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SUCHATO, N, SHARPLES, S and KALASHNIKOV, A.N.
<<http://orcid.org/0000-0003-1431-3836>>

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Design and Experimental Evaluation of a Test Rig for Ultrasonic Monitoring of Accelerated Corrosion

Nutthawut Suchato* and Steve Sharples

Department of Electrical and Electronic Engineering
University of Nottingham
Nottingham, England
Email: eexns26@nottingham.ac.uk*

Alexander Kalashnikov

Department of Engineering and Maths
Sheffield Hallam University
Sheffield, England

Abstract—The design of a test rig for ultrasonic monitoring of corroding steel samples and results of its experimental evaluation are presented. In order to accelerate and quantify corrosion, the monitored sample acts as an anode in a typical constant current electroplating setup. An Arduino-powered microcontroller is used to log the relevant voltage and current values on an SD card, and a high accuracy ultrasonic waveform acquisition instrument is employed to record the ultrasonic waveforms reflected from the corroding surface. Experimental assessment of the designed rig confirmed that it met the design objectives and could be used for experimental studies of accelerated corrosion in steel samples.

Keywords— *constant current electroplating; accelerated corrosion; ultrasonic monitoring; non-destructive ultrasonic evaluation*

I. INTRODUCTION

The need for in-service continuous corrosion monitoring is especially acute for sea vessels because the state of the hull determines the out-of-service maintenance time and costs. Unfortunately, many corroding surfaces are difficult to access from outside the vessel and/or generally inconvenient for human inspection. Automated ultrasonic non-destructive evaluation (NDE), conducted in the pulse-echo mode from inside the vessel, can potentially be used for sea vessel corrosion monitoring, provided that the cost of instrumentation and transducers is low enough for their permanent installation *in situ*, and the recorded echo waveforms can be interpreted to determine corrosion penetration.

Both the above mentioned conditions require extensive knowledge of the reflection of a finite ultrasonic beam, emitted at a close proximity, from a highly uneven (and to a significant extent random) corroded surface. We believe such knowledge cannot be gathered purely from simulations; therefore, experimental waveforms must be acquired from real samples, albeit any experimental datasets will have limitations.

The experimental test rig to monitor the corrosion of steel samples must be designed to ensure continuous recording of the echo waveforms with high accuracy and to accelerate corrosion, because natural corrosion is too slow to collect reliable and comprehensive datasets within a reasonably short timeframe. The first requirement was met by using a high accuracy waveform acquisition instrument to record the echo

waveforms [1]. The second requirement was addressed by using the corroding sample as an anode of a constant current electroplating setup.

II. DESIGN AND CONSTRUCTION OF THE EXPERIMENTAL SETUP

A. Electrodeposition and its Utilization for Accelerating Corrosion

Electrodeposition, also called electroplating, is a well-known, well-understood, and industrially-proven electrochemical process. It is frequently used to deposit a protective layer on metallic surfaces to prevent corrosion. Electroplating is accomplished by connecting an electrode, made of the metal that is to be deposited onto the surface of the part of the material that is to be protected, to the positive terminal of a power supply (anode). The negative terminal is connected to the protected part (cathode). Both the electrode and the protected part are placed inside a vessel with an electrolyte, which is used as the medium through which the particles that are dissolved from the anode reach the cathode [2].

Although corrosion leads to a considerable loss of metallic material in structures over time, its natural rate is rather slow, in the order of tens of microns per year. This rate makes it difficult to conduct extensive experimental studies within short timeframes, making some acceleration of the process under investigation highly desirable. We used reversed electroplating for this purpose. Both the cathode and anode were made from the same carbon steel (iron rods), and the electrochemical bath was filled with an aqueous solution of ferric chloride (FeCl_3), which contained iron ions. Electric current, which flowed through the solution, forced the dissolution of the anode causing it to corrode. An advantage of this way of accelerating corrosion, compared to, for example, adding acid to the solution where the corroding sample is located, was the simplicity of controlling and logging the major process parameter (electric current).

