Journal of Electroanalytical Chemistry 812 (2018) 115–121

Contents lists available at ScienceDirect

Journal of Electroanalytical Chemistry

journal homepage: www.elsevier.com/locate/jelechem

On quantitative corrosion rate monitoring with ultrasound

Fangxin Zou*, Frederic B. Cegla

Non-Destructive Evaluation Group, Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK

ARTICLE INFO

Keywords:
Corrosion monitoring
Corrosion rate
Ultrasound
Piezoelectric transducer
Non-destructive evaluation
Structural health monitoring

ABSTRACT

Wall-thickness loss rate (WTLR) is an important parameter that defines a corrosion process. The speed at which a WTLR can be determined is directly related to how quickly one can intervene in a process that is heading in the wrong direction. Ultrasonic testing has been widely used as a convenient and efficient technique for online corrosion monitoring. One of the key performance parameters of ultrasonic corrosion monitoring is detection speed. While WTLRs can be determined by fitting linear lines to wall-thickness loss (WTL) measurements, the presence of noise in the measurements makes it difficult to judge the confidence levels of the slopes that are calculated this way. In this paper, a statistics based approach for assessing the detection speeds that are achievable by ultrasonic corrosion monitoring systems is presented. Through the statistical analysis of experimental data, a state-of-the-art laboratory setup is shown to be able to detect both WTLRs and changes in WTLR that are of interest to industry (i.e. 0.1–0.2 mm/year) within 1–2 h.

1. Introduction

In the US alone, corrosion costs the oil and gas industry billions of dollars a year [1]. Corrosion induced component failures have caused devastating environmental, social and financial consequences [2,3]. Online corrosion monitoring helps to improve the safety and the sustainability of assets. Conventional corrosion monitoring techniques, such as linear polarisation resistance measurements [4,5] and weight loss measurements [6–8], are intrusive since they require probes to access the interiors of closed vessels. Also, the estimation of wall-thickness loss rates (WTLRs) by these techniques depends on a number of assumptions (e.g. the chemical reactions that take place and the areas over which they occur) which often lead to loss of accuracy.

Ultrasonic testing (UT) offers a non-intrusive and more direct approach for corrosion monitoring. In the past, UT could only be carried out manually, and due to the uncertainties associated with transducer positioning and coupling, the method suffered from poor measurement repeatability (i.e. 0.1–0.5 mm) [9]. The use of permanently installed transducers has significantly improved the measurement repeatability of the method [10]. Ultrasonic wall-thickness loss (WTL) measurements with micron level precision were subsequently reported [11,12]. Lately, the authors constructed a state-of-the-art laboratory setup that is able to achieve an unprecedented WTL measurement repeatability in the range of 10s of nanometres [13].

The simplest way of determining WTLRs from ultrasonic WTL measurements is by linear least squares regression. When very small WTLRs are to be determined, it is crucial to be able to differentiate genuine WTLs from measurement noise. In this paper, a statistical approach is used to assess the speeds at which corrosion processes and changes in corrosion rate can be detected. The approach quantifies the confidence levels with which WTLRs and changes in WTLR can be estimated by linear line fitting. WTL measurements that were acquired during open-circuit corrosion processes, using the setup constructed by the authors, were quantitatively analysed to demonstrate the state-of-the-art measurement capability of ultrasonic corrosion monitoring. The statistical approach offers a convenient way of evaluating the performances of ultrasonic corrosion monitoring systems.

2. State-of-the-art ultrasonic wall-thickness loss measurements

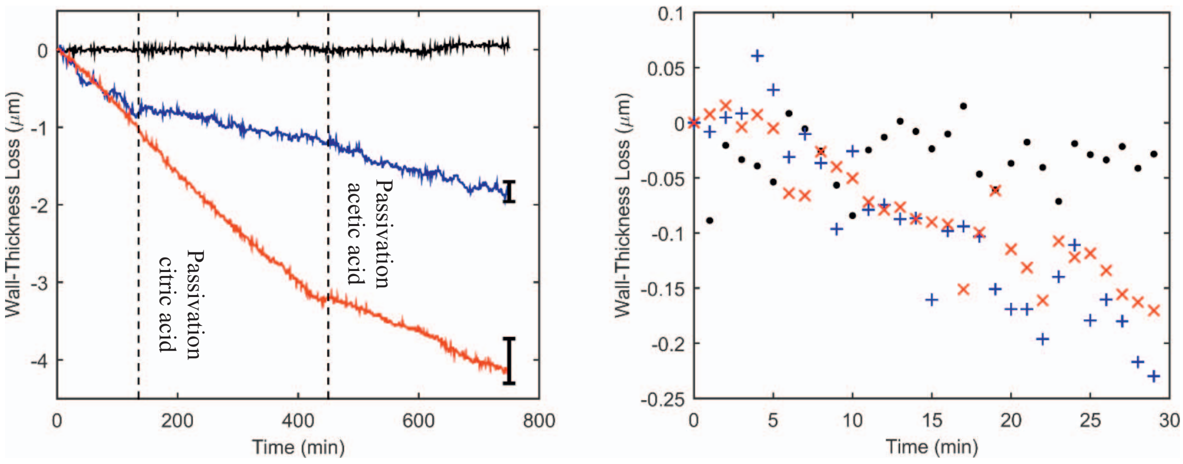
Fig. 1 shows the ultrasonically measured WTLs of a 10 mm mild steel sample (BS 970:1983:080A15, UNS G10160) during open-circuit corrosion experiments. The experiments were conducted using the ultrasonic monitoring setup constructed by the authors [13] which has a thickness measurement repeatability of ~20 nm over 1 h and that of ~40 nm over 24 h. The measurements were acquired at 1 min intervals. The electrolytes used are distilled water, 0.1 M citric acid and 0.1 M acetic acid. The ultrasonic measurements were validated by optical surface profile scans which were obtained by a white light interferometer (TMS-100 TopMap Metro.Lab, Polytec, Germany) after the corrosion experiments had finished. The procedure for carrying out the optical scans can be found in [13].

