1. Introduction

Electromagnetic processing of materials (EPM) plays a key part in new materials developments and processing. Electromagnetic fields can exert great influences on the transports of heat and momentum in processed melt or solidifying material systems through Lorentz force and Joule heat without the contact between the processed materials and the EM field generator. Therefore this kind of technique can serve as a clean materials preparation method with high quality.  

Electromagnetic casting (EMC) is an inter-disciplinary technique, involving foundry engineering, solidification processing, EM fluid dynamics and so on, which is usually under a joint control of multi-fields, including the fields of electromagnetic, temperature, concentration, pressure and flow velocity, etc.  

A lot of theoretical and experimental efforts have been made in this research area, for example, an Electromagnetic-constrained (mold-less) directional solidification technique of dual-frequency for highly reactive alloy parts with irregular cross-sections was proposed. Nonlinearly allocated induction coils were designed for EM-constrained DC technique for Al alloy ingots. Techniques of EM-meniscus-shape control and EM-inclusion separation control of inverse segregation, the application of M-EMS and EMBR, etc. in EPM have also been extensively investigated.  

However, as foregoing mentioned, the transport phenomena of heat energy, species mass and momentum usually coexist in an EM solidification process. These transport phenomena are strongly coupled and under direct influences of an applied EM-field, which in turn control the EMC solidification process. The aim of this work is to present a joint numerical simulation technique for the solidification transport phenomena (STP) in shaped alloy castings which are under various EM directional solidification conditions. In the present cooperative computer modeling of multi-fields, the STP in the EMC processes are simulated using the authors' newly modified finite difference method (FDM)-based program, while the EM-fields are calculated using ANSYS 6.1 software which is based on a finite element method (FEM). Special research efforts of this paper will focus on the numerical coupling techniques to convert the ANSYS FEM-analyzed EM-field data to those available for the authors' FDM-based STP computer simulation in shaped alloy castings.

2. EM-solidification Mathematical Model

The continuum model proposed in Refs. 11), 12) and extended in Refs. 13), 14) is applied to the present modeling for the STP in shaped castings under EM-fields. The continuum model is further extended to account for the effects of Joule heat and Lorentz force on the solidification transport behaviors caused by the applied EM-fields. The corresponding modifications include:

Numerical techniques for FEM/FDM joint simulation of solidification heat, mass and momentum transport phenomena in directional solidification processes of shaped alloy castings under electromagnetic (EM) fields are developed. In the present joint computer modeling for the EM-fields coupled solidification transport processes, the relevant EM-fields are calculated using a FEM-scheme-based computer code, while the changing fields of temperature, solid-fraction, concentrations, pressure and flow velocity of liquid phase are simulated by the FDM-based numerical methods extended from a previous numerical solidification model of the authors. Specific data-processing techniques are proposed for the conversion of FEM-based EM-fields results to those in the FDM format. The sample computations for EM-fields influenced solidification transport processes of directionally solidified γ(TiAl)-Al% castings are performed to demonstrate the feasibility and effectiveness of the proposed solidification model and numerical methods.
Solidification heat energy transfer

\[
\partial \left\{ \left( \rho c_p \rho T \right) \frac{\partial T}{\partial t} + \mathbf{V} \cdot \left( \rho \mathbf{f}_s \mathbf{c}_T \mathbf{V} \right) \right\} = \nabla \cdot \left( \kappa \mathbf{V} \right) + \rho h \left( \partial \mathbf{f}_s / \partial t \right) + Q_s, \tag{1}
\]

where, the electromagnetically induced Joule heat

\[
Q_t = \mathbf{J} \cdot \mathbf{E} = J^2 / \sigma, \tag{2}
\]

where \( \mathbf{J} \) is the induced current density vector, \( \sigma \) is the conductivity coefficient of casting materials.

