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電磁・静電・ガスジェット浮遊中の浮遊液滴内の熱流動に関する数値解析的研究

Numerical simulation of thermofluidic in droplet levitated by electro-magnetic, aero-dynamic, and electro-static methods

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1 Introduction

Metal additive manufacturing (AM) is expected to be applied in the field of automobiles, aircrafts, and medicine. Especially the Ti6Al4V, which is the most frequently used material in metal AM, is applied in the prosthetic tooth or artificial bones. As shown in **Fig. 1(a)**, these products are manufactured through layer and stack processes. The strength of the AM-manufactured objects is dependent on the crystal structures, as shown in **Fig. 1(b)**. When the pure Ti6Al4V is used, the crystal grains are grown in layer-wise direction, because the solidification occurs at the melting front (phase boundary). This crystal structure has anisotropic properties of the strength, which is usually not preferred in general purpose materials. This problem can be resolved by adding the little amount of the TiC into Ti6Al4V. In this way the TiC acts as nucleation sites for the solidification, which leads the isotropic crystal grains [1]. However, the detailed mechanism of this effect is not completely clarified. For instance, how much amount of TiC should be added cannot be preliminary predicted. In order to clarify the detailed solidification processes for TiC-added Ti6Al4V, the containerless levitation experiments are needed. As the levitation methods, electro-magnetic levitation (EML), electro-static levitation (ESL), and aero-dynamic levitation (ADL) are widely used. Because the internal flow may affect on

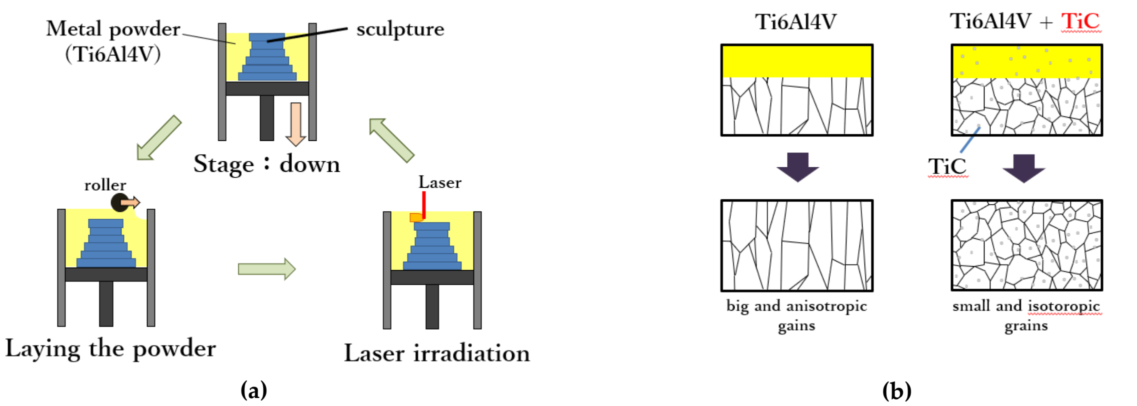


Figure 1. Main parts of metal additive manufacturing process (a), and crystal structures of the generated objects(b).

the solidification process, it is required to be suppressed. Since the magnitude of the internal flow depends on the type of levitation method and/or the material properties, there are variations in the droplet size which can be levitated, or realizable temperature. This study aims to mathematically formulate the physical phenomena for three levitation methods and numerically analyze the thermofluidics in the molten Ti6Al4V during levitation. In these levitation methods, the convection in the droplet is driven by multiple phenomena such as Lorentz force, buoyancy due to Joule heat/laser heating, and Marangoni effect. Therefore, it is difficult to predict the magnitude of thermofluidic in advance. In addition, the size of the droplets which can be levitated is dependent on the levitation methods and detailed configurations. Therefore, the magnitude of the convection should be evaluated by the nondimensional number, such as Reynolds number. In the followings, the mathematical formulation is described, then the representative numerical results are shown. The magnitude of the convection is evaluated by the Reynolds number.

