Temperature Behavior in a Tandem Type of Modulated Induction Thermal Plasma for Materials Processings

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Abstract. A tandem type of modulated induction thermal plasma (Tandem-MITP) system has been developed using two rf power supplies and two coils for one plasma torch. This system was developed to control temperature and reaction fields temporally and spatially in a thermal plasma. The modulation of each coil current can change the thermal plasma temperature in the torch temporally and spatially. Time variation of Ar excitation temperature was estimated by the two-line method using Ar atomic lines. The Tandem-MITP could be established successfully, and the Ar excitation temperature in the thermal plasma could be controlled temporally and spatially by the developed system.

1. Introduction
We have so far developed a series of modulated induction thermal plasma system: a pulse modulated induction thermal plasma (PMITP) system [1], an arbitrary-waveform modulated induction thermal plasma (AMITP) system [2] and a feedback control type of modulated induction thermal plasma (FBC-MITP) system [3]. These systems can modulate the coil current amplitude to control the temperature of thermal plasmas in the time domain. Such a modulation of the coil current can produce periodical temperature field or non-equilibrium effects even in thermal plasmas. These unique features of the modulated induction thermal plasma lead to their various applications. One example of the PMITP application is TiO₂ nanoparticle synthesis using Ar-O₂ PMITP [4]. That result implied that the PMITP can control the size and phase of TiO₂ nanoparticles [4].

The contribution of this paper is to provide a new modulated induction thermal plasma system: a tandem type of modulated induction thermal plasma (Tandem-MITP) system. The tandem type of induction thermal plasma without modulation had been developed by Uesugi et al [5]. However, there is few report concerning a Tandem-MITP. The Tandem-MITP is expected to produce a modulated gas flow field and a modulated temperature field not only temporally but also spatially in one torch. Furthermore, injection of reactive gases to such a Tandem-MITP can provide more effective modulated reaction fields which will be useful for various materials processings. One expected example is in particle treatments or nanoparticle synthesis to heat up injected particles along particle flight at specified time and spatial position. For a fundamental study of a Tandem-MITP, we measured response of the effective power.
from these two coils and Ar excitation temperature $T_{\text{ex}}^\text{Ar}$ at different positions. Results indicated that a Tandem-MITP could be established successfully, and that $T_{\text{ex}}^\text{Ar}$ in the thermal plasma could be controlled in more detail by the Tandem-MITP system spatially and temporally. This paper provides fundamental data for controlling temperature of a Tandem-MITP.

2. Experimental setup and conditions for Tandem-MITP

2.1. RF power supply for Tandem-MITP system

Figure 1 shows a schematic of the tandem type of modulated induction thermal plasma (Tandem-MITP) system. The tandem-MITP needs two rf power supplies: an rf power supply for the upper-coil and an rf power supply for the lower-coil. These two power supplies consist of four main parts: a rectifier circuit, an insulated gate bipolar transistor (IGBT) dc-dc converter (chopper) circuit, a metal-oxide semiconductor field-effect transistor (MOSFET) full-bridge inverter circuit, and an impedance-matching circuit with a matching transformer and an LC series circuit. The differences between them are the rectifier circuits with or without reduction of the current ripple, and the driving frequency for MOSFETs as described later. They can also modulate the coil current amplitude.

2.2. Plasma torch

Figure 2 illustrates a configuration of the plasma torch used in the experiment. The torch is composed of two coaxial quartz tubes with 430 mm in length, which is much longer than the conventional torches. The inner tube has an inside diameter of 70 mm. Between the inner and outer quartz tubes, cooling water flows from the bottom to the top side to keep the wall-temperature around 300 K. The sheath gas is supplied from the top of the plasma torch along the inner wall of the inner tube with swirl. This torch has two eight-turn induction coils: the upper-coil and the lower-coil. Distance between the upper-coil end and the lower-coil top is 50 mm. The two coils are connected with rf power supplies, respectively.

2.3. Experimental conditions

In order to measure a fundamental behavior of a Tandem-MITP, the following condition was set for experiment. The sheath gas was Ar, and its gas flow rate was set to 40 slpm for axial gas and 40 slpm for swirl gas. The pressure in the chamber was fixed at 70 torr. The driving frequency of the upper-coil current was fixed at 430 kHz, while that of the lower-coil current was set to about 300 kHz.
difference between these driving frequencies was required to reduce the mutual electromagnetic coupling between two circuits. Meanwhile, generally the input power to the thermal plasma is proportional to the square value of the driving frequency. Thus, too lower frequency than 300 kHz was not adequate for the driving frequency of the lower-coil. As a modulation waveform for coil currents, a rectangular waveform was chosen for a fundamental study. The phase difference $\phi$ between two rectangular modulation signals for the upper-coil and the lower-coil was set to be $\pi/2$, $\pi$ and $3\pi/2$. From this experiment, we also estimated the mutual influence between the two thermal plasmas produced by the upper and lower coils current.

