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REVIEW

Advances in detection of magnetic fields induced by electrochemical reactions–a review

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Abstract The paper summarizes achievements in applications of superconducting quantum interference device (SQUID) magnetometry in electrochemical activity sensing, especially in that related to remote corrosion detection. The studies deal with application of the SQUIDs operating in liquid helium or nitrogen with a spatial resolution of magnetic field detection of the order of a millimeter or greater. This made it possible to observe macroscopic magnetic fields, which originated from the large-scale surface currents (ionic and electronic), which resulted from electrochemical potential gradients on electrochemical interfaces. The gradients owed to variations in temperature, alloy composition, sample geometry, electrolyte flow characteristics (velocity, direction, and turbulence), etc. The measurements demonstrated the capability of SQUIDs to remotely sense corrosion across the integrated media consisting of gaseous and solid dielectrics, metal, and electrolyte. The results have shown the potential of magnetometry for practical corrosion detection in the restricted locations such as in ground or concrete. Despite significant efforts, the field is considered to be at an early stage from both fundamental and practical points of view.

Keywords SQUID · Magnetometry · Electrochemistry · Corrosion

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Introduction

Magnetoelectrochemistry deals with the magnetic fields induced by electrochemical reactions or vice versa, the influence of magnetic fields upon electrochemical reactions. The detection of magnetic fields induced by electron and ion transfer at conducting interfaces provides an opportunity for noninvasive and remote study of electrochemical processes. Among different areas of electrochemistry, corrosion of metals has attracted the most significant attention to magnetometric studies because of its greatest practical significance. The efforts to introduce magnetometry into corrosion science and engineering were directed to a challenging goal—development of a new technique, which would be capable of corrosion sensing noninvasively and remotely across dielectric media.

The corrosion process consists of at least two associated charge transfer reactions, i.e., metal oxidation and reduction of corrosion agent, e.g.,

$$Me \rightarrow Me^{z+} + ze^- \tag{1}$$

$$O_2 + 4e^- + 2\,H_2O \rightarrow 4\,OH^- \tag{2}$$

The reactions usually take place on highly inhomogeneous surfaces and the transfer of electrons and ions occurs through a system of charged interfaces with different types of conductivity: electronic (metal), semiconductor (corrosion product structures), and ionic (solution containing dissolved oxidizer/s and corrosion products). The surface inhomogeneity on an atomic scale is caused by crystallographic formations such as ad-atoms, kink sites, steps, dislocations, crystal imperfections, distortions, etc. On a larger scale, the inhomogeneity is caused by corrosion inhibitors, corrosion pits, crevices, cracks, incorporated inorganic particles (composites), delaminating of protective coatings, etc. Owing to the inhomogeneity, reactions 1 and 2 are spatially separated. It means that the electrons produced by reaction 1 flow from the metal ionization site to the oxygen reduction site and the separation degree of these sites depends upon the numerous factors mentioned above. An ionic current owes to OH^- surface and subsequent bulk diffusion and migration (the current is terminated when OH^- is recombines with Me^{z+}). The detection of associated magnetic fields of both currents provides an opportunity for remote sensing of electrochemical activity.

SQUID magnetometers and instrumentation

The currents generated by corrosion reactions are rather low (usually of the order of microamperes per square centimeters, μA cm^{-2}) and only a fraction of them is expected to be detectable by magnetometry. Therefore, for corrosion investigations, highly sensitive magnetometers have to be applied. Most researchers have utilized superconducting quantum interference device (SQUID) magnetometers—the most sensitive sensors of magnetic fields. There are numerous other techniques for sample magnetic field imaging: for instance, magnetic force microscopy, scanning electron microscopy with polarization analysis, scanning Hall bar microscopy, scanning magnetoresistive microscopy, electron holography, inductive pickups using a video head, decoration techniques, and fluxgate magnetometers. The advantages and disadvantages of various techniques in comparison with SQUIDs are summarized in a review [1].