If a constant electric current, I , is applied to an electrochemical bath, the weight loss rate of the anode metal is also constant. According to the Faraday's law, the theoretical weight of the product of electrolysis, W_t , can be found as [3,4]:

$$W_t = M \times I \times T / (z \times F), \quad (1)$$

where T is the time duration of electroplating, $M = 55.845$ g/mol is the molar weight of Fe, z is the change in the oxidation state, and $F = 96,487$ C/mol is the Faraday's constant. This equation does not account for limited current efficiency, which reduces the weight loss that is observed experimentally, because some of the current causes dissociation of some of the water molecules [3,4].

If no special measures are taken, the electroplating current, caused by a fixed voltage power supply, would fluctuate during the process. This would cause uneven mass loss, resulting in complications related to the loss of the recorded ultrasonic waveforms. If the electroplating current is kept constant, one would expect a constant rate of weight loss throughout the experiment as quantified by (1). Because the corroding samples were weighted before and after the process, the expected constant corrosion rate was found by dividing the measured weight loss by the duration of the process. The schematic diagram for the constant current electroplating setup is presented in Fig. 1.

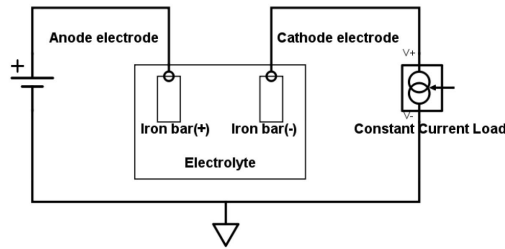


Fig. 1. Schematic diagram for the electroplating bath with the constant current load.

B. Construction of the Electrochemical Bath

Several laboratory power supplies were used to power the experimental setup, but none of them were found capable of supplying a sufficiently high current at very low voltages between the electrodes. Thus, an additional DC/DC buck converter was used at the output of a laboratory (12-17V, 1A) power supply. The constant current load (Re: load) [5] could be adjusted to operate at any current in the range of 0...3 A, which we found was sufficient for accelerating corrosion, producing well-measurable weight loss over the course of the experiments lasting approximately one hour without notable dissociation of water.

The photograph of the assembled experimental setup is presented in Fig. 2. Re: load provided a voltage output where each milliamp of current was converted to a millivolt in order to easily monitor and set the operating current. As shown in Fig. 2, an instrument was connected to this output, and the current of 1.461 A was read at the time of taking the photograph.

