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Separation of Al and Cu powders in the Magneto-Archimedes Levitation Field

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The possibility of separation and efficient recovery of aluminum (Al) and copper (Cu) with the difference of magnetism and density based on the magneto-Archimedes effect were examined. Al and Cu powders levitated at 3.9T and 7.9T in Mn^{2+} aqueous solution of 2.83M. Al powder levitated further than the Cu one in the lower magnetic field. Because the absolute value of paramagnetic susceptibility of the aluminum and diamantic susceptibility of the copper are limitlessly near for 0, it is considered that the difference of the density is a dominant factor for the levitation difference of aluminum and copper powders. Because each metal powders levitated to the solvent interface, it was verified that separation and recovery of each powders were possible by the change of strength of the applied magnetic field.

Key words: Magneto-Archimedes Levitation Field, Separation of the powder mix, Recycling technology of the useful metal chip, Paramagnetic material (Al), Diamagnetic material (Cu)

1. INTRODUCTION

The material separation technique has played a important role in material science. Recently, the examination of new separation technique based on magnetic field effect has been started by the popularization of the super-conducting magnet of which the generation is easily possible the comparatively strong magnetic field of about 10T. The possibility has been examined the separation using magnetic field effects until now for isotope separation by photochemical reaction, magnetic adsorption of gas, separation of the ion by electrophoresis, electromagnetic migration separation by magnetic gradient gel, particle separation according to the magneto-Archimedes effect, etc [1].

It was reported that diamagnetic materials such as water and plastic levitated by the magnetic field by Beaugnon and Tournier in 1991[2] .The magnetic levitation of the diamagnetic material has been noticed in the field of materials science such as the utilization as a field of invention process of the new material. However, because the diamagnetic susceptibility is small, Very strong magnetic field and steep gradient are required for the levitation. For example, the magnetic levitation of the water has been realized only by use of the hybrid magnet of which can generate magnetic field over 20T. Recently, it became clear that the levitation of diamagnetism materials and paramagnetic materials using the super-conducting magnet which generates about 10T magnetic field (the magneto-Archimedes levitation) by controlling the magnetism of noticing material circumference (solvent) [3] [4] . One of large features of the magneto-Archimedes levitation is to determine position the material stability in solvent. Levitation position for which respectively differs for the different material exists on the stability position in order to decide by difference of the bulk susceptibility and the density between a noticed material and a circumference (solvent). By using this principle, the material separation becomes possible. Actually, the practical separation process of diamagnetic and paramagnetic material (glass bead included the rare earth element, high polymer material, etc.) by using the technology of magneto-Archimedes levitation were examined[5] [6] . Because the magneto-Archimedes separation utilizes both differences of density and magnetic susceptibility is possible, it is expected that the multiplied separation is possible for the materials with the difference in slight magnetic susceptibility and density.

Until now, the examination considered to the recovery of separated material in which the research of the magneto-Archimedes separation was not performed. Authors examined the possibility of separation and efficient recovery of aluminum (Al) and copper (Cu) with the difference of magnetism and density based on the application of the metallic value to the resource recycling technique

2. EXPERIMENTAL

Fig.1 shows the construction of experimental setup in the super-conducting magnet (Japan magneto technology Co.,Ltd). A cylindrical space (1.0dm diameter, 7.5dm length) exists near the center of magnet. The container bottom was installed for the center location in the cylindrical space with the strongest magnetic flux density. The container used the 50ml graduate cylinder. The magnetic field was perpendicularly applied upward from under container basal plane. The graduate cylinder which added the powder which mixed Al and Cu and 20ml Mn^{2+} aqueous solution was installed in the magnetic field center, and the magnetic flux density was made to rise to 0～10T.