SQUID magnetometers have been introduced in the 1970s and, since then, they were used in a wide variety of applications to measure weak magnetic fields. Single-channel SQUIDs were initially used to study macroscopic magnetic fields. Multi-channel systems comprising of 64–250 SQUIDs were optimized for measurements of macroscopic magnetic fields generated by an electrical activity in human brain [1, 2]. Magnetic imaging systems with a raster scan of the sample have been also widely used. The scanning SQUIDs have been successfully applied to study magnetism in a variety of scientific fields; especially promising researches were conducted in biology, biomedicine, and materials science. The history, instrumentation, and criteria for the successful applications of SQUIDs (especially in biomagnetism, clinical applications, and nondestructive evaluation) are surveyed in [3–8].

The main physical phenomena explored in SQUIDs are the superconductivity, Josephson effect, and flux quantization. In 1962, Josephson predicted that a super-current exists between two superconductors separated by a thin insulating barrier (only a few atoms) at no voltage conditions owing to quantum mechanical tunneling effects [9]. This super-current is proportional to the sine of the quantum mechanical phase difference between the two superconductors. The current flow through Josephson junction is unresistive up to a certain value, which is called the critical current. When exceeding this value, the current becomes resistive with a voltage drop between the two superconductors. The flux quantization means that the magnetic flux through a superconducting ring multiples the flux quantum, which equals to $h/2e=2.07\times10^{-15}$ T m^2. This extremely low value makes the SQUIDs capable of sensing extremely weak magnetic fields.

There are two possibilities for SQUIDs making: a superconducting ring with one Josephson junction for rf SQUID and that with two junctions for dc SQUIDs. The dc SQUIDs operate at a current slightly greater than the critical current and the voltage drop is dependent on the external magnetic field. A special electronic part amplifies this field-dependent voltage to a user-convenient value. In rf mode, SQUID is coupled to a parallel resonant circuit, consisting of an inductor coil and a capacitor in parallel. An alternating current of high frequency is introduced in the SQUID ring through the coil, which periodically switches Josephson junction from the superconductive to the resistive state. In the latter case, the junction consumes energy which leads to a decrease in voltage across the resonant circuit, which can be measured. The degree of damping depends on the external magnetic field.

The SQUIDs are most sensitive technique for magnetic fields imaging. The field sensitivity increases with the pickup area and is typically characterized by the SQUID flux noise divided by the effective pickup area. The typical resolution of SQUIDs is of the order of several femto-Tesla (fT/$Hz^{1/2}$) for 1 cm^2.

From an instrumental point of view, the main difficulty in SQUID application in corrosion studies is a relatively modest spatial resolution (roughly 1 mm or greater), which is not sufficient to study the magnetic activity of a single corrosion pit (the size of which could be of the order of micrometers or even less). On a macroscopic scale, however, the corroding surface could be magnetically silent due to statistically distributed corrosion pits and randomly oriented surface currents. The SQUID microscope with an improved spatial resolution, which was originally developed to measure biomagnetic and paleomagnetic fields, suggests some progress in the field [10]. The authors used submillimeter pickup coils wound with a low-temperature superconducting niobium wire coupled to the input circuit of a SQUID. It should be mentioned that an improvement of spatial resolution is achieved at the expense of field sensitivity: the authors achieved a spatial resolution of 250 μm with a magnetic field sensitivity of 850 fT/$Hz^{-1/2}$

and a spatial resolution of 500 μm with 330 fT/$Hz^{-1/2}$ sensitivity.

An achievement of improved spatial resolution was also reported recently by other authors [11]. They used a needle with high magnetic permeability as a probe and attained the micron-level spatial resolution (the achieved field sensitivity of the equipment was not reported by the authors).

Another limitation of SQUID application to corrosion sensing lies in the necessity of excluding natural or man-made magnetic noise, i.e., performing the measurements in a specially shielded environment. To overcome this problem, SQUID gradiometers are often used, although attempts have recently been undertaken to apply the fluxgate gradiometer with two magnetic sensors (Wrobel et al. at http://www.elektroctechnik.hs-magdeburg.de).