For the present modeling, the body force term, \( \mathbf{f}_s \), during solidification can be further expressed as \(15, 16)\):

\[
\mathbf{f}_s = \nabla f_m \\mathbf{V} + \left( f_m \rho \mathbf{V} \right) / \rho, \tag{3}
\]

For the present modeling, the body force term, \( \mathbf{F}_m \), induced by external fields includes the gravity and Lorentz force:

\[
\mathbf{F}_m = \rho \mathbf{g} + \mathbf{F}_L, \tag{4}
\]

where the Lorentz force acting on the moving liquid phase during solidification can be further expressed as \(15, 16)\):

\[
\mathbf{F}_L = \sigma \mathbf{f}_t \left( \mathbf{E} + \mathbf{V} \times \mathbf{B} \right) \times \mathbf{B} = \mathbf{f}_t \left\{ \mathbf{J} \times \mathbf{B} + \sigma \left[ \left( \mathbf{V} \times \mathbf{B} \right) \mathbf{B} - \mathbf{B} \times \mathbf{V} \right] \right\}, \tag{5}
\]

where \( \mathbf{B} \) stands for magnetic flux density vector, \( \mathbf{V} \) is velocity vector, \( f_t \) is liquid volume fraction.

The other STP model equations for the solidification species-mass transfer and total mass continuity etc are same as those presented in Refs. 13), 14). In the present EM-STP modeling, a further assumption is made that the variations in the free-surface shape of the alloy melt region is small and negligible. Under such condition and assumed constant EM-properties for the solidification system's materials, the coupling between any an applied EM-field and STP can be simplified as a one-way influence of former on the solidification behaviors, therefore the applied EM-fields can be separately analyzed prior to the STP-computations.

3. Numerical Calculation Methods

In the present work, the applied magnetic flux density \( \mathbf{B} \) and inducted current density \( \mathbf{J} \) are analyzed by ANSYS 6.1* in a 2-D FEM scheme. Figure 1(a) shows a schematic FEM-meshed casting domain, in which the meshed elements can be either irregular triangle or quadrilateral. The FEM solution results for the EM-fields are node-located or element-located, i.e. the solved EM-fields are in the form of discretized results either at the nodes of each FEM element or on the whole FEM element. On the other hand, the fields of temperature, concentration, solid volume-fraction, pressure and velocity vectors of liquid flow in the solidifying casting domain are calculated in FDM schemes as described in Refs. 11), 12), 16). Figure 1(b) shows a FDM-meshed pattern for the same casting domain as illustrated in Fig. 1(a). In a FDM scheme the representative field values are taken at an inner point, usually center-located, in each FDM element. These regularly arranged FDM representative points may randomly distribute in a FEM element, and some of them may locate on the boundaries, and even possibly at the nodes of the FEM elements.

Figure 1(c) illustrates the spatial relationships between the FDM points and the FEM elements through superposing Fig. 1(b) over Fig. 1(a). It can be seen that in order to convert the FEM-based EM-field results to a set of FDM-formatted data, some steps of further mathematical processing on the ANSYS FEM-analyzed EM-results are required. These mathematical treatments include judging the spatial relationship of each FDM point corresponding to the available FEM element, and determining the relevant EM-results at this FDM point based on FEM-interpolation technique.17)

The procedures for determining the spatial relationship of each FDM representative-point in the corresponding FEM mesh are as follows. The maximum boundaries (dot lines in Fig. 2(a) of each FEM element are first set. For each FDM point, such as point \( P_1 \), or point \( P_2 \), if it falls into the maximum boundaries, a further judgment whether this

![Fig. 1](image1.png)

![Fig. 2](image2.png)
FDM point is inside the corresponding FEM element will continue. This further judgment step is illustrated in Figs. 2(b) and 2(c).

