1. Introduction

Surface reaction is in general classified into non-homogeneous one because it takes place at the interface between two phases at least. Corrosion reaction of metals proceeds at the interface between metal and solution when dissolution of metals at anodic sites is coupled with cathodic reaction such as oxygen reduction or hydrogen evolution. Charge transfer in vertical direction to the surface: diffusion of chemical species from/to the interface or electron transfer reaction at the interface; determines the dissolution rate. Since the reactions are not localized, that is, homogeneous in horizontal direction to the surface, the dissolution rate can be represented by current density which is defined with dissolution current per unit of surface area.

On the other hand, some surface reactions proceeds locally. In these cases, non-homogeneity in horizontal direction to the surface is important as well as one in vertical direction because fluctuation in surface properties would give differences in dynamics and kinetics of the surface reaction. For example, pitting corrosion takes place at the site where the passive film on metal is locally broken down in solution containing aggressive ions. The induction of the local breakdown changes the passive metal surface from stable homogeneous state to localized heterogeneous state and finally a pit is formed. In pitting corrosion, real dissolution rate should be calculated from dissolution current per size of each pit. This means that dissolution current and size for every pit have to be measured even if a number of pits form and/or diminish.

From the above view-points, it is necessary to investigate non-homogeneous surface reaction in horizontal direction as well as in vertical. Recently various experimental methods of detecting non-homogeneous surface reaction have been developed and applied to fields of surface science. Scanning electrochemical microscopy (SECM)\(^1\) is one of powerful tools for investigating non-homogeneous reaction at interface in solutions. The SECM probe consisting of a micro-disk electrode can detect Faradaic current near the interface. Therefore scanning probe electrode allows to address the electroactive sites and to image the distribution of electrochemical activity at the interface. Furthermore the probe electrode can be used as a local generator to induce new species electrochemically to the interface. In this paper, the results of SECM applied to corrosion field will be reviewed and discussed.

2. SECM

For detecting non-homogeneous in surface reactions, information of surface geometrical parameters is collected by scanning a “probe” above the surface. In case of SECM, the probe is a micro-disk electrode with the following features and benefits\(^2\):

1. fast attainment to a steady-state current or semi steady-state current
2. less contribution for charging current
3. high sensitivity and rapid response to measurement
4. ability of measuring chemical or electrochemical reaction rates under the steady-state
5. usability in solvents with low polarity or in solvents containing a small amount of electrolyte
6. capability of measuring electrochemical reactions of electrolyte itself
7. facility of monitoring local events of electroactive species
induction of electrochemical interaction by combination of microelectrodes

The SECM probe electrode acts as a working electrode as well as a specimen electrode in an electrochemical cell as shown in Fig. 1. Both working electrodes are connected with a bipotentiostat to control potentials, independently, and to flow current against a counter electrode. SECM probe electrode works electrochemically and flows Faradaic current above the specimen electrode surface.

In case of electrochemical reaction on a micro-disk electrode under diffusion-controlled conditions, a hemispherical diffusion layer of reactant species forms on the micro-electrode. The diffusion limiting current, \( I_{\text{limit}} \), flowing through the microelectrode, which is located in solution bulk, is expressed as follows:

\[
I_{\text{limit}} = 4nDFc^*a \tag{1}
\]

where \( n \) is the number of electrons passed per reacted atom, \( F \) is the Faraday constant, \( a \) is the radius of employed disk electrode, \( D \) and \( c^* \) are the diffusion coefficient and bulk concentration of reactant species, respectively.

Depending on potentials of both working electrodes and shapes of diffusion layer on electrodes, SECM is classified into three modes, i.e., feedback (FB), tip generation/substrate collection (TG/SC), and substrate generation/tip collection (TG/SC) modes. In FB mode, the specimen electrode is kept at an open circuit potential. The probe electrode can sense the conductivity of specimen surface by using feedback current flowed through the probe electrode. In both generation/collection modes, a couple of working electrodes are polarized. A collector electrode detects the products diffusing from a generator electrode. When the probe electrode is a generator, the field interacting between both electrodes is limited to the size of the probe electrode and the lateral resolution of SECM image is the same as one in FB mode. On the other hand, when the specimen electrode is a generator, the lateral resolution of SECM image is poor because the interacting field exceeds the size of the probe electrode can pick up. The details of the principle and theory have been discussed by Bard et al.\(^2,5–7\)