Basic corrosion studies by SQUID magnetometry

The first attempts to apply SQUIDs for detection of magnetic fields generated by metals exposed to electrolyte were reported by Bellingham et al. in 1986 and 1987 [12, 13]. The authors studied two metal surfaces coupled by a metal conductor and immersed into electrolyte. The potential difference between two electrodes caused an ionic current flow in the solution phase and an electronic one in the connecting metal. The large-scale magnetic fields associated with these currents were detected by a SQUID magnetometer. Other early SQUID applications in electrochemistry deals with electrodeposition of zinc simulating recharging of Zn/Ni and Zn/Ag batteries [14] and the use of SQUID as a highly sensitive ammeter to perform electroanalytical measurements by cyclic voltammetry [15]. The investigation showed nearly identical results of current registration by the SQUID to those obtained by conventional electrochemical measurements.

It should be noted that the subjects in the early studies defined as corrosion ones, in principle, were a kind of battery with a cathode and an anode. Such systems simulated to a certain extent practically important galvanic corrosion. Much later, the fields induced by the galvanic couples (Zn/Cu and Zn/Au) have drawn attention again [16, 17]. The Zn/Au couple was successfully applied to discriminate between the electronic and ionic currents, which will be discussed in more detail below.

In 1992, Hibbs reported an exhaustive study on Zn corrosion in hydrochloric acid using the first SQUID magnetometer specifically designed for corrosion studies [18, 19]. The magnetometer had a spatial resolution of the order of 1 mm and the magnetic field sensitivity was according to the noise characteristics 2–5 pT $Hz^{-1/2}$. The design of the system allowed rotation of the dewar about its axis, thereby changing the coil axis from vertical to horizontal. This made it possible to orient the corroding sample vertically and so to avoid undesirable gas bubble accumulation on the surface. The electrodes were prepared from a Zn bar with two surfaces exposed to solution, i.e., the electrochemical system was analogous to that used by Bellingham et al. [12, 13]. Hibbs also performed experiments with four exposed surfaces and one 'long electrode'.

The measurement protocols in [18] included spatial and temporal types of SQUID measurement. The spatial type consisted of two-dimensional scans at 1–2 min intervals over a period of 1–2 h. In the temporal type, the corrosion cell was positioned in front of the pickup coils and continuous field measurements were performed on four SQUID channels. It should be mentioned that the measurements were performed in an unshielded laboratory environment, i.e., natural or man-made magnetic noises were not excluded from the data, if any. The two-electrode configuration determined two types of current: intraelectrode (which is typically called the corrosion current) and interelectrode, which flow between the two electrodes owing to differences in their corrosion potentials. The corrosion currents derived from magnetic data were compared with those calculated from the mass loss. There was a large discrepancy between the currents obtained by the two methods, which indicated that in the used experimental design the majority of corrosion currents (more than 99%) was not detectable by the SQUID (similar conclusions were also drawn later by other authors, which will be referred to below). The study also showed small-scale temporal variations of magnetic field (fluctuations), the frequency of which increased steadily throughout the experiment. The evolution of hydrogen bubbles during zinc corrosion was considered as a cause of these fluctuations, though no clear evidence by experiments without gas evolution was provided. The main conclusion that was drawn by Hibbs was that the imaged magnetic fields owed to the currents generated by a two-sample system, while it was not possible to directly image the corrosion currents, which flowed within one single electrode surface.

The early studies [12, 13] had dealt with zinc in acids, which represents a more or less uniform type of corrosion attack. The Vanderbilt group leaded by Wikswo has launched the SQUID studies of aluminum alloys, the corrosion on which takes place locally according to so-called pitting mechanism [20–22]. They studied 2024-T3 and 7075-T6 alloys in a 3.5% NaCl solution supplemented with 50 ppm Cu(II) as a pitting agent. Another distinctive difference is that the corrosion products of aluminum in neutral media show retention on the surface (as Al_2O_3, for instance) while the majority of Zn(II) ions in acid solutions are emitted into the solution. This should be taken into account when analyzing generation of ionic currents. The studies produced maps of the magnetic field over corroding aluminum alloy plates, which was shown to be dependent upon the immersion time, chloride concentration, distance between the SQUID detector and the sample, and sample thickness. However, the electrochemical processes from which the magnetic fields stem remain unclear. The studied subject represents a rather complicated electrochemical system. Copper is reduced on the aluminum surface in the solution and the developed copper formations act as a system of microcathodes, on which reduction of water (oxygen) is accelerated. (A study of Al and Al–Mg alloys corrosion in 3.5 NaCl + 50 ppm Cu(II) performed by atomic force microscopy and quartz crystal microgravimetry is reported in [23, 24].) The copper-free surface should act as an anode, where in certain preferential places aluminum undergoes a change from the ground state to ionized species, the majority of which are attached to the surface as insoluble compounds. Of course, identification of electronic and ionic current paths in the system requires careful examination of the surface state, the properties of the interphase layer, and the localization of electrochemical reactions.

