S7-2

高エンタルピープラズマ流による材料プロセッシングの数値解析的研究
Numerical study for material processing using high-enthalpy plasma flows

茂田　正哉
Masaya SHIGETA

大阪大学接合科学研究所
Joining and Welding Research Institute, Osaka University

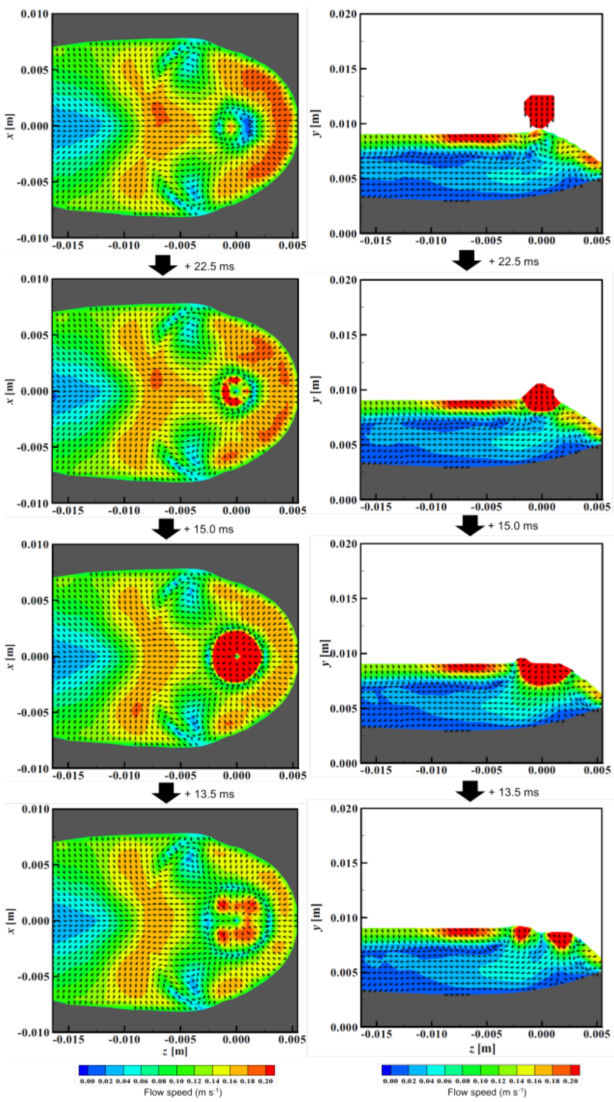
1. Introduction

High-enthalpy plasma offers a unique flow with high temperatures of not only electrons but also heavy species, high chemical reactivity, intensive light emission, and variable fluid-mechanical properties. Because it is also electrically conductive fluid, it responds to an electromagnetic field. Therefore, its plasma state can be sustained by Joule heating and controlled by Lorentz force [1-4]. Taking advantages of those features, high-enthalpy plasma has been applied to material processing, e.g. arc welding with high-speed metal melting [5] and nanopowder fabrication with remarkably high rates [6-8]. This paper discusses examples of numerical studies on these applications presenting the demonstrative simulations.

2. Molten metal flows in arc welding

Arc welding is a fundamentally important technology of craftsmanship in various manufacturing fields such as transportation equipment including automobiles, railroad vehicles, ships, and aircraft, and for civil engineering, construction, and plant facilities.

Figure 1 depicts the three-dimensional simulation result of a molten metal flow behavior of a weld pool and reinforcement in gas metal arc welding obtained using SPH (smoothed particle hydrodynamics) method [5,9]. SUS304 was assumed as the base metal. The rate of change of surface tension to temperature was set as 1.0×10^{-4} N/m-K. The melting point was set as 1,750 K. Arc plasma obtained at a welding current and voltage of 300 A and 31.5 V, respectively, and a distance between electrode – base metal of 5.0 mm was assumed as a heat source. The numerical data of approximate temperature and velocity distribution obtained by numerical simulation with a stationary state assumed in an earlier study [10] was used as boundary values at the base material surface. Numerical data of the current density distribution was given to the inside of the base metal. The welding speed was set to 300 mm/min. A complicated flow is observed on the surface and inside of the weld pool because of the Lorentz force, the Marangoni effect, and the metal droplet transfer.



(a) on surface　　(b) at central cross-section

Fig. 1 Ensemble averaged flow field of weld pool.

3. Nanopowpder fabrication using plasma flows

High-enthalpy plasma is anticipated as a promising device for nanopowder fabrication with remarkably high rates [6]. The process involving collective growth by nucleation, condensation, and

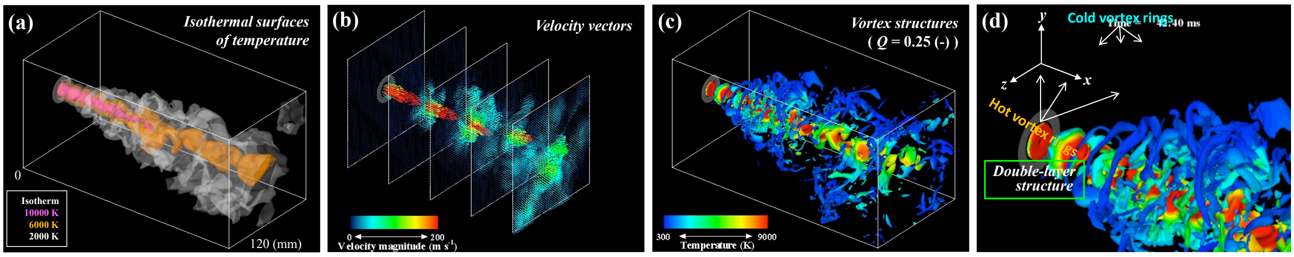


Fig. 2 Instantaneous thermal flow fields in and around a thermal plasma jet obtained by the advanced method.