![Fig. 1. Schematic diagram of SECM apparatus.](image)

![Fig. 2. Schematic diagram of the diffusion layer at the tip of probe electrode located a) at bulk solution or close to the surface of b) insulating or c) conductive specimen electrode in FB mode, d) SG/TC mode and e) TG/SC mode.](image)
3. Non-homogeneity of Passive Films

Pitting corrosion starts when passive film is locally broken down and the repair is not sufficient. For better understanding of pitting corrosion, it is important to reveal non-homogeneity of passive film since the local breakdown would initiate preferentially at the thinnest or the most defective parts of the passive film. Several researchers have applied SECM to investigate non-homogeneity of passive film in solutions containing redox species as listed in Table 1. In all cases, the observed results depend strongly on the combination of redox species and SECM mode adapted.

3.1. Non-homogeneity of Passive Film Formed on a Polycrystalline Iron Electrode

Fushimi et al. have investigated the non-homogeneity of passive film formed on a polycrystalline iron electrode in pH 8.4 borate solution containing 0.03 mol dm$^{-3}$ K$_4$Fe(CN)$_6$ by using TG/SC mode of SECM in which a probe electrode was polarized at 1.2 V (SHE) to oxidize Fe(CN)$_6^{3-}$ while the passivated iron electrodes were polarized at 0.1 V (SHE) to reduce Fe(CN)$_6^{3-}$/H$_2$O$_2$ on passive film surfaces.$^{18,19}$ The oxidation current of Fe(CN)$_6^{3-}$/H$_2$O$_2$ flowed through the probe electrode depended on the distance between the probe and iron electrodes and the thickness of passive film as shown in Fig. 3. The relatively large probe current flowed above the thinner film surface as compared with the thicker one because the reduction of Fe(CN)$_6^{3-}$/H$_2$O$_2$ on passive film surface is influenced by thickness and semiconductive properties of the film. The probe current image obtained by scanning probe electrode with a constant distance, therefore, gave the thickness distribution of passive film on a polycrystalline iron electrode as shown in Fig. 4. Furthermore it was found that the thicker film was formed on the grain oriented to {100} as compared with the grains oriented to {110} and {111}. This means that growth rate of the film depends on the substrate grain orientation even if the iron electrode is polarized at the same potential for formation of passive film.

3.2. Non-homogeneity of Passive Film Formed on a Polycrystalline Titanium Electrode

The passive film on titanium is the most frequently investigated material by using SECM because the relatively thicker film has sufficient stabilities for SECM measurements. In solutions containing bromide ions, however, the passive film on titanium is likely broken down. Smyrl et al. have imaged the active site of passive film above which the reduction of bromide ions takes place more easily on the probe electrode by using SG/TC mode of SECM.$^{10,11,21,22}$ Basame et al. also have imaged the oxidized surface of titanium or tantalum electrode where several numbers of sites become active and then less active asynchronously.$^{12,13,16,17}$ It was assumed that these active sites of passive film were attacked by bromide ions and broken down locally. The local breakdown may proceed at the sites of the thinner or more defective film under which the substrate titanium has sufficient defects or inclusions.

On the other hand, Fushimi et al. have applied the TG/SC mode of SECM to investigate the non-homogeneity of passive film formed on a polycrystalline titanium electrode.$^{14}$ The larger probe current flowed more on the grain covered with the thinner film similar to the film formed on a polycrystalline iron. Fluctuation in probe current reflecting non-homogeneity of passive film is enhanced with increasing film formation potential as shown in Fig. 5. It was assumed from the combination with micro Raman spectroscopy that, at potentials more than 4 V (SHE), structural change of the film from amorphous to anatase takes place and induces the increase in the fluctuation. Furthermore Fushimi et al. have applied the SG/TC mode of SECM to image the distribution of oxygen evolution during anodic oxidation of a polycrystalline titanium electrode in H$_2$SO$_4$.$^{15}$ The probe electrode was employed to detect oxygen evolved from the tita-