As shown in Fig. 2, an area-sum method is proposed to verify whether a FDM point P locates inside the chosen FEM element ADCB. Any a point P corresponding to the quadrilateral ADCB can construct 4 triangles that only take one side of the quadrilateral by connecting the point P to each node of the FEM element, respectively. In Fig. 2, these triangles are AADP, ΔCBP, ΔDCP and AABP, and therefore the following condition can be written to determine the geometrical relationship of the FDM representative-point P with the FEM element ADCB:

\[
\text{IF } [S(=S_{\text{AADP}} + S_{\text{DCBP}} + S_{\text{CABP}} + S_{\text{AABP}}) = S_{\text{ADCB}}] \text{, THEN the FDM-point P is inside FEM-element ADCB;}
\]

\[
\text{ELSE, the point P is outside the FEM-element ............}(6)
\]

In the practical computer calculation, an error control for Eq. (6) has to be set. In the present modeling, the error control condition of \( |S(=S_{\text{ADCB}})/S_{\text{ADCB}}(\varepsilon = 3 \times 10^{-3}) | \) was used instead of the mathematically strict definition: \( S = S_{\text{ADCB}} \).

The above judgment procedure is applicable, in principle, to the case for a 3-node (triangular) FEM-element. Repeating these judgment steps for each FDM representative-point involved, the whole geometrical relationship between the given FDM and FEM mesh patterns for the same casting domain then can be determined. The final step for the EM-data conversion is to calculate the corresponding values of EM-fields at each FDM-node location based on a FEM interpolation technique. In the present FEM \( \rightarrow \) FDM data processing, the interpolating calculations accommodate for both 3-node and 4-node iso-parametric FEM-elements.

Directional solidification of a 2-D blade-like casting of binary alloy under an EM-field is adopted for the present modeling calculation. There are basically two types of EM-fields commonly used in EPM processes: static magnetic fields and harmonic alternating EM-fields. The present EM-STP FEM/FDM joint modeling accommodates both the types of EM-fields. For the case of a static magnetic field applied, it is reasonable to assume that the magnetic field distribution does not change during the whole directional solidification period.

However, in the case of applying a harmonic EM-field, due to the relative movement between the casting/mold/bottom cooler and the EM-induction coils, the induced EM-field in the solidifying casting may vary significantly. For such alternating EM-directional solidification case, a series of EM-fields in casting/mold/cooler at different movement distances relative to the induction coils, e.g. at \( h = 0, 10, 20, 30, ..., 110, 120 \) mm (i.e. \( \Delta h = 10 \) mm), are calculated by the ANSYS FEM-EM analyzer. In the subsequent simulation for the EM-STP behaviors in the directional solidification processes of the casting by the authors’ FDM-based simulator, these pre-determined EM-fields are then used to calculate the EM-fields at any distances moving down from the induction coils, using an interpolation technique. Apparently, by this interpolation method, the calculation errors for determining the varying harmonic EM-field in the solidifying casting at any directional solidification stage can be controlled to be below any error level, if the distance intervals, \( \Delta h_i (i = 1, 2, 3, ...), \) between the pre-calculated EM-fields are small enough.

### Table 1. The EM-properties used for the ANSYS FEM-EM analysis for the EM-directional solidification system.15)

| Parts | Materials | Relative magnetic permeability [-] | Resistivity [KΩ] | Dierectic permittivity [-] |
|-------|-----------|-----------------------------------|----------------|--------------------------|
| Casting | Ti alloy | 1.00005 | 1.71×10^{8} | - |
| Cooler and Coils | Copper | 1.0 | 1.67×10^{8} | - |
| Mold | CuO | 1.0 | 1.0×10^{8} | 6.5 |
| Air area | Air | 1.0000004 | - | 1.00059 |