Pitting corrosion of aluminum alloys was studied by magnetometry in highly aggressive media such as the exfoliation test solution containing peroxide and 2 M KOH [25]. The authors used two magnetometers: SQUID and nuclear magnetic resonance. They performed the measurements in a non-magnetic room applying a single sample scan at the distance of 15 mm from the bottom of cryostat. The detected magnetic signal was ascribed to corrosion because it was not detected in distilled water. The authors claimed that the magnetic signal in case of generalized corrosion in a 2-M KOH solution was stronger than that in the case of the pitting corrosion and, thus, a SQUID magnetometer reflects the susceptibility of alloys to various types of corrosion. However, consideration should be given to the fact that the processes in both solutions are quite different from the viewpoint of magnetometric detection (for instance, aluminum in a KOH solution produces soluble $Al(OH)_4^-$, which may induce ionic currents in the solution phase).

Abedi used appropriate techniques and associated models to quantify the aluminum alloy corrosion rate through measurements of associated magnetic fields [26]. He defined quantitative magnetic parameters in conjunction with mass loss measurements and concluded that spatial and temporal information on corrosion magnetic fields correlates with that of corrosion currents.

Juzeliunas et al. expanded the field to magnetic materials such as Ni–Cr–Mo and Co–Cr–Mo alloys [27, 28]. First, the samples were coarsely demagnetized in a special inductance coil by gradually increasing the ac magnetic field to 20 mT and returning to zero. This was repeated three times for each *x*, *y*, and *z* sample orientation. Then, the samples were fastened upon the SQUID adapter in an electrochemical cell inside the magnetic shield. The final remnant of magnetization was eliminated when the shield was closed by cycling in the range 0 to 0.2 mT.

The authors focused on performing experiments under strict control of corrosion process [27, 28]. They ascertained initially by electrochemical means that corrosion of the studied alloys is caused mainly by oxygen reduction. This process was well suited for SQUID studies because it does not complicate the process by gas evolution (compare extensive hydrogen evolution in [18]). First, inert conditions have been achieved in the electrochemical cell by its deoxygenation by nitrogen. The solution (or water) to be applied was also deoxygenated in a separate vessel by nitrogen bubbling. Then, the solution was transferred into the shielded cell via an inlet tube under nitrogen pressure. Afterwards, water was drained off so that a hemispherical solution layer remained on the specimen surface and corrosion was initiated by diluting of the nitrogen by oxygen gas. The SQUID responded systematically to atmosphere oxygenating–deoxygenating which indicated registration of the fields associated with corrosion. However, the quantitative correlation between the corrosion rate and magnetic fields as well as current distribution on the sample remained unclear.

First, thermo-induced magnetic fields at electrochemical interfaces were reported in [27–29]. The authors used a HTC SQUID magnetometry to detect magnetic fields induced by a contact of solution and metal of different temperatures. They observed that magnetic fields were generated both normal and parallel to the interface when liquid contacted the metal, provided that both of the phases were at different temperatures. The appearance of magnetic field did not depend upon the metal or the liquid chemical nature. The generation of magnetic fields was ascribed to thermo currents inside the metal or the electrochemical currents thermally initiated between interfaces metal/air and metal/liquid. These results are of importance in SQUID studies where thermal equilibrium within the sample could be distorted, for instance, at elevated temperatures or when exothermic reactions occur. Some cooling by SQUID dewar could contribute to the fields induced by corrosion. Such possibility was pointed by Hibbs [18]. The author did not believe that in his experiments the thermal gradients higher than 1 K were externally imposed by dewar onto the measurement area. However, it remains unclear how significant the gradients were within the solid metal bar, whose small projections contacted the electrolyte at elevated temperatures. The thermo-effects could be of importance also when discussing the appearance of the magnetic fields immediately after solution introduction to the metal, which were ascribed to corrosion [30]. It is also interesting to note here that SQUIDs have been also applied to study high temperature gradients or the so-called chemomagnetism [31]. The studied magnetic fields were generated by chemoionization processes during combustion and propagation of a high-temperature front.

