MELTING AND EVAPORATION OF POWDER PARTICLES
IN REACTIVE PLASMA SPRAYING

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ABSTRACT

A model of liquid droplet combustion was applied to the numerical simulation for powder heating in an RF thermal plasma. The trajectories and the temperature histories of aluminum powder were calculated using this model. In the experiments, aluminum powder and additional gas (Ar, O_2 or N_2) were introduced into an RF thermal plasma. The powder was evapolated and reacted with oxygen or nitrogen. The amounts of evaporated powder were evaluated. The calculation results with the combustion model and the experimental ones showed similar tendencies.

1. INTRODUCTION

A radio frequency (RF) inductively coupled plasma has offered a clean high-energy source. The RF plasma has been used more extensively in recent years for producing ultrafine powders of various materials.

A reactive RF plasma is one of the new research subjects with great interest in plasma spraying and in production of ultrafine powders. For example, Al_2O_3 and AlN ultrafine powders are produced from aluminum powder in an RF thermal argon-oxygen and argon-nitrogen plasma, respectively. These powders produced in the reactive plasma are usable as refractory materials in plasma spraying.

The efficiency of the powder heating process depends on the temperature histories of the powder. Prediction of the trajectories and the temperature histories is important for these processes. A number of investigations have been reported on the powder heating in an RF plasma [1,2]. In this paper, an attempt was made to propose the application of the model of liquid droplet combustion in the numerical simulation for the powder heating.

2. EXPERIMENTAL
2.1 Plasma Generator

The plasma generator consisted of a plasma torch, a control board, and a power supply (4 MHz, 0 - 35 kW). The plasma torch, shown in Fig. 1, consisted of a quartz tube and a working induction coil (4 turn); the coil was positioned between 68 mm and 117 mm below the top of the torch. The torch was prevented

from melting by water.

2.2 Procedure

The experimental conditions are given in **Table 1**. The plasma supporting gas (argon) and the additional gas (argon, oxygen or nitrogen) were introduced from the top of the torch under atmospheric pressure. Aluminum powder (30 - 105 μm) was injected at 100 mm below the top of the torch at the center. The powder was fed at the rate of 0.5 g/min through a water-cooled pipe with argon carrier gas. The evaporated powder behaved itself like smoke, and floated around the torch. The unevaporated powder fell down and was collected on a plate; the plate was positioned at 300 mm below the torch exit. The amount of unevaporated powder was measured for various conditions.
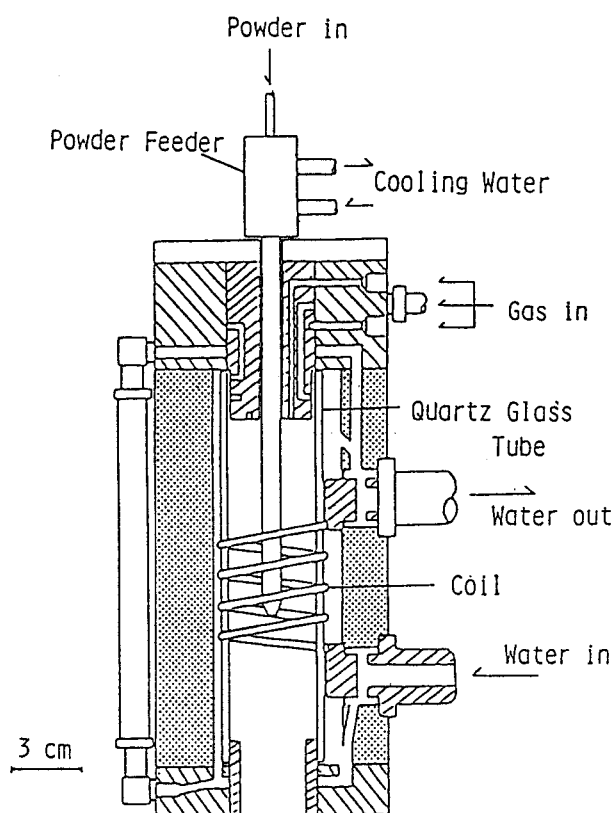