### Table 1. SECM evaluation for heterogeneity of passive film.

| Substrate | Mediator | Electrolyte | Ref. |
|-----------|----------|-------------|-----|
| Cr        | MV$^{7+}$/MV$^{2+}$ | KCl + KBr | 8   |
| Ru(NH$_3$)$_6^{2+}$/Ru(NH$_3$)$_6^{3+}$ | KCl | 8   |
| Fe(CN)$_6^{3-}$/Fe(CN)$_6^{4-}$ | KCl | 8   |
| Ti        | Ru(NH$_3$)$_6^{2+}$/Ru(NH$_3$)$_6^{3+}$ | KCl + KBr | 9   |
| Br/Br$_2$ | KBr | 10-13 |
| Fe(CN)$_6^{3-}$/Fe(CN)$_6^{4-}$ | OH$_2$/OH | 12-15 |
| Ta        | Fe$_{12}$ | K$_4$SO$_4$ + KI | 16, 17 |
| Fe(CN)$_6^{3-}$/Fe(CN)$_6^{4-}$ | Fe$_{20}$ | 16 | 10 |
| Fe(CN)$_6^{3-}$/Fe(CN)$_6^{4-}$ | Borate + K$_4$Fe(CN)$_6$ | 18, 19 |

$^{*}$ MV: methyl viologen
nium electrode. It was found that oxygen evolution takes place preferentially on the grain with the thinner film as well as reduction of Fe(CN)$_6^{3-}$/H$_2$O$_2$ during SECM measurement of TG/SC mode in the solution containing Fe(CN)$_6^{4-}$/H$_2$O$_2$ as shown in Fig. 6. This means that electron transfer reaction through the film for reduction of Fe(CN)$_6^{3-}$/H$_2$O$_2$ or oxygen evolution depends on the thickness and semiconductive properties of the film. Figure 7(a) shows the probe current profiles when a polycrystalline titanium electrode is polarized at several potentials of $E_p$ in 0.1 mol dm$^{-3}$ H$_2$SO$_4$ solution. The marks, A, B, ..., and F in Fig. 7(a) represent the position of line scan by the probe electrode, whereas numbers, 2, 3, ..., and 10 represent $E_p$. It is clear that the changes in probe current depend on position of the line scan and anodic potential. Figure 7(b) shows the probe current at each position normalized with that at position B as a function of anodic oxidation potential. The positions are classified into the following 3 types:

1. oxygen evolution is relatively poor, independent of potential, corresponding to the area where thicker oxide films form (at positions, D and F).
2. oxygen evolution is relatively active, dependent on potential, corresponding to the area where the thinner oxide films form (at positions of A and E).
3. oxygen evolution is relatively poor at potentials less than 4.0 V, but active at 4.0 V (SHE) (at position of C).

This means that the structure changes in oxide film from amorphous to anatase at 4.0 V (SHE) contribute to the passage of current through the film.

4. In-situ Electrochemical Monitoring and Sensing

As described above, the SECM probe electrode is also effective for detecting the reaction products from specimen surface in solutions. Ferrous and ferric ions could be detected during anodic polarization of iron electrode in pH 2.3 sulfate solution. It was found that the active dissolution rate of iron depends on the substrate grain orientation. From the grain oriented to {111}, iron dissolves more actively than the grain oriented to {110} or {100}. Surface atomic density may be reflected to the difference in dissolution rate.

Furthermore, SECM was applied to detect hydrogen and to analyze the mechanism of galvanic corrosion when magnetite was in contact with carbon steel. Hydrogen evolved from magnetite could be detected during cathodic polarization of magnetite electrode. The current efficiency, 50%,
for hydrogen evolution on magnetite electrode was estimated from the comparison with the hydrogen evolution on platinum electrode. Figure 8 shows the probe current profiles of single crystal magnetite and carbon steel electrodes embedded into epoxy resin in deaerated pH 3.3 sulfate solution. The probe electrode was polarized at 0.3 V (SHE) while the carbon steel electrode was coupled or uncoupled with the magnetite electrode. Since hydrogen is oxidized to protons on the probe electrode at 0.3 V (SHE), the degree of hydrogen generation can be evaluated from the probe current. The probe current at each position corresponds to the concentration of hydrogen generated from the specimen surface. During uncoupling, the probe current is high on the carbon steel electrode as compared with that of the epoxy resin or magnetite electrode. The same current profiles were obtained after 1 ks-uncoupling. On the other hand, during coupling, the probe current profile above the magnetite surface shifts to the anodic direction with time and attains a steady state after 4 ks-coupling. The anodic shift in probe current profiles indicates that hydrogen evolves on the magnetite due to coupling. In contrast, the probe current profile above the carbon steel surface during coupling is not significantly different from that during uncoupling. The significant change in the probe current profile above the magnetite surface during coupling as compared with that above the carbon steel surface indicates that the galvanic corrosion of carbon steel is accelerated by cathodic reaction of the magnetite.

