Giant Circular Motion of Zinc Particles in Sulfuric Acid under High Magnetic Field

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Under high magnetic field, giant circular motion of zinc particles during dissolution in sulfuric acid was observed. This effect was ascribed to the Lorentz force arising from the interaction between the dissolution current penetrating through the inside of the particle and the external magnetic field. According to theoretical predictions, it was concluded that the coagulated zinc particles take the circular motion, and the particle velocity is proportional to the magnetic flux density.

In electrochemistry, it is well known that the MHD (magnetohydrodynamic) effect leads to the remarkable acceleration of mass transfer accompanied with a solution flow (the MHD flow), which is ascribed to the Lorentz force generated by the interaction between the electrolytic current and the magnetic flux density.[1-5] Chemical dissolution of metal with acidic solution essentially proceeds via. electrochemical processes. In this case, the electrolytic current flows between anodic active site and cathodic active site, which form a spontaneous electrochemical cell.[6,7]

Therefore, when metal particles like zinc powder dissolve in acid solution, the mechanism of reaction may be illustrated as Figure 1; Inside the particle, the electrolytic current flows from cathodic site to anodic site, whereas in surrounding solution phase, the current flows in the opposite direction just like a kind of closed electric circuit. From the geometrical configuration, the current converges inside the particle, and on the contrary, diverges outside. In high magnetic field, such asymmetrical distribution of the current thus produces the imbalance of the Lorentz force worked on the particle. In the case where the force on the particle side is acted much more intensely than that of the solution side, some special movement of the particles can be predicted.

In the present paper, we firstly observe the motion of zinc particles suspended in sulfuric acid under high magnetic field up to 10 T. Then, theoretical consideration will be applied.

Figure 2 shows the schematic of the experimental set-up. The superconducting magnet was a liquid-helium-free magnet with cryocooler, which has a bore space of 10 cm in diameter (Sumitomo Heavy Industries, HF10-100VHF). The magnetic flux density up to 10 T was generated upward along the inner wall of the bore.

Zinc powder (99.7% pure) was composed of the particles with diameters of 2 to 17 μm. They were dispersed in water containing 5 gdm^{-3} polyvinyl alcohol (polymerization degree 500). Just before experiment, the dispersed solution was mixed with 0.5 $moldm^{-3}$ H_2SO_4 + 1 $moldm^{-3}$ Na_2SO_4 solution. For comparison, non-acidic solution without H_2SO_4 was prepared. The solution temperature was adjusted to 27±1 ℃. Then, the whole solution was poured into an acrylic vessel (7 cm in diameter and 10 cm high) settled inside the bore.

As illustrated in Figure 2, a light beam was projected from the bottom of the tube, illuminating the zinc particles in motion.

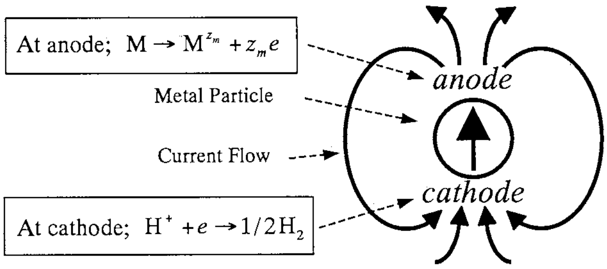

Figure 1. Mechanism of chemical dissolution of metal particle in acid.

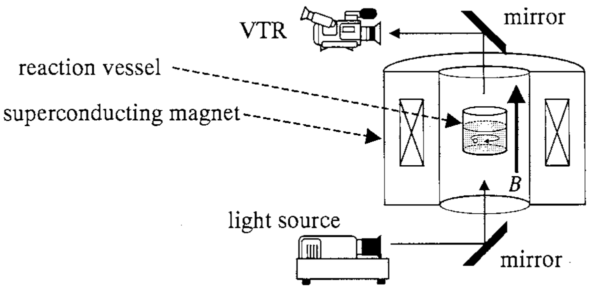

Figure 2. Schematic configuration of experimental set-up.

The particle motion was taken by a video camera from the upper side of the bore.

The zinc particles tended to coagulate with each other due to high ionic strength of the test solution. In the case of acidic solution, many coagulated particles formed a kind of clusters, which started to revolve in circular motion. The direction of the revolution seemed to be decided randomly, *i.e.*, clockwise and anti-clockwise motions were equally observed. Figure 3 shows an example of the photos of the motion taken by multi-exposure. The focus of the coagulated particles is largely diffused because of the mechanical vibration of the cryocooler. On the other hand, in the case of non-acidic solution without dissolution of zinc, coagulated particles did not move even under 10T magnetic field.