Fig.1 Plasma torch

Table 1 Experimental conditions

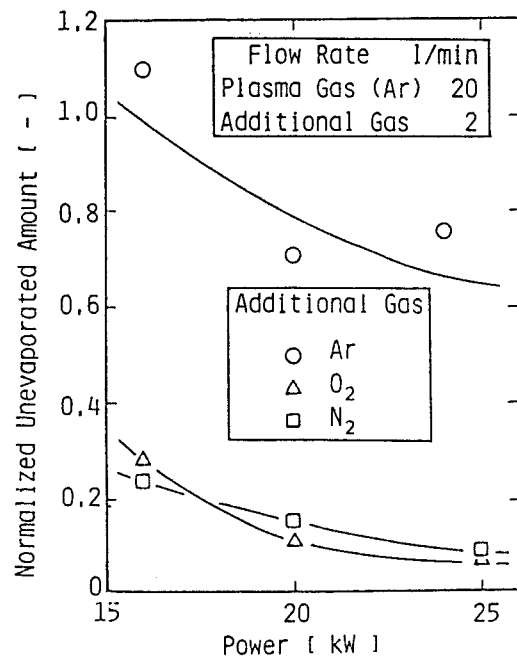| Powder (Al)	
Diameter	: 30-105 μm
Feed Rate	: 0.5 g/min
Plasma Supporting Gas (Ar)	
Axial	: 10.0 l/min (Q1)
Tangential	: 10.0 l/min (Q2)
Additional Gas (Ar, O_2, N_2)	
Tangential	: 0,2,4,6,8 l/min (Q3)
Source Power	: 16,20,25 kW

2.3 Experimental Results

The SEM photographs showed the evaporated powder was under 100 nm in diameter and in the range of ultrafine particles. The results of X-ray diffraction indicated that the only evaporated powder reacted with oxygen or nitrogen.

The variation of the amount of unevaporated powder with the additional gas flow rate are represented in **Fig. 2(a)**. The amount decreases as the additional gas flow rate increases when the additional gas is oxygen or nitrogen; these decreases in the amount are ascribed to the reaction of aluminum with oxygen or nitrogen. The amount of unevaporated powder decreases with an increase in input power, as shown in **Fig. 2(b)**. This decreases results mainly from an increase in the plasma temperature.
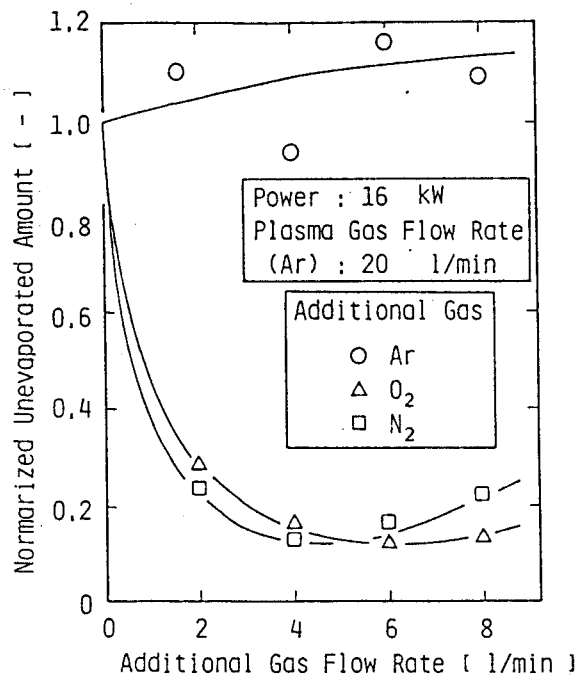
Fig. 2   The amount of unevaporated powder (a) at different additional gas flow rate   and (b) at different power

