Numerical modeling on thermal interaction between thermal plasma and solid powder for materials processing

DISSERTATION ABSTRACT

NUMERICAL MODELING ON THERMAL INTERACTION BETWEEN THERMAL PLASMA AND SOLID POWDER FOR MATERIAL PROCESSING

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Abstract

Thermal interaction between feed rate powder and thermal plasma was calculated using the developed numerical model for inductively coupled thermal plasma (ICTP) with particle injection. The interaction between feed powder and thermal plasmas is greatly important to consider the stable establishment of the ICTP and effective heating and evaporation of injected particles, for example, for particle synthesis. Injected particles are heated by thermal plasma, and they are melted and evaporated to contaminate the thermal plasma, which influences the thermal plasma properties. The ICTP model was used in this research because it has benefit of good repeatability and no contamination process. Interactions between ICTP and injected powder are very complicated to be understood only by related experiments. The developed numerical model solves mass, momentum and energy conservation equations of thermal plasmas as well as mass transport equation for evaporated materials. In addition, particle motions were derived by solving the lagrange equation of motion. The temperature distribution inside the particles and phase transition from solid, liquid to gas of the particles were also taken into account.

Furthermore, numerical simulation in inductively coupled thermal plasma was made on the temperature distribution in argon (Ar)+ hydrogen (H_2) induction thermal plasma torch with silicon (Si) powder injection to obtain the temperature distribution and gas flow fields. The ICTP model was used in this research because it has benefit of good repeatability and no contamination process. The temperature distributions of thermal plasma and Si vapor distribution were compared at input powers of 20 kW, 30 kW, and 40 kW. Results indicated that higher input power increases the temperature of the thermal plasma with doughnut shape but it slightly enhances evaporation of the powder at the center axis of the plasma torch.

In addition, thermal interaction between titanium feedstock powder and thermal plasma was calculated using the developed numerical model for inductively coupled thermal plasma

(ICTP) with particle injection. The interaction between titanium powder and thermal plasmas is greatly important to consider the stable establishment of the ICTP and effective heating and evaporation of injected particles, for example, for particle synthesis. Injected particles are heated by thermal plasma, and they are melted and evaporated to contaminate the thermal plasma, which influences the thermal plasma properties. The developed numerical model solves mass, momentum and energy conservation equations of thermal plasmas as well as mass transport equation for evaporated materials. In addition, particle motions were derived by solving the Lagrange equation of motion. The temperature distribution inside the particles and phase transition from solid, liquid to gas of the particles were also taken into account. Finally, a parametric study was conducted to show the influence of different important physical parameters such as input power, sheath gas flow rate, and Ti powder feeding rate.

In this thesis, tandem ICTP is formed using two coil currents (upper coil and lower coil) in a single plasma torch, that was already developed for nanoparticle synthesis. The temperature distribution of the tandem ICTP and evaporation of feedstock Ti powder were obtained for different gap lengths between the upper and lower coil and coil turn numbers. Results indicate that increasing the gap length between the upper and lower coil produces two separately controlled high-temperature areas in tandem ICTP. This result suggests that tandem ICTP provides a temperature field that is favourable for particle evaporation of injected particles while maintaining ICTP in the upper region of the plasma torch for stable operation

2019 年　8 月　6 日

学位論文審査報告書（甲）

１．学位論文題目（外国語の場合は和訳を付けること。）

Numerical modeling on thermal interaction between thermal plasma and solid powder for materials processing（材料加工のための熱プラズマと固体粉末の間の熱相互作用に関する数値モデリング）

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３．審査結果の要旨（600～650 字）

2019 年 8 月 6 日に第 1 回学位論文審査委員会，同日に口頭発表，第 2 回審査委員会を開催し，慎重審議の結果，以下のとおり判定した。なお，口頭発表における質疑を最終試験に代えるものとした。

本論文は，材料プロセス用誘導熱プラズマと，そこに投入する固体粉体との間の熱的相互作用のモデリングに関する研究である。誘導熱プラズマはガス温度が 10000 K にも達する高温高気圧のプラズマである。この誘導熱プラズマに原料固体粉体を導入することで，原料を蒸発させ，さらにそれを冷却することでナノ材料を大量に得ることがなされている。この物理過程を把握するためには，様々な診断とともに数値モデリングすることが重要である。本論文では，誘導熱プラズマを電磁熱流体で，固体粒子をラグランジュ粒子としてモデル化している。熱プラズマ流内での固体粒子の運動と，プラズマからの熱伝達による粒子の温度変化，さらに粒子の溶融・蒸発を考慮している。誘導熱プラズマは電磁場からジュール発熱とローレンツ力とを受け，これらが熱プラズマ温度と流れ場を決定する。さらに，粒子の蒸発蒸気が熱プラズマの温度分布・流速分布に影響する。そのため，これらを包括的に考慮し，熱プラズマの電磁熱流体解析と粒子の運動・蒸発とが収束するまで計算している。本論文では，開発したモデルを用いて，TiO_2 ナノ粒子生成に使用される $Ar\text{-}O_2$ 誘導熱プラズマと Ti 原料粉体との相互作用，Si ナノ粒子生成に使用される $Ar\text{-}H_2$ 誘導熱プラズマと Si 原料粉体との相互作用を明らかにしている。さらに「タンデム型誘導熱プラズマ」についてもモデリングし，原料粉体の効率的蒸発と誘導熱プラズマの安定動作とが同時に実現できることを明らかにしている。

以上，本研究は誘導熱プラズマによる材料プロセスの物理解明に貢献するものであり，本論文は，博士（工学）に値すると判定した。

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５．学位論文及び参考論文に不適切な引用や剽窃が無いことの確認

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