Furthermore it was found that the cathodic polarization...
The magnetite surface may result from fluctuation in chemical composition of the magnetite surface because the electrochemical activity such as reduction of Fe(CN)$_6^{3-}$ is strongly influenced by chemical composition of oxide.

5. Liquid-phase Ion Gun to Induce Local Breakdown of Passive Film on Iron

SECM can be employed not only for imaging the distribution of surface electrochemical reactivity but also for inducing a certain surface electrochemical reaction locally on the specimen. It is well known that the local breakdown of passive film on iron is induced in solutions containing chloride ions. When a silver microelectrode covered with silver chloride was employed as a probe electrode and polarized cathodically, chloride ions can be generated from the microelectrode, i.e., operated as an ion gun. The concentration of chloride ions generated from the ion gun in the narrow space between the ion gun and specimen surface with a distance of 75 μm was estimated about 1 mol dm$^{-3}$ at maximum when an ion gun with a diameter of 180 μm was polarized at −0.1 V (SHE) in pH 6.5 borate solution. The ion gun operating above the passive film on iron electrode induced the local breakdown of the film after several minutes generation of chloride ions as shown in Fig. 10. The induction period for the local breakdown depended on film thickness and aging time. Therefore the thinner passive film on grain oriented to {111} had shorter induction period for the breakdown as compared with those on the grains oriented to {111} and {100}. This may give an evidence of liquid-phase ion gun being useful to fabricate the iron electrode surface.

On the other hand, after generation of chloride ions, the ion gun microelectrode can be employed as a detector of ferric ions. From the current transients of the microelectrode, chloride ions can be generated from the ion gun in the narrow space between the microelectrode and iron electrode, the local breakdown process leading to pit growth due to local enrichment of chloride ions was discussed as follows (see Fig. 11).

1) In domain I, chloride ions are generated from the microelectrode by cathodic polarization and are enriched in the narrow space between the microelectrode and iron electrode due to spatial restriction for diffusion, whereas the iron electrode maintains complete passivity. Therefore, the electric charge, $Q_e$, consumed by the iron electrode is very small in spite of the increase in the electric charge, $Q_e$, consumed by the microelectrode.

2) In domain II, enriched chloride ions would promote dissolution of passive film as ferric ions into solution. Ferric ions once dissolved from the passive film diffuse to the microelectrode and then are reduced to ferrous ions on the microelectrode. Ferrous ions thus produced on the microelectrode diffuse to the iron electrode and are oxidized again to ferric ions on the iron electrode as far as the passive film is present on iron. This means that a positive feedback mechanism of ferric and ferrous ions via chloride ions is operative between the microelectrode and iron electrode. As passive film thins due to enrichment of chloride ions, the values of $Q_e$ and $Q_e$ increase simultaneously. The ratio of $Q_e/Q_e$ in domain II is nearly unity.

3) In domain III, a bare surface emerges on the local area of the iron electrode just below the microelectrode due to dissolution of passive film and then active dissolution as...
ferrous ion proceeds on the local bare surface. Although the dissolved ferrous ions diffuse to the microelectrode, the microelectrode polarized at $-0.1 \text{ V (SHE)}$ cannot reduce ferrous ions to metallic iron. Moreover, no ferric ions are produced on the iron surface subjected to active dissolution. Therefore, the positive feedback of ferric and ferrous ions between the microelectrode and iron electrode diminishes and finally disappears in domain III, corresponding to negligibly small cathodic current at the microelectrode. The continuous anodic current flow at the iron electrode implies the continuous growth of corrosion pit in depth after complete dissolution of passive film due to chloride ions generated from the microelectrode.