### Table 2. The physical properties used for the present computer modeling of solidification transport phenomena of γ(TiAl)–Al%at. pseudo-binary alloy.15)

| Physical parameters | Values |
|---------------------|--------|
| Thermal conductivity | \( \lambda_d(T) = \lambda_i(T) = 2.3 \times 10^2 \) [W/mm·°C] |
| Solid specific heat | \[ 0.67832 - 6.4328 \times 10^{-3} T + 2.5417 \times 10^{-5} T^2, \] (25°C < T ≤ 600°C) |
| | \[ 0.68286 + 1.3644 \times 10^{-4} T, \] (600°C < T ≤ 882°C) |
| | \[ 0.65193 + 1.0513 \times 10^{-2} T, \] (882°C < T ≤ 1,490°C) |
| Liquid specific heat | \( c_{s}(T) = 0.86074, \) (1490°C < T ≤ 2727°C) |
| Solid density of the alloy | \( \rho_s(T_d) = 3.8 \times 10^3 \) [g/mm^3] |
| Liquid density of the alloy | \( \rho_l(T_d) = 3.63 \times 10^3 - 2.0 \times 10^{-2} (T - T_d)^3, \) 9.32 × 10^6 (C_ol - C_o) |
| Latent heat of fusion | \( l(C_o) = 453.4 \) [J/g] |
| Liquidus of the y(TiAl)-Al%at. alloys: | \( t_{ALy} = \frac{0.92 \times 10^{-0} + 23.01 \times 10^{-0} C_ol - 0.20279 C_ol^2 + (C_ol)[54.86, 74.61 at.%Al]}{[°C]} |
| Partition coefficient: | \( k(C_{ol}) = 69.24438 - 0.03153 C_{ol} + 8.894 \times 10^{-3} C_{ol}^2 - 1.71 \times 10^{-3} C_{ol}^3 - 3.1859 \times 10^{-4} C_{ol}^4 \) [\( C_{ol}[54.86, 74.61 at.%Al] \)] |
| Liquid diffusion coefficient: | \( D_{OLd}(T°C) = 5 \times 10^7 \) [\( \text{mm}^2/\text{s} \)] |
| Solid diffusion coefficient: | \( D_{OLd}(T°C) = 0.1 \times 10^{-3} \times (T°C + 273.15) \) [\( \text{mm}^2/\text{s} \)] |
| Dynamic viscosity coefficient: | \( \mu(T) = 3.5 \times 10^6 \) [\( \text{Pa s} \)] |
| Permeability coefficient: | \( K = \begin{cases} 1.6318 \times 10^{-10} \ (H/m) & (50 \text{psi}) \\ 0.7088 \times 10^{-10} \ (kPa) & (0.099999) \end{cases} \) [\( \text{mm}^2 \)] |
| Primary dendrite spacing: | \( d_1 = 1.4 \times 10^{-11} \) [\( \text{mm} \)] |
| Secondary dendrite arm spacing: | \( d_2 = 3.0 \times 10^{-11} \) [\( \text{mm} \)] |
4. Computation Examples and Result Discussion

To demonstrate the feasibility of the FEM/FDM joint modeling method presently proposed for the computer simulation of EM-STP behaviors in an EM-directional solidification of alloy shaped casting, the same directional solidification configuration for a blade-like alloy casting as that described in Refs. 18, 14 but under a harmonic EM-field is adopted. The blade-like casting is assumed to be of a $\gamma$(TiAl)-55at%Al pseudo-binary alloy for the present modeling sample, and is 112 mm high with a neck of 28 mm wide between its bottom and top blocks of 56(w)$\times$38(h) mm and 56(w)$\times$32(h) mm, respectively. The shell mold is assumed to be made of CaO and has an equal thickness of 10 mm.

The downward withdrawal velocity for the casting/mold/bottom-cooler assembly is set at a constant of 0.15 mm/s for the entire directional solidification process. The alloy melt is assumed to be static in the shell mold of a uniform initial temperature of 1 550°C, and has a uniform temperature distribution at 1 500°C at the moment of the directional cooling/solidification to start. The temperature distributions in the heating and cooling chambers, and in the bottom cooler are assumed to be uniform at constants of 1 600°C, 45°C and 45°C, respectively. In the ANSYS FEM-analysis for the harmonic EM-fields, the used EM-properties for each part in the EM-directional solidification system are assumed all to be constant, and listed in Table 1. Table 2 gives a list for the temperature/composition/liquid-fraction-dependent properties for the $\gamma$(TiAl)-Al%at pseudo-binary alloy, which are used for the FDM-based simulation of the STP in the EM-directional solidification process.