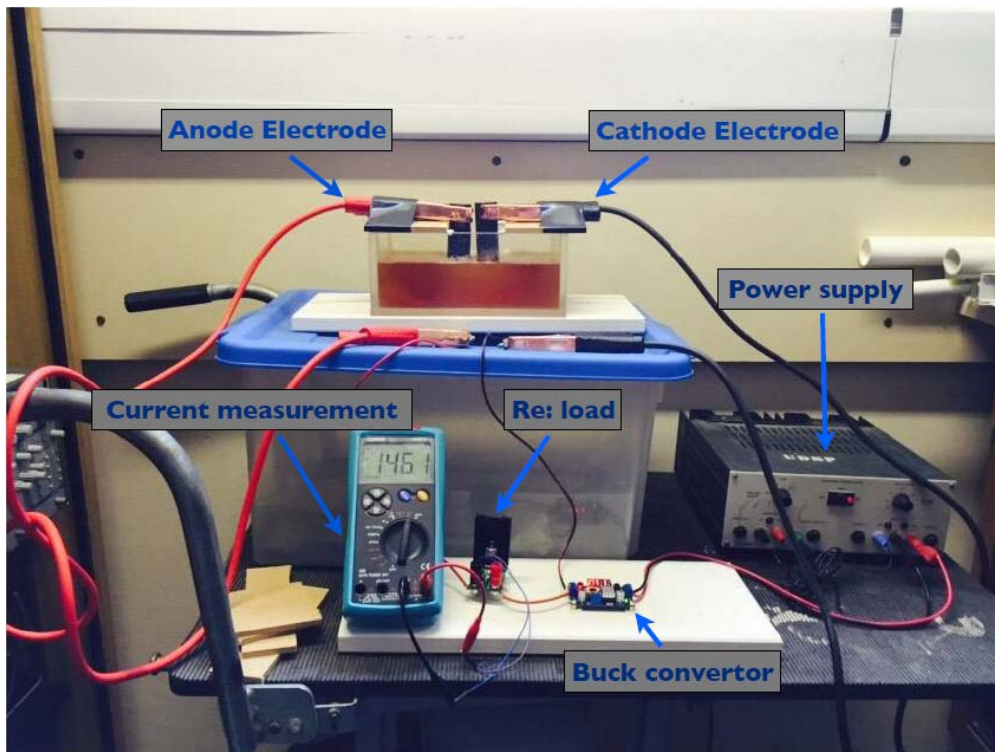


Fig. 2. Photograph of the assembled electrochemical bath.

C. Acquiring and Storing Real Time Electroplating Process Parameters

Because the corroding sample's weight cannot be measured during the course of an experiment, relating periodically acquired ultrasonic echo waveforms to particular weight losses requires confidence in the consistency of the electrochemical bath operation. We decided to verify this consistency by monitoring and storing the operating parameters in real time using a suitable microcontroller and an SD card.

An Arduino Nano microcontroller board was selected to record the voltages at both the anode and cathode, and the electric current flowing through these in the electroplating bath. The measured data were logged to an SD card for further retrieval. Potential dividers were used to protect the

microcontroller board's ADC inputs from the maximum power supply voltage, if they were accidentally applied to any of the electrodes. Because the constant current load was powered from the same external +5V power supply as the Arduino Nano, its output voltage was directly connected to an ADC input. Finally, a voltage reference source, TL431A [6], was added to the setup in order to reduce the dependence of the recorded ADC values on room temperature and the power supply voltage's fluctuations. The connection diagram of the complete setup and the photograph of the assembled monitoring board are presented in Fig. 3.