6. Conclusions

It is concluded that SECM is useful in evaluating the distribution of electrochemical reactions taking place on the electrode surface such as corrosion reaction, redox reaction on passive film and so on. In the active-dissolution, passive, and oxygen-evolution regions, the heterogeneity of probe current images could detect clearly the distribution of the respective electrochemical reaction over the specimen surface. They depended on the substrate crystallographic orientation. Particularly, on iron in the passive region, the redox reaction of Fe(CN)$_6^{3-}$/Fe(CN)$_6^{4-}$ proceeded more easily on passive film formed on the grain with high packing density than that on the grain with low packing density, which is mainly due to the difference in film thickness. Moreover, LPIG was developed as a state of art technique to investigate the local breakdown of passive film. Application of LPIG to the passive film formed on iron revealed the details of its local breakdown process.

REFERENCES

1) R. C. Engstrom, M. Weber, D. J. Wunder, R. Burgess and S. Winquist: Anal. Chem., 58 (1986), 844.
2) A. J. Bard, F.-R. F. Fan, J. Kwak and O. Lev: Anal. Chem., 61 (1989), 132.
3) K. Aoki, M. Morita, T. Horiuchi and O. Niwa: Electrochemical Methods by Using Microelectrodes I, The Institute of Electronics, Information and Communication Engineers, Tokyo, (1998), 4.
4) Y. Saito: Rev. Polarogr. Jpn., 15 (1968), 177.
5) A. J. Bard, F.-R. F. Fan, D. T. Pierce, P. R. Unwin, D. O. Wipf and F. Zhou: Science, 254 (1991), 68.
6) A. J. Bard, F.-R. F. Fan and M. V. Mirkin: Electroanalytical Chemistry, Vol. 18, ed. by A. J. Bard, Marcel Dekker, New York, (1994), 243.
7) A. J. Bard and M. V. Mirkin: Scanning Electrochemical Microscopy, Marcel Dekker, New York, (2001).
8) C. Lee and A. J. Bard: Anal. Chem., 62 (1990), 1906.
9) C. Wei and A. J. Bard: *J. Electrochem. Soc.*, **142** (1995), 2523.
10) N. Casillas, P. James and W. H. Smyrl: *J. Electrochem. Soc.*, **141** (1994), L16.
11) N. Casillas, S. Charebois, W. H. Smyrl and H. S. White: *J. Electrochem. Soc.*, **141** (1994), 636.
12) S. B. Basame and H. S. White: *J. Phys. Chem.*, **99** (1995), 16430.
13) S. B. Basame and H. S. White: *J. Phys. Chem.*, **B102** (1998), 9812.
14) K. Fushimi, T. Okawa, K. Azumi and M. Seo: *J. Electrochem. Soc.*, **147** (2000), 524.
15) K. Fushimi, T. Okawa and M. Seo: *Electrochemistry*, **68** (2000), 950.
16) S. B. Basame and H. S. White: *Langmuir*, **15** (1999), 819.
17) S. B. Basame and H. S. White: *Anal. Chem.*, **71** (1999), 3166.
18) K. Fushimi and M. Seo: Zairyo-to-Kankyo, **46** (1997), 797.
19) K. Fushimi, K. Azumi and M. Seo: *ISIJ Int.*, **39** (1999), 346.
20) K. Azumi, T. Ohtsuka, and N. Sato: *Denki Kagaku*, **53** (1985), 306.
21) P. James, N. Casillas and W. H. Smyrl: *J. Electrochem. Soc.*, **143** (1989), 3853.
22) N. Casillas, S. Charebois, W. H. Smyrl and H. S. White: *J. Electrochem. Soc.*, **140** (1993), L142.
23) K. Fushimi and M. Seo: *Electrochim. Acta*, **47** (2001), 121.
24) K. Fushimi, T. Yamamuro and M. Seo: *Corros. Sci.*, **44** (2002), 611.
25) K. Fushimi, K. Azumi and M. Seo: *J. Electrochem. Soc.*, **147** (2000), 552.
26) K. Fushimi and M. Seo: *J. Electrochem. Soc.*, **148** (2001), B450.