Magnetic fields resulting from corrosion of an asymmetric U-shaped AA 2024 sample were studied in various solutions [32]. Macroscopic electronic current flow along the sample was indicated by distinctive magnetic field images with a spatial resolution of the order of 1 mm. It was concluded that the macroscopic current originated from the corrosion potential gradient within the sample due to its asymmetric geometry; this current was negligible on an equipotential (symmetric) sample. The asymmetric sample was magnetically sensitive to corrosion: a higher corrosion rate with increased oxygen concentration resulted in a higher magnetic activity. By contrast, the sample of analogous shape but cut in single sections did not produce a magnetic field that reflected increases in corrosion rate, and the magnetic activity of this sample was much less as compared to that of its monolithic counterpart. These data indicated that uniformly corroding surface (it means one with statistically distributed corrosion pits) could be magnetically silent on a macroscopic scale, if no special measures are undertaken to induce non-equipotential zones on the surface.

In the sample geometry used in [32], the electronic currents in the aluminum alloy produced a magnetic field that was oppositely directed to that from the ionic currents flowing in the larger volume of the electrolyte bath. This contributed to reduction in strength of the observed magnetic field as compared to that produced by the electronic currents alone. The fact that the electronic and ionic currents flow in differently shaped volumes that are at different distances from the SQUID prevents the complete cancellation of the electronic magnetic field by the ionic one.

The phenomena of magnetic field cancellation by electronic currents in metal and ionic currents in solution were studied by Yashiro et al. [17]. The authors studied the magnetic fields resulting from a Zn/Au galvanic couple. An artificial obstacle was set in a solution to modify the ion path. A comparison of the magnetic effects caused by galvanic currents with those resulting from external dc-currents allowed for drawing the conclusion that electronic and ionic currents, which are the same in magnitude but opposite in direction, may cancel the magnetic fields induced by corrosion reactions.

The SQUID magnetometer was demonstrated to be capable of remote sensing of corrosion under hydrodynamic conditions across the multiphase system 'air–plastic–metal/solution' [33–35]. The sample in these studies comprised a variety of single sections of different size and geometry separated by 1-mm insulating gaps as shown in Fig. 1. Analogously to [32], it has been demonstrated that, under no flow conditions, no fields associated with aluminum corrosion appear. The system exhibited in quiet solution a relatively low magnetic activity and the patterns did not indicate any distinctive magnetic field distribution, which could be associated with the configuration of the single sections, entire system or electrolyte channels (which were of the same U-shaped geometry as the sample system). It is also important that a substantial increase in solution corrosivity by its oxygenation did not lead to a magnetic response. Thus, the data showed that pitting corrosion on a macroscopic scale (millimeter or greater) is magnetically silent. It seems, therefore, that reports in the literature on detection of magnetic activity of pitting corrosion should be taken with some precaution.

Clear magnetic anomalies under solution flow are demonstrated in Fig. 1. The activity zones are localized around the corners where solution turbulence was possible. The hydrodynamic induction of magnetic fields was owing to the corrosion potential gradients, which in turn are due to the differences in transport conditions of the oxidizing agents and corrosion products. It is important that the intrinsic magnetic activity of the electrolyte flow was significantly less than that of the corroding sample [34]. Three field components (x, y, and z) determined under solution flow are demonstrated in Fig. 2.

The experiments were also performed under flow conditions, in which differentiation between the electronic and electronic–ionic currents was possible [35]. It has been shown that magnetic field generation by electronic–ionic current prevailed when compared to electronic current alone.