3. CALCULATION

3.1 Flow, Temperature and Concentration Fields

The flow, temperature and concentration fields in the RF thermal plasma have to be calculated before modeling the powder heating. The fields in the torch were calculated by solving the two dimensional continuity, momentum, energy and species equations simultaneously and the one dimensional electric and magnetic fields equations. The dissociation of oxygen was taken into account in these equations. The torch configuration used is shown in **Fig. 3.**

The basic assumptions are as follows: 1) Steady state laminar flow: 2) Local thermodynamic equilibrium (oxygen dissociation rate is considered):   3) Axially symmetric: 4) Optically thin plasma: 5) Negligible viscous dissipation: 6) Negligible displacement current: 7) Negligible thermal diffusion.
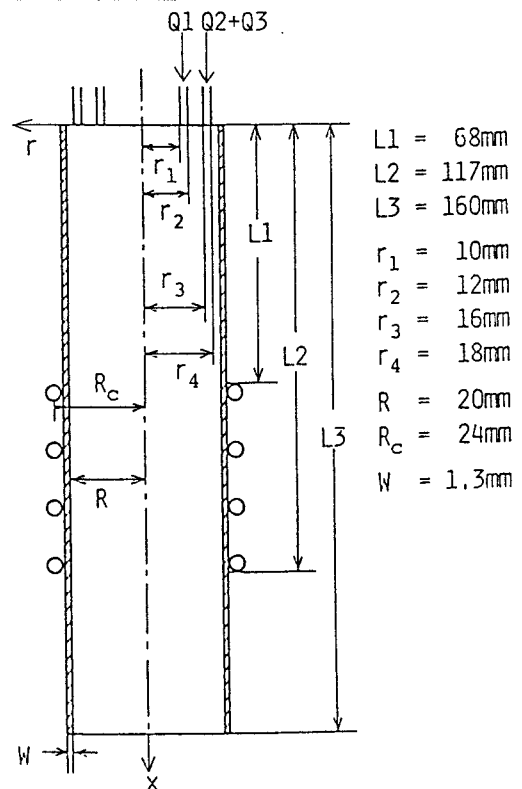

$L1 = 68mm$
$L2 = 117mm$
$L3 = 160mm$

$r_1 = 10mm$
$r_2 = 12mm$
$r_3 = 16mm$
$r_4 = 18mm$

$R = 20mm$
$R_c = 24mm$

$W = 1.3mm$

Fig. 3   Calculation model

3.2 Numerical Procedure

The governing equations were solved using the SIMPLER algorithm [3]. The SIMPLER algorithm is a general algorithm for the solution of elliptic fluid flow, heat transfer and diffusion. The governing equations can be formulated as follows.

$$\nabla \cdot (\rho u \Phi) = \nabla \cdot (\Gamma \nabla \Phi) + S \tag{1}$$

where Φ is called the dependent variable, Γ and S are the diffusion coefficient and the source term, respectively. The boundary conditions and the electromagnetic equations are the same to the model proposed by J. Mostaghimi et al. [4]. The calculation was performed for a 10 X 16 grid system in the radial and axial directions, respectively.

3.3 Particle Trajectory and Temperature History

Single particle trajectories were calculated by solving the following equations:

$$\frac{d u_p}{d t} = -\frac{3}{4} C_D (u_p - u_g) |u_r| \left(\frac{\rho_g}{\rho_p \cdot D_p} \right) \tag{2}$$

$$\frac{d v_p}{d t} = -\frac{3}{4} C_D (v_p - v_g) |u_r| \left(\frac{\rho_g}{\rho_p \cdot D_p} \right) \tag{3}$$

where u_r is the relative velocity; the subscripts g and p indicate the plasma gas and particle, respectively. D_p is the particle diameter; ρ is the density. Calculations were made assuming that the particle was spherical and entered the torch at the center with velocity of a carrier gas. The drag coefficient, C_D, in these equations were estimated from the following equation [5]:

$$C_D = \frac{24}{Re} \left(\frac{\rho_g \cdot \mu_g}{\rho_{ps} \cdot \mu_{ps}} \right)^{-0.45} \tag{4}$$

where μ is the viscosity; subscript ps indicates the particle surface.

