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Wavelet power, entropy and bispectrum applied to AE signals for damage identification and evaluation of corroded galvanized steel

Rosa Piotrkowski [a,b], Enrique Castro [a], Antolino Gallego [a,*]

[a] Departamento de Física Aplicada, Universidad de Granada, E.U. Arquitectura Técnica, 18071 Granada, Spain
[b] ECyT, Universidad Nacional de San Martín, 1650 Pcia, Buenos Aires, Argentina

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ABSTRACT

Acoustic emission (AE) signals obtained from scratch tests on hot dip galvanized samples with different corrosion levels were processed by wavelet transform (WT) analysis. Wavelet power was distributed in different frequency bands, according to damage mechanisms. The frequency bands were automatically obtained by searching for the relative minima of the wavelet entropy of signals and appropriate clustering methods. Correlation between the different mechanisms was corroborated by bispectrum analysis (BA). The damage evaluation entailed studying the evolution of the wavelet power in a specific frequency band, which corresponded to the fracture of the zeta phase columns of the galvanized coating. Results showed damage to increase along with the level of corrosion, but adherence was not dramatically affected in the studied corrosion range. The application of two signal-processing techniques, WT and BA, contributed to the consistency of our results. Besides the addressed technological application, we could demonstrate that that signal-processing techniques, when applied carefully, and results classified with care, are able to contribute to what is certainly an important problem, specially in cases like the treated here, where a complete physical theory relating damage and AE is not yet available.

1. Introduction

The identification of damage processes by acoustic emission (AE) is very effective in many applications [1–4]. Besides, AE through signal processing can be applied on line as a non-destructive technique on remote or inaccessible parts of a structure. This approach is rooted in the broad field of pattern recognition and damage detection in materials and structures.

The present paper is within a program destined to evaluate the adherence of commercial galvanized coatings, working under different load and corrosion conditions (see [5,6] and references within). The paper applies two signal-processing techniques: wavelet transform (WT) and bispectral analysis (BA). These techniques were applied to AE signals coming from scratch test (ST) on corroded and non-corroded galvanized steel in order to identify damage mechanisms through the assignment of a few concise and precise parameters to different coating damage processes.

Hot dip galvanized samples were corroded in a salt chamber and then submitted to ST. Damage mechanisms involving deformation, fracture and/or extraction of the different phases that conformed the corroded coating—briefly denoted in [5]

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[*] Corresponding author. Tel.: +34 958 249 508; fax: +34 958 243 104.
E-mail address: antolino@ugr.es (A. Gallego).

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as oxide, chloride, eta phase and zeta phase—were identified. WT results were adequately obtained as time–frequency AE patterns, which revealed that AE power was distributed in five frequency bands. Consequently, the evolution of AE wavelet power (WP) in different frequency bands was carefully compared with scanning electron microscopy (SEM) and energy dispersive X-rays (EDX) observations along scratches, which permitted to correlate mechanisms and bands. In particular, signals due to corrosion and non-corrosion mechanisms could be easily separated; different mechanisms coexisted along the ST.

In the present paper, adherence evaluation is investigated in non-corroded (level 0) and corroded samples (levels 1 and 2). We present a new automated method to assign frequency bands to damage mechanisms based on wavelet entropy considerations. Correlation between mechanisms is assessed by BA. We also address galvanized damage evaluation by studying different features of WP in the band related to damage in the zeta phase columns.

Although the automated method that assigns frequency bands of the AE signal to different damage mechanisms is totally based on the WT, the other applied signal-processing method, BA, besides corroborating the previous results, is needed to show the correlation between the different mechanisms and to give an idea of their degree of gaussanity.

The present paper addresses to a specific important technological topic like the identification and evaluation of damage in corroded and not corroded galvanized steel. Moreover, it is also an investigation concerning the potential of applying both WT and BA techniques to AE signals, including the ulterior careful classification of results. A full theoretical justification that relates degree of damage an AE features is not still available. Nevertheless, signal processing that implies the extraction of parameters from noisy signals, often gives important clues to understand the underlying physical processes. These are the goals of our work.

2. Experimental

The preparation procedure of hot-dip galvanized samples (50 mm × 20 mm × 4 mm plates) was as in [5]. Samples were hot-dip galvanized at 450 °C for 3 min, and then some of them were submitted to corrosion.

Results from one sample of each type (corrosion levels 0, 1 and 2) are presented, since the outcomes from equivalent samples were essentially coincident. According to the corrosion levels samples are, respectively, named as T0, T1 and T2. The mean coating thicknesses were 152, 158 and 166 μm, in that order. T1 and T2 were, respectively, corroded for about 900 and 1800 h in a salt mist chamber to simulate a marine environment. Sample T0 was left as cast and was taken as a reference. The coating of sample T0 appeared quite homogeneous. The Zn–Fe phases, gamma (very thin), delta (well defined and homogeneous), zeta (columnar grains) and eta (almost pure Zn), were observed from steel to Zn (top). The interior part of the coating of sample T1 remained largely unchanged, and only the top of the eta phase was affected by corrosion. Corrosion also affected the eta–zeta two-phase region of the coating of sample T2. As was stated in [5], corrosion products are a mixture of a Zn oxide and a hydrated Zn chloride.

Two scratches were performed on each sample, according to the procedure described in [5]. STs with AE were performed under controlled conditions using a device that consisted of a loaded probe with a diamond indenter moving linearly along the sample at constant speed, and with linearly increasing force (0–150 N) during 180 s; the scratch length was about 1 cm. The piezoelectric sensor was in the 100–1000 kHz range, signals were pre-amplified (60 dB), the threshold was at 25 dB and digitization was at 4 MHz/16 bits.

We noted the nth AE signal recorded over the test as $s^n(t)$, with $n = 1,\ldots,N_r$. The total number of registers (N_r) depends on the sample and the scratch that corresponds to each ST. If $\Delta t = 2.5 \times 10^{-7}$ s is the sampling period, $s^n(k)$ corresponds to $s^n(k\,\Delta t)$ with $k = 1,\ldots,N$; it thus denotes the kth sample of the signal $s^n(t)$. In our case, 4000 data were recorded for each AE signal, which means $N = 4000$ for all signals.

The supra-index n is related with the position along the scratch. If T_n is the instant at which the AE signal $s^n(t)$ was captured, the corresponding position on the scratch is given by $x_n = vT_n$, where v is the speed of the diamond indenter. At the beginning of the ST time is initialized to zero, and at the end it is set at $T_e = 180$ s. We emphasize that two temporal scales are involved. One is designated with lower case t to measure time in each register, which ranges within (0–10^{-3}) s, and the other is designated with capital T that measures time among registers, ranging within (0–180) s.

For practical reasons, we use the relative position in %, $X_n(\%)$, on the scratch instead of the real position x_n. Thus, the relative position at which the signal $s^n(t)$ is captured is at $X_n(\%) = 100\ (T_n/T_e)$.

SEM and EDX observations showed in [5] that the failure mechanisms in the non-corroded samples were the slipping of the eta phase and the breakage of zeta phase columns with eventual ulterior extraction of the zeta phase cracked particles. Other mechanisms besides the aforementioned appeared when the first level of corrosion was considered—namely, the transversal cracking of the oxide phase and the interfacial cracking and extraction of the chloride particles. The same mechanisms operated in samples corroded up to level 2. Fig. 1 shows the central part of scratches in the three samples. For samples T1 and T2, we can observe transversal oxide cracks in the middle of scratches and extracted chloride particles (white and sized in the order of microns) at the borders. The density of transversal cracks is higher for sample T2.