Due to the symmetry of the harmonic EM-directional solidification system, only a half of the system needs to be simulated for the EM-fields and the EM-STP as well. In the EM-STP numerical computations various boundary conditions are involved, which are set as the follows for the present modeling:

1. For the thermal transfer, the same boundary conditions are adopted as those described in Ref. 14;
(2) For the solidification species mass transfer, zero species mass flux is set for each boundary of the solidifying casting due to the assumption that no solute volatilization or reaction with the mold/cooler materials occurs during the solidification;

(3) For the momentum transfer of liquid flow,
   i) the boundaries of the center-symmetric side and the top free-surface are fully slippery tangentially (zero-viscous) but rigid;
   ii) the boundaries with the mold or cooler are fully viscous and rigid.

(4) For the EM-field computation in a half infinite-equivalent domain, as shown by Fig. 3(a), the magnetic flux is set to be parallel to the symmetrical axis along the symmetrical boundary, and the vector magnetic-potential decays to zero at a sufficiently far position from the induction-coils (i.e. at the infinite-equivalent boundary as shown in Fig. 3(a)).

An ANSYS 6.1 FEM-calculated sample for the harmonic EM-field of 20kHz and with coil-loads of 10k Ampereturns (At) for an EM-directional solidification case, in which the shaped casting has moved down for 40 mm away from the EM-induction coils, is shown in Fig. 3. Figure 3(a) shows the whole FEM-mesh pattern for the ANSYS EM analysis, in which 40 infinite elements around the outer periphery of the computational domain are used for the far EM-field boundary. Figure 3(b) shows an amplified local FEM-mesh pattern around the central region for the EM-directional solidification system of the shaped casting (a right half part). In this FEM-meshing, the region near the casting surface was more finely meshed in order to account for more reasonably the skin effects of the inducted EM-field in the solidifying casting. Figure 3(c) gives the distribution of magnetic potential contours in the EM-casting system at the current EM-directional solidification stage. All the graphics in Fig. 3 are directly output from the ANSYS 6.1 software. It can be seen from Fig. 3(c) that at this directional solidification stage the highest magnetic potentials are around the corners of the upper block of the casting.

The magnetic flux density and Joule heat inducted in the casting corresponding to the FEM results of Fig. 3 are converted into FDM-format data that are available for the authors’ FDM-based STP simulator, using the presently proposed mathematical processing methods. The comparisons between the FDM-converted EM-data and the original ANSYS FEM-calculated results are shown in Fig. 4.
Fig. 5. Calculated directional STP of a γ(TiAl)-55at%Al shaped casting (CaO mold) under a harmonic EM-field (20 kHz, 10 kA/m) at 10.03 s: (a) FDM-converted/interpolated magnetic flux density vectors from the ANSYS 6.1 FEM-results; (b) y-component of the magnetic flux density; (c) z-component of the magnetic flux density; (d) Lorentz force vectors; (e) y-component of the Lorentz force; (f) z-component of the Lorentz force; (g) velocity vectors of the alloy melt; (h) relative pressure contours of liquid phase; (i) contours of inducted Joule heat; (j) temperature contours; (k) contours of solid volume fraction; (l) liquid concentration contours for solute Al (at%).
Figures 4(a) and 4(c) present the meshing patterns for the ANSYS FEM-analysis and for the authors’ FDM-based STP-simulation, respectively, in which the grid size is \(1(w) \times 1.5(h)\text{mm}^2\) for the FDM-mesh. First, it can be seen that the relatively large magnetic flux density vectors again occur in the corners of the upper casting block and in the up-right corner of the lower block, see Fig. 4(b) and Fig. 4(d), where the induced Joule heats are also sharply high accordingly, see Fig. 4(e). Through the comparisons between the FDM-converted and ANSYS FEM-analyzed results, it can also be seen that the EM-field distributions and the changing tendencies in both the magnetic flux density vectors and Joule heats are pretty identical. Therefore, the presently proposed methods for FEM→FDM EM-data conversion are feasible, and the converted EM-field results, as shown in Figs. 4(d) and 4(e)-left, can be reliably used for the subsequent FDM-based numerical simulation for the EM-coupled STP in alloy castings solidification.