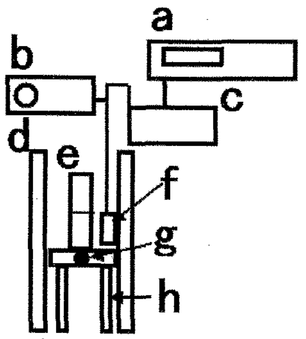

Fig.1 Construction of experimental setup. **a**, video; **b**, light source; **c**, CCD camera; **d**, super-conducting magnet; **e**, sample; **f**, Endoscope; **g**, center of magnetic field; **h**, nonmagnetic mount.

The levitation of powder was photographed from the transverse direction using the endoscope system (Olympus Co.,Ltd:IF 6C5XI-30 MR) with CCD camera (Olympus Co.,Ltd:OH-412 W/OAC). Probe tip of the optical fiber was nonmagnetic. The image was stored as digital data in 1/15 frame in the computer.

The levitating materials used a powdery aluminum (WAKO :>99.5%) and copper (WAKO :>99.85%). The paramagnetic aqueous solution was prepared by Manganese(Ⅱ) Sulfate Pentahydrate ($MnSO_4 \cdot 5H_2O$; WAKO :>99.0 %). The concentration prepared the three types of 0.70,1.41 and 2.83M. The powders of Al and Cu weighed 0.100g, and sufficiently mixed.

3. Principle of magneto-Archimedes levitation

The magneto-Archimedes levitation utilizes the magnetic buoyancy considering the magnetic force acted in the solvent. If the solvent is the paramagnetism, they are drawn for the center of magnetic field. This means that the effective weight of the solvent increases, and that it is necessary for the material levitation in the solvent is eased. **Fig.2** shows a balance of the force considering a density and a magnetic susceptibility of the circumference medium in the magneto-Archimedes levitation field. The gravity direction is defined as a Z axis. The powders receive buoyancy for an upward (right-hand side of **equation (1)**) by eliminating by the volume of powders with the downward force (left edge of **equation (1)**) by the gravity. Levitation condition can be introduced by the Archimedean principle.

$$m_s g = \rho_l V_s g \quad \cdots \quad (1)$$

$$\rho_s = \rho_l \quad \cdots \quad (2)$$

m_s,g, ρ_l,V_s and ρ_s are mass [kg], gravitational acceleration [ms-[1]], solvent density [kgm-[3]], volume of the powder [m^3] and the density of powder [kgm-[3]], respectively.

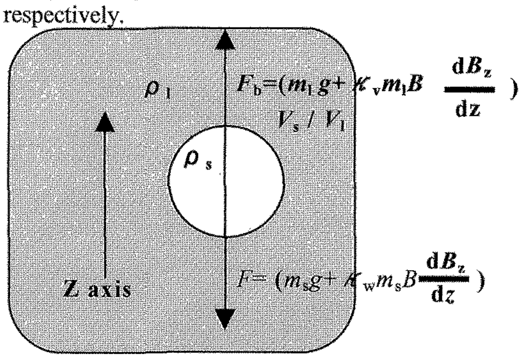

Fig.2 A balance of the force in the magnetic field. ρ_l, density of the liquid; ρ_s, density of the powder; F_b, Buoyancy; m_l, mass of liquid; g, gravitational acceleration; κ_v, bulk susceptibility of liquid; B, magnetic flux density; dB_z/dz, magnetic field Gradient; V_s, volume of powder; V_l, volume of liquid; F_d, Downward force; m_s, mass of powder; κ_w, mass magnetic susceptibility of powder.

