Figure 12 shows the comparison between calculated and experimental results of the width of plasma treated zone. Quantitative correspondence was obtained.

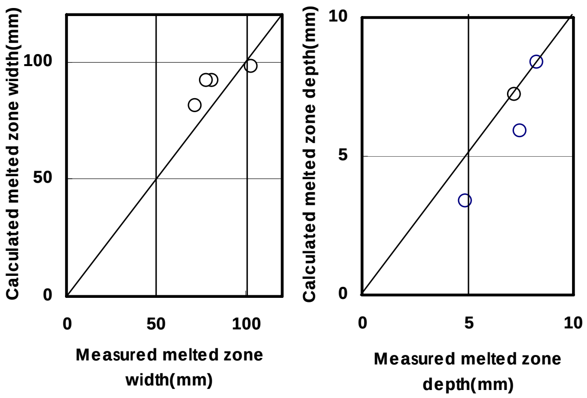

Figure 12: Comparison between calculated and experimental results of the plasma treated zone.

CONCLUSIONS

Multi-physics phenomena in the EPM applications to the continuous casting of steel were analysed by use of full FVM approach. As the example cases of the coupled analysis, electromagnetic braking technology applied to CC and surface treatment technology of the cast slabs with DC arc plasma oscillated by AC magnetic field were demonstrated.

Coupled analysis including phase change model showed that the electromagnetic braking slows down the discharged flow from the submerged entry nozzle, which contributes to decrease remelting phenomena of solidifying shell and to make a more uniform solidified shell.

Modelling of plasma arc could simulate the reciprocal motion of the arc and enabled to obtain the heat transfer to the treated sample. The total heat transfer model including melting and solidification was established and showed good correspondence between experimental and numerical results.

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