A full set of FEM/FDM-coupled simulation results for the EM-directional solidification transport phenomena in \(\gamma(\text{TiAl})–55\text{at}\%\text{Al}\) shaped casting under a harmonic EM-field at cooling/solidification time of 10.03 s is shown in Fig. 5. The harmonic EM-field for this EM-directional solidification system is the same as that shown in Figs. 3 and 4 (i.e., at a frequency of 20kHz and with coil loads of 10kA). For the present EM-STEP modeling problem, totally seven independent fields are involved, including the fields of magnetic flux density and inducted current vectors, liquid flow velocity vector, relative pressure, solid volume fraction, temperature and liquid concentration. In the calculated results group of Fig. 5, the Joule heat field (Fig. 5(i)) and Lorentz force fields (Figs. 5(d)-5(f)) are derived from the inducted current field and interactions among the fields of inducted current, magnetic flux density and liquid flow velocity, respectively, see Eqs. (2) and (5). Except the EM-converted magnetic flux density fields (but interpolated for the initial EM-directional solidification stage at 10.03 s.), i.e. Figs. 5(a)-5(c), the simulation results for all the other fields shown in Fig. 5 are calculated by a PC-based computer program that are originally developed and recently extended by the authors.\(^{11-14,16}\)

From Fig. 5 it can be seen that under the present EM-induction condition by a coil load of 20kHz and 10kA, (in the same EM-solidification configuration as that depicted in Fig. 3, but here the casting only moving down for 1.506 mm), skin effects for both the magnetic flux density and inducted current exist, Figs. 5(a)-5(c) and 5(i), which in turn induce a relatively stronger Lorentz forces in the outer region in the upper block of the directionally solidifying casting. Furthermore, driven by a Lorentz force of such kind, a few fast melt circulations occur there, Fig. 5(g), the maximum velocity of which is 22.4 mm/s. Because the liquid flow is not very strong, though somewhat complex, at this EM-solidification stage, the contours of liquid pressure appear to be roughly near to a static type, Fig. 5(h). However, from Fig. 5(j) and Fig. 5(l) it can be seen that, even though under such not very strong alloy melt circulations, both the isotherm and iso-concentration contours show to be near to types of convection-driven transfers, especially in the upper-block region of the solidifying casting.

5. Conclusions

A FEM/FDM joint computer simulation for the solidification heat, species mass and momentum transport phenomena in directionally solidified alloy shaped castings under harmonic alternating EM-fields has been successfully performed. The sample computation results for the solidification transport behaviors in a \(\gamma(\text{TiAl})\) shaped casting under the EM-fields show that the adopted EM-solidification continuum model, the numerical solution methods as well as the presently proposed FEM/FDM data conversion/processing techniques are feasible and effective. It is also worth to point out that the proposed model and the relevant solution/data-processing methods are readily to be extended to a 3-D case of EM-solidification transport phenomena for shaped alloy castings.

Acknowledgements

The authors wish to thank the supports for the present work from a Key China National Natural Science Foundation (NNSF) of grant No. 50395102 and a National Key Project (973) of grant No. G2000067202-2. The authors also acknowledge Mr. Feng Gao’s efforts during his graduation thesis work in the authors’ research group.

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