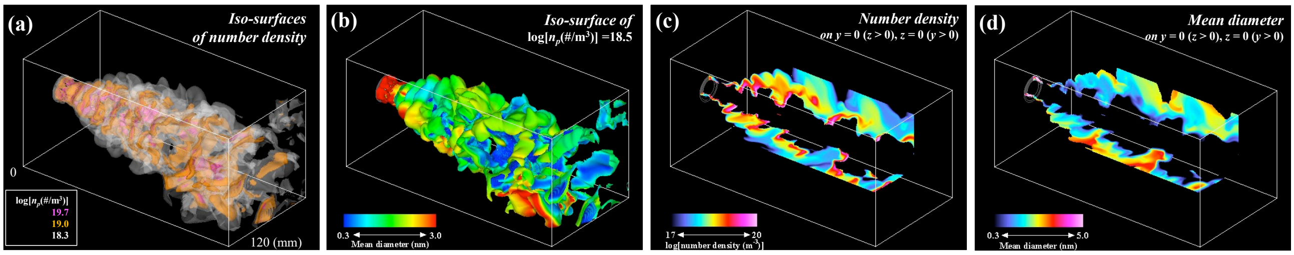


Fig. 3 Instantaneous distributions of nanopowder obtained by the advanced method.

coagulation and transport by convection, diffusion, and thermophoresis in/around a plasma is a complicated mass transfer problem in the microsecond to millisecond time scales.

Demonstrative simulation is performed to highlight the importance of capturing steep gradients of nanopowder concentration and plasma temperature and 3D dynamic motions of turbulent multi-scale vortices in/around a thermal plasma jet. Therein, a non-transferred argon thermal plasma jet is ejected from a circular nozzle with the diameter of 8.0 mm. At the nozzle exit, the plasma jet has steady profiles of temperature with the maximum 12000 K and velocity with the maximum 400 m/s. Silicon vapour is supplied at 0.1 g/min with the plasma jet. The thermodynamic and transport properties of argon thermal plasma and the material properties of silicon are obtained from Refs. [11] and [12], respectively. To obtain the numerical solution, the demonstrative simulation adopts an advanced method (named as Method-III in Ref. [13]) which is expected not only to express turbulent features but also to perform numerically stable computation even with a large increment of time steps.

Figures 2 and 3 show the snapshots of the instantaneous thermal flow fields and silicon nanopowder distributions, respectively. It is noted that the region only near the jet nozzle is presented here. It is apparent that a complex flow field with widely spreading multi-scale vortices is simulated. Many vortices, which are visualized by Q-criterion, are generated even far from the plasma jet cores. This vortex structure is similar to the Schlieren photograph by Pfender et al. [14]. Large vortices have higher temperatures whereas small vortices have lower temperatures as predicted on the basis of Kolmogorov theory [13,15]. Nanopowder collectively grows up and diffuses outside the plasma region. The larger size regions coincide with smaller number density regions. This result indicates that simultaneous coagulation decreasing particle number plays an important role for nanopowder growth as well.

References

[1] T. Sato et al., *Int. J. Thermal Sci.* **40**, 273 (2001).
[2] M. Shigeta et al., *Int. J. Heat Mass Transfer* **47**, 707 (2004).
[3] M. Shigeta & H. Nishiyama, *Trans. ASME, Journal of Heat Transfer* **127**, 1222 (2005).
[4] M. Shigeta, *J. Flow Control, Meas. & Visual.* **6**, 107 (2018).
[5] M. Shigeta & M. Tanaka, *Jpn. J. Appl. Phys.* **59**, SA0805 (2019).
[6] M. Shigeta & A.B. Murphy, *J. Phys. D: Appl. Phys.* **44**, 174025, (2011).
[7] M. Shigeta, *IEEJ Trans. Electri. Electro. Eng.* **14**, 16 (2019).
[8] M. Shigeta, *Plasma Chem. Plasma Process.* **40**, 775 (2020).
[9] H. Komen et al., *Int. J. Heat Mass Transfer* **121**, 978 (2018).
[10] Y. Tsujimura, *Ph. D. Thesis Osaka University*, (2013). (in Japanese)
[11] M.I. Boulos et al., Thermal Plasmas Fundamentals and Applications **1**, Plenum Press, New York (1994).
[12] Japan Institute of Metals, Metal Data Book, Maruzen, Tokyo (1993). (in Japanese)
[13] M. Shigeta, *J. Phys. D: Appl. Phys.* **49**, 493001 (2016).
[14] E. Pfender *et al.*, *Plasma Chem. Plasma Process.* **11**, 529 (1991).
[15] M. Shigeta, Plasma Sources Sci. Tech. **21**, 055029 (2012).