Magnetometric studies of the subjects of technological significance

Murphy et al. reported in 1988 about utilizing of SQUID magnetometry to evaluate large-scale subjects—buried metallic structures [36]. The study was published very soon after the first report in 1986 on SQUIDs application to the electrochemical cell [12]. The SQUID magnetometer was used in [36] as a remote current detector in conjunction with electrochemical impedance spectroscopy. The technique was termed as magnetically detected electrochemical impedance spectroscopy. This study laid foundations for further investigations in the field of practical evaluation of large structures with spatially varying corrosion rates.

Weinstock summarized in 1991 the early works in application of SQUID magnetometry for non-destructive evaluation (NDE) of electrically conducting and ferromagnetic structures [37]. The ability of SQUIDs to detect corrosion currents, defects in a buried pipe, and fatigue of

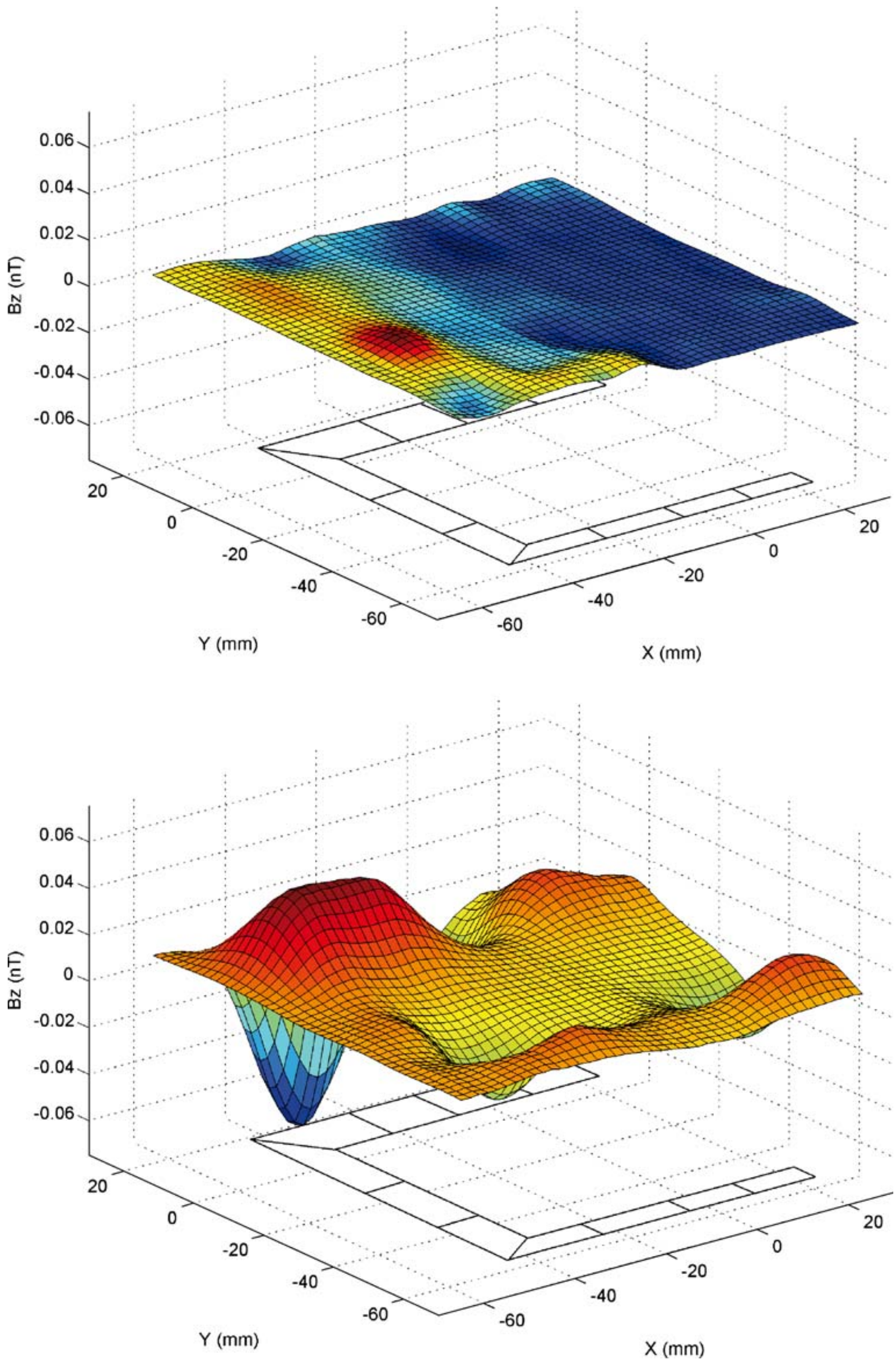

Fig. 1 Magnetic field image (B_z) obtained for U-shaped AA 2024 sample cut in 11 sections of different size and geometry in naturally aerated 3.5% NaCl solution under no-flow conditions (*upper figure*) and under electrolyte flow at 8 ml s^{-1} (*figure below*). The solution flow channel is of the same U-shaped geometry as the sample system but only by 1–2 mm wider to place the sample inside. Spatially integrated activity is SIMA=28 nT mm^2 in quiet solution and SIMA=129 nT mm^2 under solution flow. Adapted from [37]