From these experimental data, a mechanism on this specific circular motion is proposed as follows. When a small particle moves in a fluid, the kinetic energy is rapidly dispersed into the thermal energy by the thermal motion of solution particles. The driving force, *i.e.*, the Lorentz force is quickly balanced with the viscous shear stress. Assuming that the electrolytic current flows inside the particle, we can estimate the magnitude of the Lorentz force as $Bi \cdot 2r$, which equates the Stokes equation $6\pi r \eta v$;

$$6\pi r \eta v = Bi \cdot 2r \tag{1}$$

where r particle radius, η viscosity, v velocity, B magnetic flux density, and i is electrolytic current. From Eq. (1), the velocity

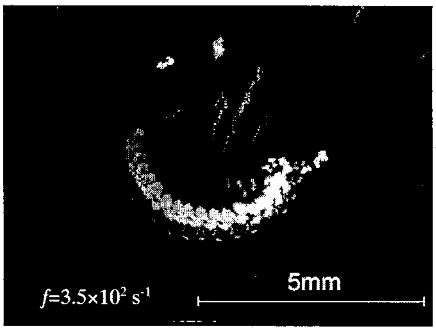

Figure 3. A locus for giant circular motion of zinc particles under high magnetic field of 10 T. Wide spread focus comes from the mechanical vibration of the cryocooler. Solution contains 0.5 moldm^{-3} H_2SO_4 + 1 moldm^{-3} Na_2SO_4 and a small amount of polyvinyl alcohol. Temperature is 27±1 ℃.

is expressed as

$$v = \frac{Bi}{3\pi\eta} \tag{2}$$

To describe the circular motion of the particle, the centrifugal force equated with the Lorentz force is introduced as follows,

$$\frac{mv^2}{R} = Bi \cdot 2r \tag{3}$$

where m is the particle mass ($=4\pi r^3\rho/3$, where ρ is density of zinc) and R indicates the revolution radius.

Furthermore, expressing the particle velocity v with frequency f and angular velocity ω, we can obtain the following relation,

$$v = R\omega = 2\pi Rf \tag{4}$$

Substitution of Eqs. (3) and (4) into Eq. (2) allows us to derive the expression of the particle radius in the following,

$$r = \frac{3}{2}\left(\frac{\eta}{\pi\rho f}\right)^{1/2} \tag{5}$$

Figure 4 represents the plot of the dissolution rate of zinc in the same solution as mentioned above. The dissolution rate is kept constant against the magnetic flux density. Figure 5 exhibits the plot of the velocity against the magnetic flux density. As shown in this figure, the revolution velocity is independent of the revolution radius, only proportional to the magnetic flux density.

According to Eq. (2), at the constant i, which corresponds to the constant dissolution rate, the velocity v is in proportion to the magnetic flux density B. Equation (3) leads to the same linear dependence of v on B as Eq. (2) because the revolution radius R has a relation $R = v/\omega$ in Eq. (4). Therefore, it is concluded that the experimental result in Figure 5 indicates the validity of this theoretical prediction.

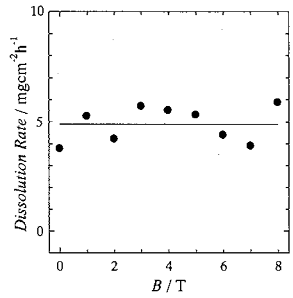

Figure 4. Zinc-dissolution rate under various magnetic flux densities. Sample is zinc sheet (99.99% in purity) with 3.5x3.5cm^2 in used area and 0.05mm in thickness. Other experimental conditions are the same as Figure 3.

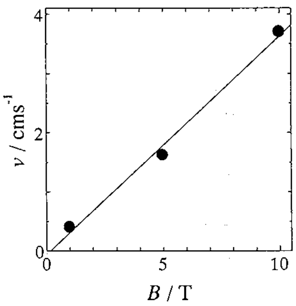

Figure 5. Velocity measurement of zinc particles with different revolution radiuses by means of intermitted exposure. Experimental conditions are the same as Figure 3.

Using the experimental data, $f = 3.5\times10^{-2}$ s^{-1} together with $\rho = 7.12\times10^3$ kgm^{-3}, and the viscosity of water $\eta = 8.93\times10^{-7}$ m^{2}s^{-1},[8] as a coagulated particles radius, r = 50.7 μm is obtained. From this value, it can be estimated that several 10 particles are coagulated.

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