The temperature of the particle was estimated from the Ranz and Marshal equation [5] until the boiling point (2400 K).

$$Nu_f = (2 + 0.6 Re_f^{0.5} \cdot Pr_f^{0.33}) \left(\frac{\rho_g \cdot \mu_g}{\rho_{ps} \cdot \mu_{ps}} \right)^{0.6} \left(\frac{Cp_g}{Cp_{ps}} \right)^{0.38} \tag{5}$$

where C_p is the specific heat, the subscript f corresponds to properties evaluated at the film temperature. After the particle temperature reached the boiling point, the temperature remained constant and the particle mass decreased due to evapolation. The model of liquid droplet combustion (Fig. 4) was adopted [6]. The rate of mass decreasing was estimated from the following equation.

$$\frac{d m}{d t} = 2 \pi D_p \frac{k}{C_p} \ln (1 + B) \tag{6}$$

$$B = \frac{H \cdot M_o}{Q \cdot i} + \frac{C_p (T_g - T_{ps})}{Q}$$

where k is the thermal conductivity of plasma; H is the heat of combustion; Q is the latent heat due to evaporation; M_O is the mass fraction of O; i is the stoichiometric coefficient for oxygen in the reactant. The calculations were made for the particles with different diameters (30 - 105 μ m). The amounts of unevaporated particles were calculated and compared with the experimental results.
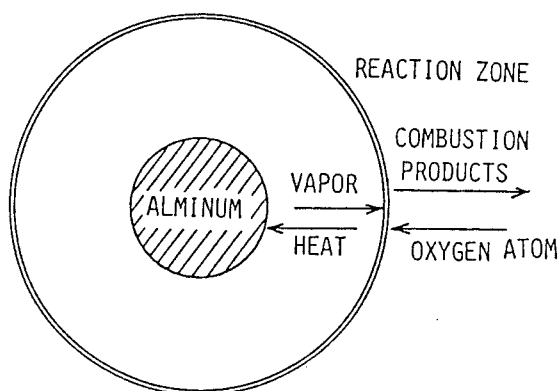

Fig. 4   Combustion model

3.4 Calculation Results

The flow, temperature and concentration fields in the RF plasma (Ar 20 liter/min; O_2 4 liter/min) are shown in **Figs. 5 (a)-(d)**. In combustion model, aluminum reacts only with O, because O_2 does not exist around the area which the powder passes through. The products due to the combustion are assumed to be AlO or Al_2O. The results for the amount of unevaporated powder are shown in **Fig. 6**. The calculation results with combustion model and the experimental ones show similar tendencies. Some differences are seen between the calculation results and the experimental ones; the differences are attributed to the following reasons; The heat of combustion is not taken into account in the RF plasma fields; The off-centered pass on the powder is not considered.

4. CONCLUSIONS

Al_2O_3 and AlN ultrafine powders were produced from aluminum powder in an RF thermal argon-oxygen and argon-nitrogen plasma, respectively.

The trajectories and the temperature histories of the aluminum powder were calculated using the model of liquid droplet combustion. The calculation results with the combustion model and the experimental ones showed similar tendencies.