steel was reviewed. The use of SQUIDs for NDE, in principle, was determined by the author as a form of detection of magnetic anomaly, which is associated with ferromagnetism or an electric current. The latter one may originate from corrosion, induction of eddy currents, and induction of specific magnetic environment to detect some kind of defect.

The electrochemical activity within components from actual aircraft has also been monitored by LTS and HTS SQUIDs [30, 38]. Richter and Knecht used HTS SQUID to study the magnetometric behavior of AA 2024 alloy, which underwent long-term corrosion during aircraft exploitation. They observed some magnetic activity immediately after application of water or a sodium

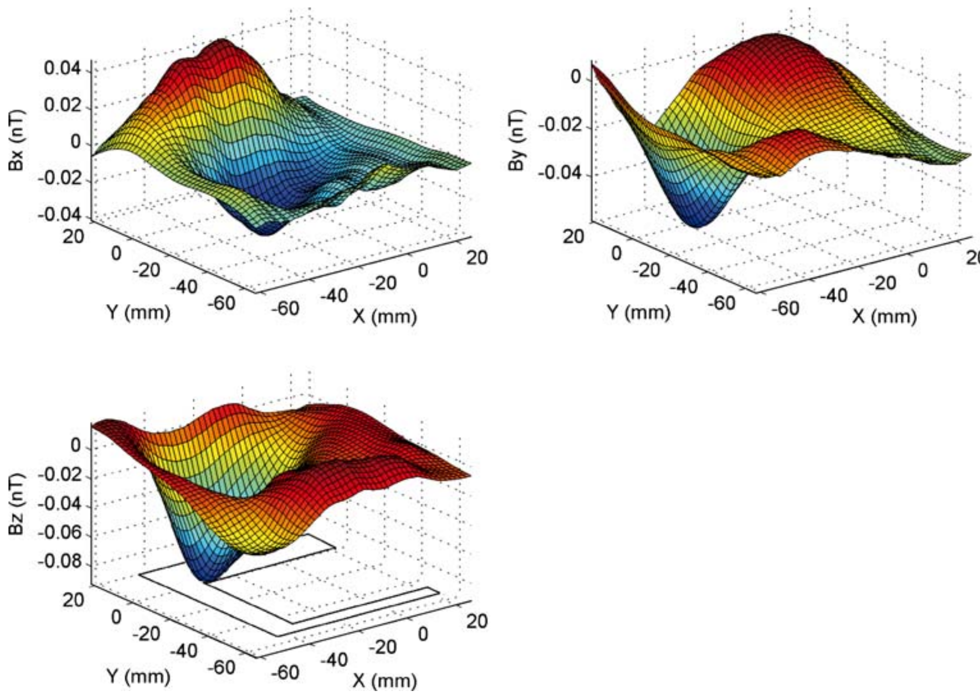

Fig. 2 Magnetic field images (B_x, B_y, and B_z) obtained for a monolithic U-shaped AA 2024 sample in naturally aerated 3.5% NaCl solution at a net flow velocity of 7 ml s^{-1}. The scanning data obtained under no-flow conditions were subtracted from those obtained under flow conditions. SIMA=166 nT mm^2. Adapted from [37]

chloride solution over a surface of 3 cm^2. The activity gradually decreased to negligible values and no significant differences were observed between the signals in water and NaCl solution. (Note that in [25] an opposite effect was reported—no magnetic activity in water.) The results may be discussed from the viewpoint whether the fields in fact arise from corrosion. The contribution of some artefacts such as dissolution of corrosion products or/and thermal distortions by solution addition may be considered (the thermal effects at solution/metal interfaces were discussed above [27–29].