2.4. Spectroscopic observation system

Figure 3 shows the spectroscopic observation system. Spectroscopic observation was carried out at three positions: at 10, 25 mm below the upper-coil end and at 10 mm below the lower-coil end at the center axis of the plasma torch, which are designated by A, B and C, respectively. The light radiated from each observation position is transmitted through an optical lens and an optical fiber bundle to the slit of the monochromator. Use of this system enables us to measure time evolution in the radiation intensities at different three wavelengths simultaneously. The wavelength resolution of the whole system including the monochromator and the optical fiber bundle is about 0.6 nm. In the present experiment, we measured temporal variations in the radiation intensities at 703.0 nm and 714.7 nm for Ar atomic lines and at 709 nm for continuum. These spectral lines are available because they satisfy the temperature estimation criteria [6]. Subtracting the measured radiation intensity at 709 nm from those at 703.0 nm and 714.7 nm yields the net radiation intensities of the Ar atomic lines at 703.0 nm and 714.7 nm. Using the net radiation intensities, Ar excitation temperature $T_{\text{ex}}^{\text{Ar}}$ between the specified levels was estimated by the two-line method assuming Boltzmann distribution for the excited population. The $T_{\text{ex}}^{\text{Ar}}$ was calculated in real-time in a Digital Signal Processor (DSP). Note that $T_{\text{ex}}^{\text{Ar}}$ was estimated by the apparent intensities integrated along the line of sight without Abel inversion, and thus it may be underestimated. In spite of this, time evolution in the estimated $T_{\text{ex}}^{\text{Ar}}$ was regarded as a parameter to understand thermal state of the Tandem-MITP formed. The above whole optical system was calibrated using a standard tungsten-halide lamp. This temperature determination includes relative errors $\Delta T/T \sim 0.06$ around 10000 K, while $\Delta T/T \sim 0.5$ around 4500 K due to intensity measurement errors.

3. Experimental results

3.1. Coil current and effective power

Various types of Tandem-MITPs were successfully established stably for the given conditions. To perceive responses of two rf power supplies for Tandem-MITPs, the instantaneous current $i_{\text{inv}}(t)$ and
voltage \( v_{\text{inv}}(t) \) for these two supplies were measured at the output terminal of each inverter circuit in Fig. 1. The effective power \( P(t) \) was calculated by \( i_{\text{inv}}(t) \) and \( v_{\text{inv}}(t) \). Figures 4 (I) and (II) show time evolutions in (a) modulation signal for the upper-coil, (b) inverter output current for the upper-coil in root-mean-square (rms), (c) inverter output effective power for the upper-coil, (d) modulation signal for the lower-coil, (e) inverter output current for the lower-coil, and (f) inverter output effective power for the lower-coil. The root mean square values were estimated by integrating instantaneous value in each fundamental cycle. Panel (I) corresponds to the result for phase difference \( \theta_d = \pi \), whereas panel (II) is the result for \( \theta_d = 3\pi/2 \).

As seen in Figs. 4(I)(a) and (I)(b), the rms value of the upper-coil current could be controlled to follow the modulation signal. Following to this current modulation, effective power \( P(t) \) of the upper-coil is also modulated periodically from 2.5 kW to 12 kW. The effective power changes gradually following the modulation rectangular waveform with a time constant around 8 ms. This long time constant of 8 ms is attributed to thermal inertia \( \rho C_p \) of the thermal plasma in the upper-coil, where \( \rho \) is the mass density and \( C_p \) is the specific heat at constant pressure. Meanwhile, the effective power of the lower-coil shows a rapid initial rise in corresponding rapid initial rise of the lower-coil current around \( t=25 \text{ ms} \). Here, \( t \) is the time referred to the horizontal time axis in this figure. After that, the effective power of the lower-coil increased until \( t=30 \text{ ms} \). This may arise from the following fact: The high-temperature plasma with high electrical conductivity and with low \( \rho C_p \) still flows into the lower-coil region although the upper-coil current is rapidly decreased down around \( t=25 \text{ ms} \). Thus, the electric power from the lower-coil is rapidly elevated by the increased lower-coil current. On the other hand, from \( t=30 \text{ ms} \) to 50 ms, the effective power of the lower-coil decreases to 4.8 kW gradually although the lower-coil current remains 120 A. This may be because the high-temperature plasma flowing from the upper-coil into the lower-coil region becomes to have the weak intensity. As seen, the developed system can controls the temporally and spatially modulated induction thermal plasma.