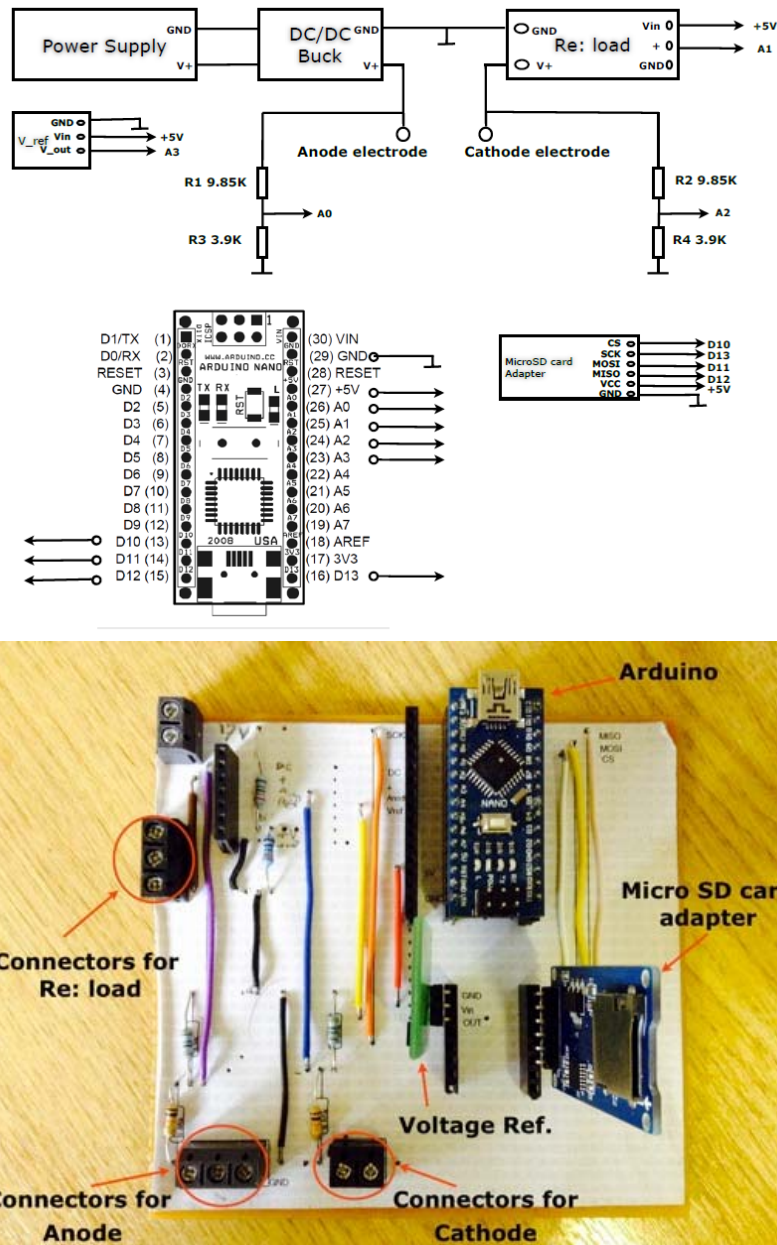


Fig. 3. Connection diagram and photograph of the monitoring board assembled.

D. Recording Ultrasonic Waveforms Reflected from the Corroding Surface

In order to record the ultrasonic waveforms reflected from the corroding surface, *in situ*, an ultrasonic transducer must be securely attached and appropriately acoustically coupled to the other end of the corroding sample. This was achieved by using Design Spark Mechanical software [7] to design two aligned and joined together custom flanges. With the addition of standard mechanical fasteners, these flanges then comprised the transducer holder. The design of the flanges and the photograph of the assembled holder, attached to a sample, with the ultrasonic transducer connected to the recording instrument, is presented in Fig.4. After experimenting with several ultrasonic transducers, we decided that the one with a 5 MHz center frequency and a sensing area with a diameter of 13 mm was the most suitable of the available set. Lower frequency transducers provided a better signal-to-noise ratio (SNR) for the recorded waveforms, but insufficient temporal/spatial localization of the pulse. Although the waveforms, recorded with higher frequency transducers, provided superior temporal/spatial resolution, the SNR was low because of the high propagation losses of ultrasound in the sample of the selected length, even after averaging for a substantial number of waveforms.

Ultrasonic echoes from the corroded surface were recorded using a high accuracy ultrasonic data acquisition system [1].

This system combined on-the-fly averaging with accurate interleaved sampling, thereby allowing controllable increases in the SNR and equivalent sampling frequency of the waveforms at the expense of the increased measurement time. Although this time increase can become prohibitive for some fast processes [8], it could easily be selected low enough not to introduce artifacts into the recorded echo waveforms. We set the equivalent sampling frequency to 300 MHz and the number of averages to 512, with 1 kHz pulse repetition frequency. Under these parameters, it took 1.536 s to acquire a single echo waveform which we considered tolerable for corrosion monitoring. The ultrasonic echoes were recorded every two seconds during the course of the experiment. The amplitude of the excitation pulse, applied to the transducer, and the gain of the receiver amplifier, were set at 60 V and 40 dB, respectively.

E. Preparation of the Corroding Samnples

It was necessary to ensure that corrosion only occurred on the surface that reflects ultrasonic waves in order to correlate the recorded ultrasonic echoes to the experimental weight loss. In particular, any side surfaces of the corroding samples needed to be protected from corrosion. This was achieved by covering the side surface of the corroding samples with PCB lacquer and by also using heat shrink tubes to protect the submerged part of the corroding sample, as shown in Fig. 5.