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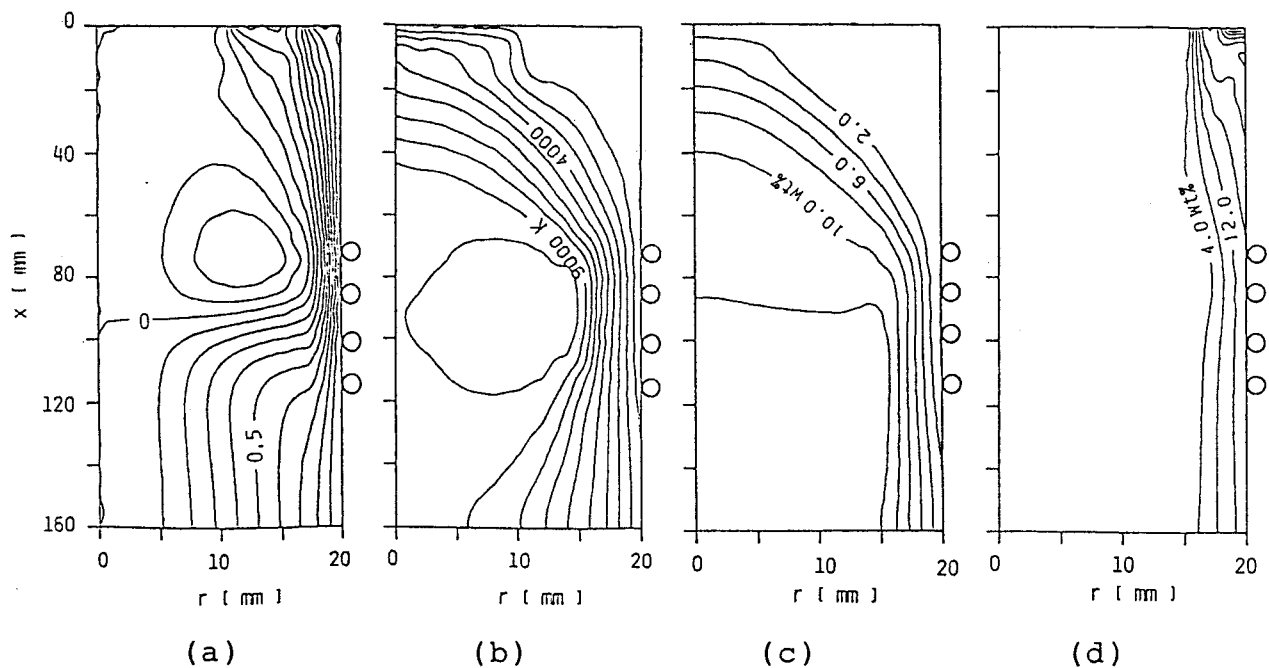[6] D. B. Spalding, Fourth Sym. on Combustion, (1953) 847

Fig. 5   Flow, temperature and concentration fields for argon 20 liter/min; oxygen 4 liter/min; power 16 kW: (a) Stream lines: (b) Temperature contours: (c) Concentration contours for O: and (d) Concentration contours for O_2.
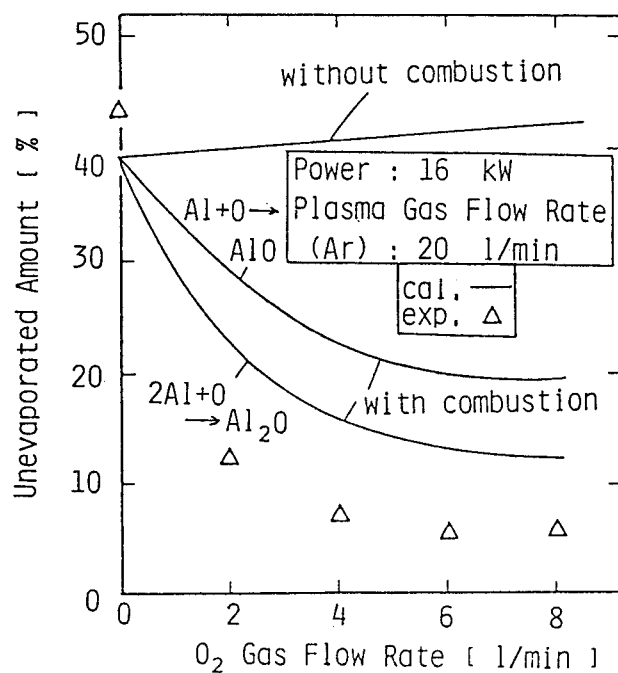

Fig. 6   The amount of unevaporated powder at different O_2 flow rate.