The above-mentioned plasma behavior in the upper-coil and lower-coil region was also observed by a high-speed video camera. Figures 5 (I) and (II) depict the dynamic behavior of a Tandem-MITP for \( \theta_d = \pi \) and \( \theta_d = 3\pi/2 \), respectively. The time \( t \) here is the same to that of Fig. 4. As seen in Figs. 4(I), a plasma with high intensity exists in the upper-coil region at \( t=4 \text{ ms} \). This plasma flows into the lower-coil region at \( t=12.5 \text{ ms} \). At \( t=30 \text{ ms} \), the plasma exists only in the lower-coil region on the contrary. In other words, the plasma seems to be transported from the upper to the lower coil regions. In case of \( \theta_d = 3\pi/2 \), from \( t=4 \text{ ms} \) to \( t=12.5 \text{ ms} \), a plasma inside the lower-coil region has the increasing intensity, arising from the increasing input power to the lower-coil region. At \( t=30 \text{ ms} \), the plasma in the lower-coil region becomes to have the weak intensity. As seen, the developed system can controls the temporally and spatially modulated induction thermal plasma.

3.2. Ar excitation temperature

As well known, the temperature is one of essential parameters to understand state of thermal plasma because the thermal plasma is often under local thermodynamic equilibrium condition. In this work, the Ar excitation temperature \( T_{\text{ex}}^{\text{Ar}} \) was estimated by two-line method using the specified Ar atomic lines at 703.0 nm and 714.7 nm, assuming the excitation population follows the Boltzmann relation. Figure 6 depicts the time evolution in (a) modulation signal for upper-coil, (b) modulation signal for lower-coil,
(I) Phase difference $\theta_d = \pi$

**Figure 4.** Time evolution in (a) modulation signal for upper-coil, (b) inverter output current for upper-coil in rms, (c) inverter output effective power for upper-coil, (d) modulation signal for lower-coil, (e) inverter output current for lower-coil (f) inverter output effective power for lower-coil.

(II) Phase difference $\theta_d = 3\pi/2$

Figure 5. High-speed video images of a Tandem-MITP.

and (c) Ar excitation temperature $T_{\text{ex}}^{\text{Ar}}$. As seen in Fig. 6(I)(c), the $T_{\text{ex}}^{\text{Ar}}$ at positions A and B change periodically and similarly with a certain time constant according to the modulation signal for the upper-coil. The $T_{\text{ex}}^{\text{Ar}}$ at A changes between 5800 K to 7700 K gradually, due to the thermal inertia $\rho C_p$ of the thermal plasma. On the other hand, the $T_{\text{ex}}^{\text{Ar}}$ at position C shows quite different temporal variation against those at A or B. The $T_{\text{ex}}^{\text{Ar}}$ at C rapidly decreases from 6000 K to 4500 K just after the lower-coil current down, for example around $t=0$ ms in Fig. 6(I)(c). After that, the $T_{\text{ex}}^{\text{Ar}}$ gradually increases between...
Temperature \[kK\]
Phase difference \[\text{rad}\]

\[t = 4.7\text{ ms and } t = 25\text{ ms because of the flowing thermal plasma from the upper-coil. From } t = 25\text{ ms to } 37\text{ ms, the } T_{\text{Ar}}^{\text{ex}} \text{ sharply rises up from 6000 K to 9300 K. This rise up in the } T_{\text{Ar}}^{\text{ex}} \text{ results from the rise up in the effective input power from the lower-coil to thermal plasma in the lower-coil region. From } t = 37\text{ ms to } 50\text{ ms, the } T_{\text{Ar}}^{\text{ex}} \text{ gradually decreases with time, since the thermal plasma flowing from the upper-coil into the lower-coil region decays as mentioned in the previous section. These results indicate that } T_{\text{Ar}}^{\text{ex}} \text{ can be controlled by the lower-coil current as well as by the upper-coil current, which leads to the large modulation in } T_{\text{Ar}}^{\text{ex}} \text{ from 4500 K to 9300 K.}

In case of } \theta_d = 3\pi/2 \text{ as indicated in Fig. 6(II), time evolutions in } T_{\text{Ar}}^{\text{ex}} \text{ at A and B are similar to those in case of } \theta_d = \pi. \text{ This means that } T_{\text{Ar}}^{\text{ex}} \text{ at A and B has a weak influence from the lower-coil at this time. On the other hand, the } T_{\text{Ar}}^{\text{ex}} \text{ at C changes with a lower amplitude compared to that for } \theta_d = \pi.

Figure 7 plots the maximum and minimum values of } T_{\text{Ar}}^{\text{ex}} \text{ measured at position C versus the phase difference. From Fig. 7, the maximum values of } T_{\text{Ar}}^{\text{ex}} \text{ at C strongly depends on the phase difference. This result implies that phase difference between the upper-coil current and lower-coil current is also an important parameter for controlling the temperature in the Tandem-MITP.

4. Conclusions
In this paper, a tandem type of modulated induction thermal plasma (Tandem-MITP) system has been developed using two rf power supplies and two coils for one plasma torch. This system was developed to provide a method for controlling temperature and reaction fields both temporally and spatially in thermal plasmas. We measured time variations in the Ar excitation temperature estimated by the two-line method using Ar atomic lines. Results suggested that Ar excitation temperature in the Tandem-MITP could be controlled in more detail temporally and spatially with two coil currents. These features of the Tandem-MITP can be useful for various materials processings.

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