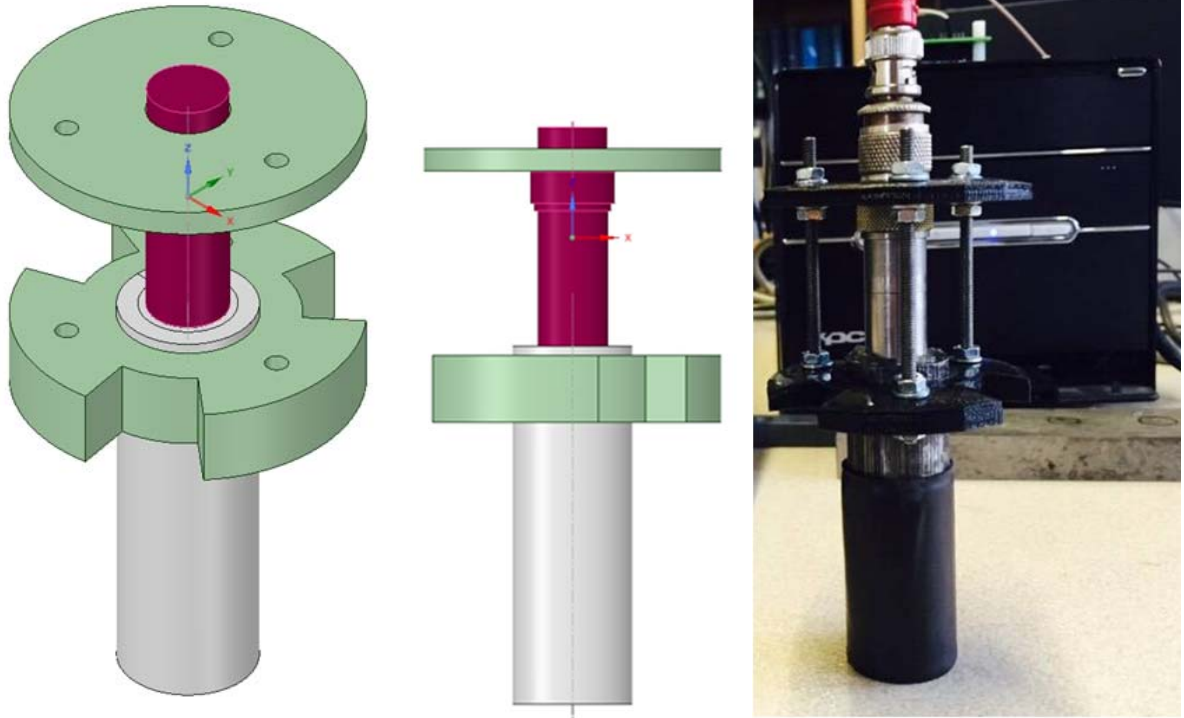


Fig. 4. Three dimensional (3D) design of the transducer holder (left) and the photograph of an ultrasound transducer attached to a corroding sample with the high accuracy ultrasonic instrument as the background (right).



Fig. 5. Preparation of the corroding samples: original iron bar, bar coated with PCB lacquer, coated bar with set heat shrink tubing

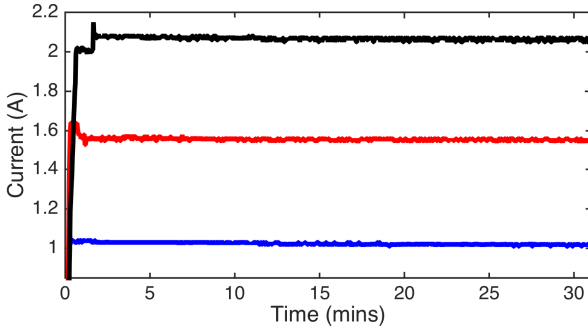


Fig. 6. Experimental records of the electroplating current overtime for various set current values