As shown in Fig. 1(a), distilled water had not caused any noticeable WTL over the time frame of the experiment. The measurements that

---

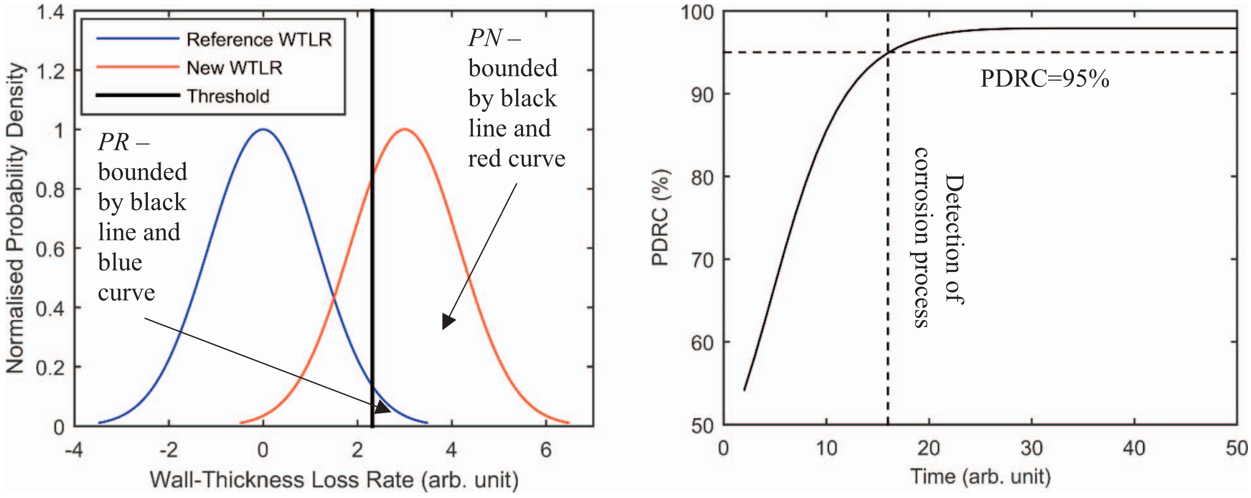
* Corresponding author.
E-mail addresses: f.zou11@imperial.ac.uk (F. Zou), f.cegla@imperial.ac.uk (F.B. Cegla).

https://doi.org/10.1016/j.jelechem.2018.02.005
Received 30 November 2017; Received in revised form 1 February 2018; Accepted 5 February 2018



(a) (b)

Fig. 1. (a) Ultrasonic measurements of the WTLs of the sample during the experiments with distilled water (black), 0.1 M citric acid (blue) and 0.1 M acetic acid (red). The mean thickness changes calculated from the optical profile scans of the corrosion surfaces are shown as error bars. (b) Measurements that were acquired in the first 30 min. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) (b)

Fig. 2. (a) PDF curves of the reference and the new WTLRs that are determined up until a given time instant. (b) PDRC curve for WTLRs.

were acquired during the experiment with distilled water are therefore indicative of the noise level of the measurement system that was employed. The two acidic solutions, on the other hand, had resulted in micron level WTLs. During the two acidic corrosion processes, the effect of surface passivation, which caused WTLRs to change, was observed at the 2nd and the 7th hour respectively. It is worth mentioning that surface passivation occurs when corrosion products gradually deposit onto the corroding surface. This leads to the formation of a corrosion-inhibiting passivation layer which hinders further diffusion of ions and hence slows down corrosion kinetics.

While it is relatively easy to retrospectively identify the two corrosion processes and calculate the WTLRs from the WTL measurements by linear least squares regression, it is not straightforward to do so at the onsets of the changes (without a large number of a priori measurements) since the presence of noise introduces uncertainty to the linearly fitted WTLRs. As illustrated in Fig. 1(b), the two acidic corrosion processes cannot be clearly identified in the first 15–20 min since the WTL measurements lie within the noise level of the ultrasonic setup. Therefore, in this paper, a statistical approach for confidently determining WTLRs and changes in WTLR is described, and it is through the consideration of confidence levels that automated, on-the-spot detection of corrosion processes and changes in corrosion rate is achieved. The statistical approach is equally applicable to analysing field measurements which expectedly have lower measurement repeatability and hence result in longer detection times. Also, it is capable of making predictions of the response times of ultrasonic corrosion monitoring systems.

3. Detection of statistically significant wall-thickness loss rates

Consider a set of N WTL measurements which have a variance of ${\sigma_w}^2$. The standard deviation (σ_r) of all the WTLRs that can be calculated from these WTL measurements is given by

$$\sigma_r = \sqrt{\frac{\sigma_w^2}{\sum_{i=1}^{N}(t_i - \bar{t})}} \tag{1}$$

where t_i is the sampling time instant of the i^{th} WTL measurement, and $\bar{t}$ is the mean value of all the sampling time instants.

A quantity named the probability of detecting a real change (PDRC)