2 Mathematical formulation

All through our model, droplets are assumed as sphere and thermocapillary and buoyancy flows are taken into account. The governing equations for all models are conservation laws of mass, momentum, and energy, written as

$$\nabla \cdot \boldsymbol{u} = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{u}) = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} + g\beta(T - T_0)\boldsymbol{e}_z + \boldsymbol{f}, \tag{2}$$

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \nabla \cdot (\boldsymbol{u}T) = \lambda \nabla^2 T + \boldsymbol{q}, \tag{3}$$

where $\boldsymbol{u}, p, T$ are velocity, pressure, and temperature, respectively. The physical properties $\rho, \nu, \beta, c_p, \lambda$ are density, dynamic viscosity, thermal expansion coefficient, specific heat, and thermal conductivity, respectively. The symbol $\boldsymbol{e}_z$ stands for a unit vector directed to z coordinate, and g is the gravity acceleration. The external force $\boldsymbol{f}$ and the local heat generation $\boldsymbol{q}$ are different depending on the detailed levitation method, which will be described in the followings.

2.1 Electro magnetic levitation (EML)

In the EML method, a high-frequency current flows through a coil. This current creates a magnetic field, which generates eddy currents in the direction is such that the magnetic field created by the eddy currents opposes the original magnetic field. This relation can be described by Faraday's law:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \tag{4}$$

$$\boldsymbol{J} = \sigma \boldsymbol{E}, \tag{5}$$

where $\boldsymbol{B}$ is magnetic field, $\boldsymbol{J}$ is eddy current, σ is electric conductivity. Lorentz force is generated by the outer product of eddy current and magnetic fields. Eddy currents also generate Joule heat.

$$\boldsymbol{f} = \boldsymbol{J} \times \boldsymbol{B}, \tag{6}$$

$$\dot{\boldsymbol{q}} = \frac{|\boldsymbol{J}|}{\sigma_e}, \tag{7}$$

where $\boldsymbol{f}$ is Lorentz force, $\boldsymbol{q}$ is heat flux. The AC magnetic field is expressed by following equation:

$$\boldsymbol{B}(\boldsymbol{x}, t) = \boldsymbol{B}(\boldsymbol{x}) \exp(i\omega t), \tag{8}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = i\omega \boldsymbol{B}, \tag{9}$$

where i is electric current, ω is angular velocity, t is time. By assuming a quasi-static field, the following equation can be obtained.

$$J = \nabla \times \left(\frac{1}{\mu}\boldsymbol{B}\right) - \frac{\partial \boldsymbol{D}}{\partial t} = \nabla \times \left(\frac{1}{\mu}\boldsymbol{B}\right), \tag{10}$$

where μ is magnetic constant. The following equation is obtained by introducing the electromagnetic potential.

$$\boldsymbol{E} = -\nabla\phi - \frac{\partial \boldsymbol{A}}{\partial t}. \tag{11}$$

From equations (8) to (11), the governing equations for the electromagnetic field can be obtained as follows.

$$\nabla^2 \boldsymbol{A} = -\mathrm{i}\omega\mu_0\sigma_\mathrm{e}.\boldsymbol{A} \tag{12}$$

From these equations, eddy currents and magnetic fields can be expressed by the following equations:

$$\boldsymbol{J} = -\mathrm{i}\omega\sigma_\mathrm{e}\boldsymbol{A}, \tag{13}$$

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}. \tag{14}$$

When the droplet is a true sphere, the analytical solution for the electromagnetic potential A is obtained as follows [2].

$$A_\varphi(r,\theta) = \frac{\mu_0 I_s \sin(\theta_s)}{2\sqrt{iprR}} \sum_{n=1}^{\infty} C_n I_{n+\frac{1}{2}}\left(r\sqrt{ip}\right) P_n^1(\cos\theta), \tag{15}$$

where C_n and p in equation (15) are expressed by the following equations:

$$C_n = \frac{2n+1}{n(n+1)} \left(\frac{R}{R_s}\right)^n \frac{P_n^1(\cos\theta_s)}{I_{n-\frac{1}{2}}\left(R\sqrt{ip}\right)}, \tag{16}$$

$$p = \sigma_e \mu_0 \omega. \tag{17}$$

When $P_n^m(x)$ is associated Legendre function、$I_{n+\frac{1}{2}}(x)$ is modified Bessel function. I_s is the amplitude of the current, and R_s, θ_s are the positions of the coils.