III. EXPERIMENTAL RESULTS

A. Verifying Consistency of the Electroplating Process Parameters

Fig. 6 presents the electroplating current values, recorded during separate, 30-minute experiments for various set values, which were fairly constant over time after some initial time required for manual current setting and its stabilization. It was found that the resistivity of the electrochemical cell markedly increased when the electroplating current was set at 2 A. Consequently, a subsequent experiment was conducted with the electroplating current value set at 1.5 A.

The process records were checked after every experiment, and there was no evidence of any substantial deviations in the electroplating current from the set value throughout later experiments.

B. Evaluation of the Consistency of the Corroded Sample's Weight Loss

An accelerated corrosion experiment was conducted using the same process parameters (electroplating current of 1.5 A) for varying times, and the corroded sample was weighed at the end of each experiment. Fig. 7 presents the experimental results and the theoretical expectations based on the weight of the corroded sample versus the accumulated time of the corrosion. Photographs of both the anode and cathode before and after the first experiment are shown in Fig.8.

It can be seen that the mass loss of the corroding sample is close to linear, and the curve fits between the predictions of the mass loss based on Faraday's law (1) for $z=2$ and $z=3$. Although the electrolyte contained ferric chloride (iron (III) chloride) with the iron ions valence of 3+, iron electroplating is commonly carried out using some ferrous (iron (II)) ions [9], and anode corrosion itself frequently produces ferrous ions [10]. Taking into account limited current efficiency, the obtained experimental curve, located just above the theoretical line for $z=2$, seems appropriate.

C. Analysis of the Recorded Ultrasonic Waveforms

Some of the recorded experimental echo waveforms are presented in Fig. 9. They are delayed in the time domain from the excitation pulse by the time it takes the ultrasound to propagate to the corroding surface and back. When corrosion progresses, the length of the corroding sample decreases; thus, it takes less time for the ultrasound to propagate through it. Consequently, one can expect that reflections from the corroded surface should move leftwards on the recorded waveforms as the corrosion progresses. This effect can be clearly seen from the first lobes of the recorded echoes

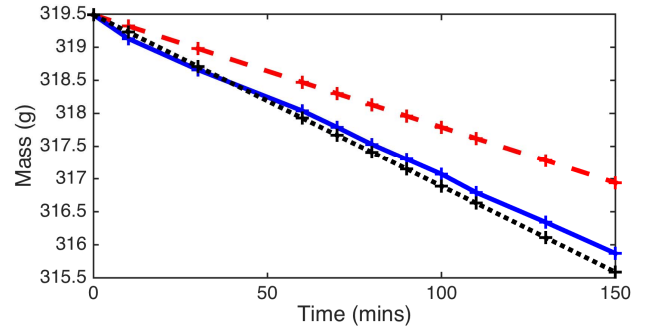


Fig. 7. Measured (solid line) and expected (dotted lines for $z=2$ and dashed lines for $z=3$) weight of the corroded sample versus the accumulated corrosion time.

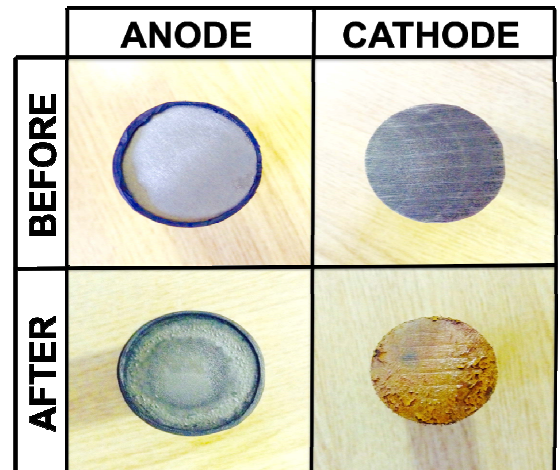


Fig. 8. Photographs of the anode and cathode before and after the first experiment