Vanderbilt group and its leader Wikswo demonstrated the ability of SQUID magnetometers to monitor electrochemical activity within lap joints removed from ageing KC-135 aircraft [38]. The comprehensive measurement protocol included the following steps: (1) dry scan images to obtain a background magnetic field image; (2) introduction of solution to the sample and measurement of the spatially integrated magnetic activity (SIMA), which is a number proportional to the net magnetic activity of the sample as recorded during the scans of one image; (3) obtaining of temporally summed SIMA (TSSIMA), which is expected to be proportional to the total mass loss during the entire experiment; and (4) determining temporally summed magnetic activity at each pixel to define the cumulative activity of that pixel throughout the experiment. A clear increase in TSSIMA when the corrosivity of environment increases in the sequence humid air, distilled water, and 0.01 M Cl^- has been determined. However, there was no significant difference between the activity in 0.01 and 0.1 M Cl^-. This shows that the measurements were not capable of making quantitative assessment of corrosion rates.

Monitoring of the corrosion activity and moisture inside aircraft lap joints was performed in [39]. Water ingress and egress were determined in lap joint by embedded fiber optics moisture sensors while corrosion activity was determined using SQUID magnetometry. The efficacy of this innovative approach was demonstrated, for example, by showing that wetting with a saline solution caused a rapid increase in corrosion activity in comparison to that under ambient conditions.

SQUID studies recently addressed composite materials, such as carbon-fiber-reinforced polymer (CFRP) which, due to high strength to weight ratio and resistance to corrosion, is increasingly favored in the aircraft industry [40]. The authors used HTS SQUID single-layer gradiometers to study the artificial defects in CFRP. The increasing interest in such research is expected because of the rapid expansion of application of composite materials in different technical fields.

SQUID studies of corrosion of steel structures have been also reported [41, 42]. A three-dimensional finite element model was developed to simulate small-diameter steel pipes due to pitting corrosion [40]. It has been shown that the signal visualization abilities of planar gradiometers were much higher when compared with a typical axial gradiometer. An attempt to identify corrosion of steel in concrete by SQUID magnetometry has been reported recently in [42]. To identify the corrosion area, an external current was imposed to the steel structure with artificially made corrosion damage supposing that the current distribution in the corroded and noncorroded areas will be different.

Identification of corrosion damage in ground and concrete by creation of special magnetic environment around the corroded area by an external current seems to be a promising way to develop practical systems of corrosion diagnostics. Base on this method, first commercial SQUID instruments of corrosion diagnostic in grounds have been piloted. As a concluding remark, it is noteworthy that, so far, there is no well-established SQUID technique for practical characterization of corrosion defects. This goal remains challenging for future investigations.

Conclusions

Despite significant efforts to introduce SQUID magnetometry to corrosion science and engineering, the field remains at an early stage from both fundamental and practical points of view. There are very few studies aimed at demonstrating a relationship between the corrosion rate (j_{corr}) and the corresponding magnetic activity (B) and no quantitative expressions between these parameters are known. So far, there is not a well-established magnetometric technique for practical characterization of corrosion defects.

The studies revealed that only some fraction of corrosion currents could be detected by SQUIDs, while the majority of the corrosion process is magnetically silent due to random orientation of surface currents and cancellation of the fields owing to the opposite electronic and ionic current flow. Relatively modest spatial resolution of conventional SQUIDs do not yet allow taking a look at the micromagnetic world of corrosion phenomena: single pits, defects, etc. However, SQUID magnetometry was qualitatively proven to be capable of detection of corrosion remotely across different conducting and non-conducting phases. This result shows the method to be of undoubted virtue and supposes further investigations.

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