2.2 Electrostatic levitation (ESL)

In the ESL method, the droplet is levitated by Coulomb force. This force is distributed only on the droplet surface. So, this force has little effect on the inside of the droplet. Therefore, in this study only the Marangoni convection due to laser heating was considered for thermofluidic in the droplet. The heat flux of laser heating is expressed by the following equation.

$$\boldsymbol{q_L}(\boldsymbol{x}) = I_0 \eta W(\boldsymbol{x}), \tag{18}$$

where $\boldsymbol{q_L}$ is heat flux, I_0 is laser power, η is absorption rate. $W(x)$ is expressed by the following equation.

$$W(\boldsymbol{x}) = \frac{1}{2\pi R^2} \exp\left(-\frac{r^2}{2R^2}\right), \tag{19}$$

where R is droplet radius, r is the position of heating by laser.

2.3 Aerodynamic levitation (ADL)

The ADL is a method of levitating droplets by blowing gas on them. The blowing gas causes shear stress on the droplet surface. This force and the Marangoni convection caused by laser heating drive a flow inside the droplet. In this study, the airflow and the single-phase flow inside the droplet are numerically calculated in two stages, and the flow inside the droplet is evaluated. The calculation method is as follows.

1. Airflow calculation: only the airflow domain is calculated assuming the droplet as a solid. In this way the shear stress along the droplet is evaluated.

2. Convection inside droplet: the precedent evaluated shear stress distribution is applied on the droplet interface as a boundary condition. Then the convection inside the droplet is calculated.

3. Configuration of levitation facilities

3.1 EML

The detailed parameters for the EML model are determined according to the experimental facility of Chiba Institute of Technology [3], whose configuration of coils is shown in **Fig. 2**. The induced electric current is selected as 200 A, and the size of the droplet is $D = 6.0$ mm.

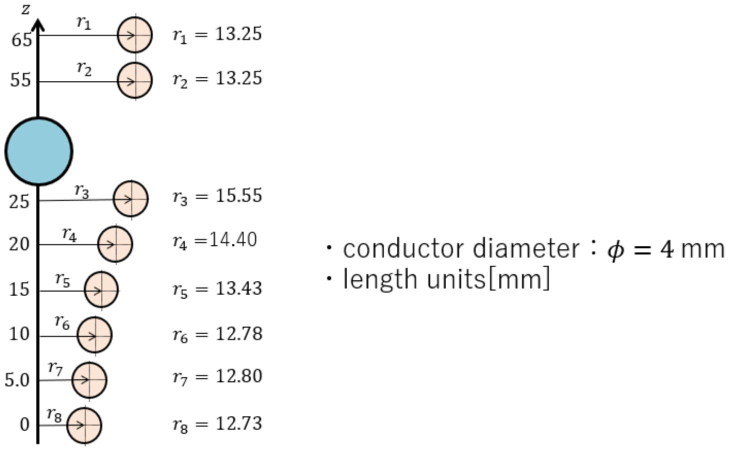


Figure 2. Configuration of coil of EML used in the present calculation.

3.2 ESL

For the calculation of ESL model, the configuration of the laser heat sources is determined according to the Electrostatic Levitation Furnace (ELF), which is installed on the International Space Station (ISS) [4]. Three separated laser heat sources are considered, with power $I_0 = 75$ W and spot diameter 0.4 mm. The heat flux caused by the single laser can be evaluated as

$$\boldsymbol{Q_0} = \frac{I_0}{2\pi D^2} = \frac{75}{2\pi \times 75^2} \approx 2.5 \times \frac{10^7\ \mathrm{W}}{\mathrm{m}^2}. \tag{20}$$

The size of droplet is selected as $D = 2.0$ mm.

3.3 ADL

For the calculation of the ADL model, the detailed configuration of the nozzle and gas flow rate are determined according to the experimental facility of JAXA-ISAS, whose schematics is shown in **Fig. 3**. The