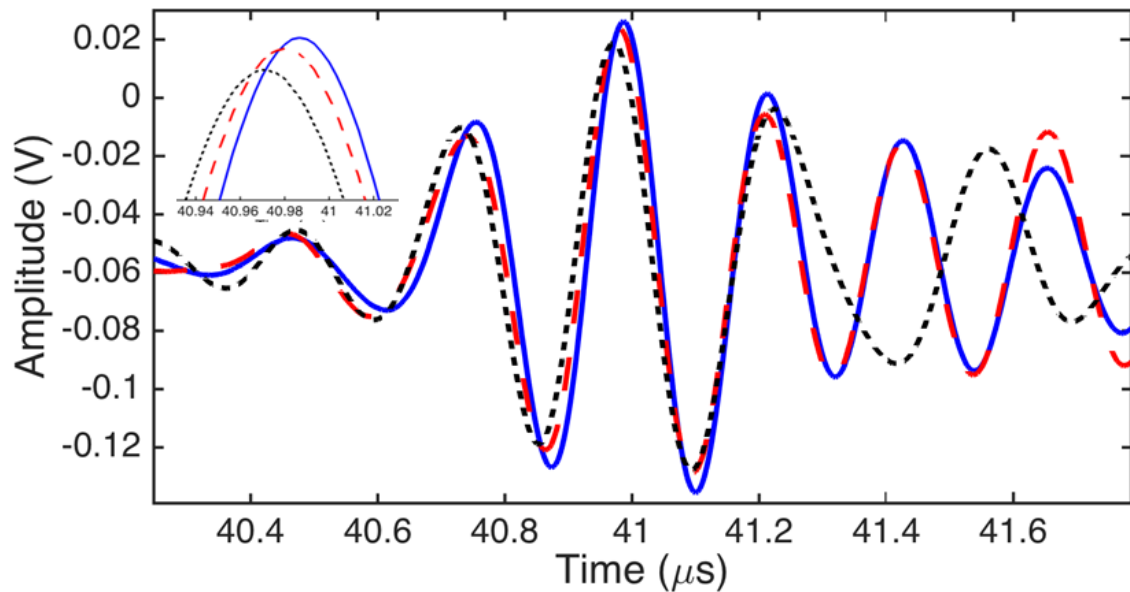


Fig. 9. Three echoes reflected from the corroded surface at the beginning of the experiment (solid line) and after 10 minutes and 20 minutes (dashed and dotted lines, respectively).

As corrosion is stochastic and uneven, one would expect the recorded echoes to disperse in the time domain as the corrosion progresses. Moreover, this dispersion should lead to a reduction of the peak amplitudes in comparison to the amplitudes recorded from the flat surface at the beginning of the experiment. Evidence for both of these expectations can be found from the experimental waveforms, with the decrease of peak amplitudes being easily noticeable. While dispersion of the echo waveforms is not very clear 10 minutes after the start of the experiment, it is evident in the waveform recorded after 20 minutes.

IV. CONCLUSIONS

A test rig was developed for the experimental evaluation of accelerated corrosion using ultrasonic waveforms reflected from the corroding surface. Acceleration of corrosion was achieved by employing a typical electroplating setup where the corroding sample acted as the anode. Special attention was paid to the provision of the same process conditions in order to achieve a constant weight loss rate throughout the experiment, and the relevant process conditions were monitored and recorded in real time. This enabled the periodically recorded ultrasonic waveforms, reflected from the corroded surface, to be correlated to the weight loss of the sample.

The suitability of the designed experimental test rig was verified experimentally by analyzing the recorded process parameters, weighting the corroding samples, and analyzing the recorded ultrasonic waveforms. All the results were found

to be consistent with the experimental expectations and the underlying theories.

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