Powders receive the gradient magnetic force for which is correspond to magnetic susceptibility in the magnetic field.

$$F_s = \kappa_W m_s B \frac{dB_z}{dz} \quad \cdots \quad (3)$$

F_s, κ_w, B and dB_z/dz are gradient magnetic force which affects the powder[N], mass magnetic susceptibility of the powder[$JT^{-2}kg^{-1}$], magnetic flux density in the center of magnetic field [T] and gradient of magnetic field from the center of magnetic field to the liquid interface[Tm^{-1}], respectively. Therefore, the downward resultant force (=F_d) affected the powder in the magnetic field becomes **equation (4)**.

$$F_d = m_s g + \kappa_W m_s B \frac{dB_z}{dz} \quad \cdots \quad (4)$$

F_d is resultant force [N] of gradient magnetic force of the powder and downward force by the gravity. Similarly, gradient magnetic force for which corresponds to magnetic susceptibility in the magnetic field affects the solvent.

$$F_l = \kappa_v V_l B \frac{dB_z}{dz} \quad \cdots \quad (5)$$

F_l, κ_v and V_l are a gradient magnetic force [N], bulk susceptibility[$JT^{-2}m^{-3}$], and solvent volume[m^3], respectively. Therefore, the resultant force affected the solvent in magnetic field becomes equation (6).

$$F_l' = m_l g + \kappa_v V_l B \frac{dB_z}{dz} \quad \cdots \quad (6)$$

F_l is a resultant force [N] of gradient magnetic force which affects the solvent and the downward force by the gravity. Apparent density of powder or solvent by gradient magnetic force in the magnetic field is shown in **equation (7)**.

$$\rho_n = m_n / V_n = F_n / g V_n \quad \cdots \quad (7)$$

ρ_n, m_n and F_n are density of solvent or powder[kgm^{-3}], mass of solvent or powder[kg] and resultant force of gradient magnetic force of solvent or powder and the downward force by gravity[N]. **Equation (8)** is obtained, when **equation (4)**, **equation (6)**, **equation (7)** are substituted in **equation (2)**.

$$[m_s g + \kappa_W m_s B \frac{dB_z}{dz}] / gV_s = [m_l g + \kappa_v V_l B \frac{dB_z}{dz}] / gV_l \quad \cdots \quad (8)$$

The levitation of the powder can be shown from the condition of a balance in **equation (9)**.

$$[m_s g + \kappa_W m_s B \frac{dB_z}{dz}] / gV_s - [m_l g + \kappa_v V_l B \alpha \frac{dB_z}{dz}] / gV_l = 0 \quad \cdots \quad (9)$$

Starting magnetic flux density in which the powder levitates can be shown in **equation (10)** by the deformation of **equation (9)**.

$$B = \{[\rho_l g + \kappa_v B \alpha \frac{dB_z}{dz}] / g - \rho_s\} gV_s / (\kappa_w m_s \frac{dB_z}{dz}) \quad \cdots \quad (10)$$

Here、 α in **equation (9)** and **equation (10)** is a proportional dimensionless constant. In this time, because the actual magnetic gradient in proportion to the change of central magnetic flux density is unknown, a parameter fitting for the measured value calculated by introducing the dimensionless proportion constant α of a for dB/dz.

4 Results and Discussion

Fig.3 (a) and **(b)** show the SEM (Shimadzu Co.,Ltd:SEM-SSX-550) image of Al and Cu. Photographing magnifications are 200 and 3000 times, respectively.

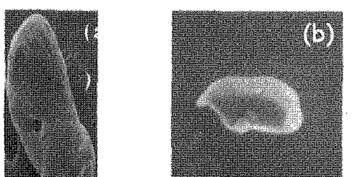

Fig.3 The SEM image of aluminum (a) and c Copper (b). Magnifications are 200 and 3000 times for Al and Cu.