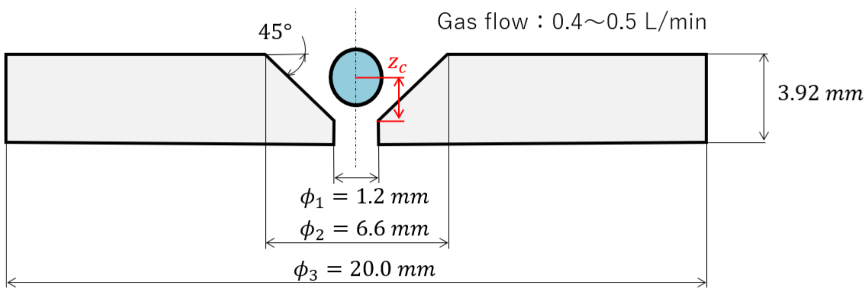
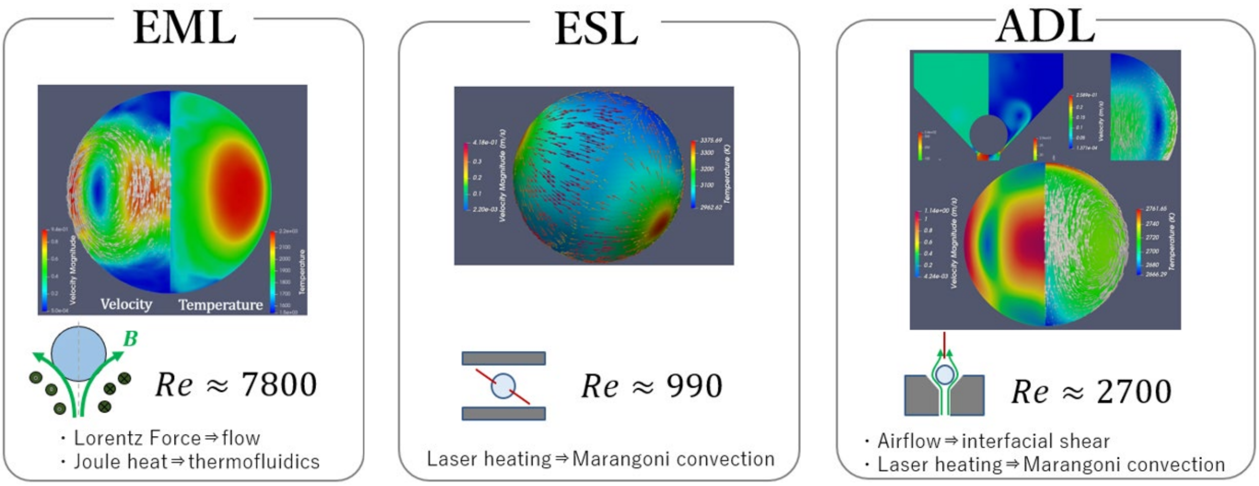


Figure 3. Schematics of the configuration of ADL facility.



(a) (b) (c)

Figure 4. Velocity (left) and temperature (right) fields in the droplets calculated for three levitation methods: (a)：EML、(b)：ESL、(c)：ADL

flow rate 0.4 ~ 0.5 L/min of gas is flowed from the nozzle of the diameter $\phi_1 = 1.2$ mm. The center of the levitated droplet z_c is determined as $z_c = 0.94$mm so that the weight of the droplet is balanced with the lift force calculated by the flow around the droplet. The size of the droplet is selected as $D = 2.0$ mm.

4. Representative results

The velocity and temperature fields calculated for three levitation methods are summarized in **Fig.4.** The maximum velocities are $U_{\max} \approx 1.09\ \mathrm{m/s}$ for the EML, $U_{\max} \approx 0.41\ \mathrm{m/s}$ for the ESL, and $U_{\max} \approx 1.13\ \mathrm{m/s}$ for the ADL. Using these velocities and droplet sizes, the magnitude of the convection is evaluated by the Reynolds number, which is defined as:

$$Re = \frac{UD}{\nu}, \tag{21}$$

where D is the droplet diameter, ν is dynamic viscosity, U is the maximum velocity described above. The same value of $\nu = 8.4 \times 10^{-7}\ \mathrm{m^2/s}$ is assigned to all cases assuming the materials of Ti6Al4V. The evaluated Reynolds numbers are $Re \approx 7800, 990, 2700$ for EML, ESL, and ADL, respectively. At least the configuration considered in the present study, the Reynolds number for the EML is the highest, whereas for the ESL is the lowest. It can be concluded that for the investigation of the solidification process of Ti6Al4V, the ESL (ISS-ELS) is most preferable. This study has been carried out as a part of the Hetero-3D project.

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