From the SEM observation, it was confirmed that the size distribution of the used Al and Cu had the width. In comparison with the length of extended axis, a size distributions of Al and Cu powder were 200～230 μ m and 4.5～10.0 μ m, respectively. An average volume of Al and Cu particle were estimated by a following procedures. From SEM image, the volume of Al and Cu were estimated by modeling the shape of the particle with the rectangle. Al had 200.0 μ m length, 80.0 μ m width and 60.0 μ m heights, and a volume was estimated with $9.60 \times 10^{-13} m^3$ as a result. By a similar procedure, Cu had 5.00 μ m length, 3.00 μ m width and 3.00 μ m heights, and the volume was estimated with $4.50 \times 10^{-17} m^3$. From volume and density of Al(2700kgm^{-3}) and Cu(8900kgm^{-3})[7], the mass of Al and Cu were estimated 1.22×10^{-9} and 4.01×10^{-13}kg/paricle, respectively. The mass magnetic susceptibility of Mn^{2+} aqueous solution was calculated from the sum of the mass magnetic susceptibility of $MnSO_4 \cdot 5H_2O$ (0.610JT^{-2}kg^{-1})[8] which is included in the aqueous solution and water mass magnetic susceptibility (- 7.20× 10^{-3}JT^{-2}kg^{-1})[8].

Table.1 shows mass, volume and mass magnetic susceptibility[8] of Al and Cu per particle. The density of Al is smaller than the Cu's one about 3.3 times. And, magnetic character of Al and Cu are paramagnetism and diamagnetism, respectively.

Table.1 Aluminum and copper parameter

	Aluminum	Copper
Length/m	2.00×10^{-4}	5.00×10^{-6}
Width/m	8.00×10^{-5}	3.00×10^{-6}
Heigth/m	6.00×10^{-5}	3.00×10^{-6}
Volume/m^3	9.60×10^{-13}	4.50×10^{-17}
Density/kgm^{-3}	2.70×10^{3}	8.91×10^{3}
Mass/kg	2.59×10^{-9}	4.01×10^{-13}
Mass magnetic susceptibility/JT^{-2}kg^{-1}	6.10×10^{-3}	$-8.60 * 10^{-4}$

Table.2 shows mass, volume and bulk susceptibility of Mn^{2+} aqueous solution at each concentration. Concentrations of the prepared Mn^{2+} aqueous solution are 2.83, 1.41 and 0.70M, respectively. Mn^{2+} aqueous solution of 2.83M is correspondent to a saturated solution.

Table.2 The parameter of Mn^{2+} aqueous solution

Concentration/molL^{-1}	2.83	1.41	7.00×10^{-1}
Volume/m^3	2.00×10^{-6}	2.00×10^{-6}	2.00×10^{-6}
Density/kgm^{-3}	1.33×10^{3}	1.14×10^{3}	1.06×10^{3}
Mass/kg	2.66×10^{-2}	2.29×10^{-2}	2.13×10^{-2}
Mass magnetic susceptibility/JT^{-2}m^{-3}	1.10×10	4.61	2.06

Fig.4 show the snap image of magneto-Archimedes levitation of the mixed powder of Al **(a)** and Cu **(b)** in Mn^{2+}aqueous solution of 2.83M. Al and Cu powders levitated at 3.9T and 7.9T,respectively. Al powder levitated further than the Cu's one in a lower magnetic field. Because a each powders levitated to the interface, it was verified that separation and recovery were possible by the change of strength of applied magnetic field. From the observation of macroscope, it was confirmed that only Cu existed in bottom of graduate cylinder after Al levitated.

Fig.5 show the measured value of central magnetic flux density of which the confirmed levitation of Al and Cu in proportion to the density of Mn^{2+} aqueous solution. Strength of an applied magnetic field for the levitation start of each metal powder increased with the lowering concentration of Mn^{2+} aqueous solution. Transversal axis show the density by converting the concentration. For the case of Al powder, the central magnetic flux densities in which the levitation starts are 6.4T and 9.8T for the concentration of 1.41 and 0.70M, respectively. On the other hand, for the case of the Cu powder, the levitation was confirmed at 9.5T for the concentration of 1.41M. However, the levitation of Cu powder could not be recognized for 10T of which was the maximum magnetic flux density of used super-conducting magnet in Mn^{2+} aqueous solution of 0.70M.

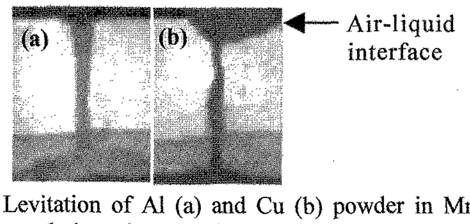

Fig.4 Levitation of Al (a) and Cu (b) powder in Mn^{2+} aqueous solution of 2.83M. (a) : 3.9T, (b): 7.9T.

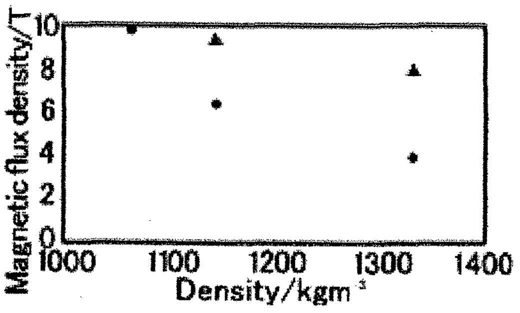

Fig.5 Experimental results of density dependence of Mn^{2+} aqueous solution against the central magnetic flux density for levitation of Al(●) and Cu(▲).

Fig.6 show the calculation results of density dependence of Mn^{2+} aqueous solution against the central magnetic flux density for levitation of Al and Cu per particle. For example, B・dB/dz at a generation of 10T is 169[T^2m^{-1}]. The values of α are 48.1 and 98.5 for Al and Cu, respectively. The calculation used the **equation (11)** by transforming the **equation (10)**.

$$B = [gV_s /(\kappa_w m_s \frac{dB_z}{dz})]\rho_l + \{[(\kappa_v B\,\alpha \frac{dB_z}{dz}) - \rho_s]V_s /(\kappa_w m_s \frac{dB_z}{dz})\} \quad \cdots (11)$$

The calculation results can explain qualitatively well for the measured value in **Fig.5**. Namely, it is shown by that the levitation of Al particle is occurred in the lower concentration of Mn^{2+} aqueous solution by applying the lower magnetic field in comparison with the Cu particle. The aluminum as a paramagnetic material is pulled for the central direction of magnetic field. On the other hands, the copper as a diamagnetic material receives a gradient magnetic force against the direction of which goes away from the center of magnetic field. Because the absolute value of paramagnetic susceptibility of the Al and diamagnetism susceptibility of the Cu are limitlessly near of 0, it is considered that the difference of the density is a dominant factor for the difference of levitation of Al and Cu.

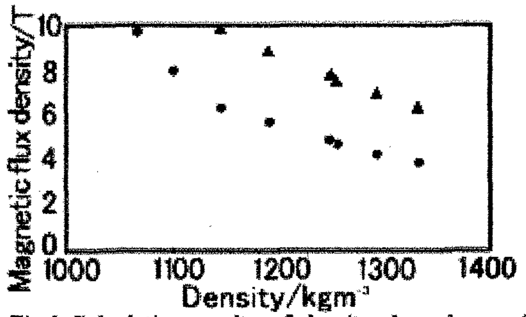

Fig.6 Calculation results of density dependence of Mn^{2+} aqueous solution against the central magnetic flux density for levitation of Al (●) and Cu (▲) particle.

5 Conclusions

It was verified that Al and Cu metal powders with μ m size levitated to the interface of Mn^{2+} aqueous solution under the magneto-Archimedes field , and that each powder can recover in the air-liquid interface. This fact indicated that metal powder with the different of magnetism and density are also possible on not only separation but also recovery. Because the order of absolute value of magnetic susceptibility for the majority of diamagnetic materials almost equivalent under the room temperature, it became clear that the separation by which used magneto-Archimedes levitation for the combination of all diamagnetic materials and the weak paramagnetic materials was possible. The examination of systems of separation and recycling by considering an economical efficiency included the noble metal materials are considered as a next research.

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