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Assessment of fatigue damage in a fully pearlitic ductile cast iron by evaluation of Acoustic Emission Entropy

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Abstract

The paper presents the preliminary results of Acoustic Emission (AE) tests on a peralitic ductile cast iron (DCI) subjected to fatigue tensile loading. The focus is on the evaluation of the information Entropy of the AE data, as an innovative tool for a reliable assessment of fatigue damage in DCIs. Two damage indexes are proposed for the identification of the damage evolution and for the prediction of the fracture failure.

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1. Introduction

Ductile cast irons (DCIs) are engineering materials obtained in the '40s by the addition of special elements such as *magnesium* or *cerium* during the treatment of cast irons; such an addition generates a peculiar microstructural arrangement. Nodular graphite elements are embedded within the iron matrix in DCIs, differently from the typical graphite *lamellae* present in cast irons (Di Cocco and Iacoviello, 2017). DCIs can be comparable to structural metals such as steels in terms of mechanical properties, as well as they have the good castability of grey cast irons (Di Cocco

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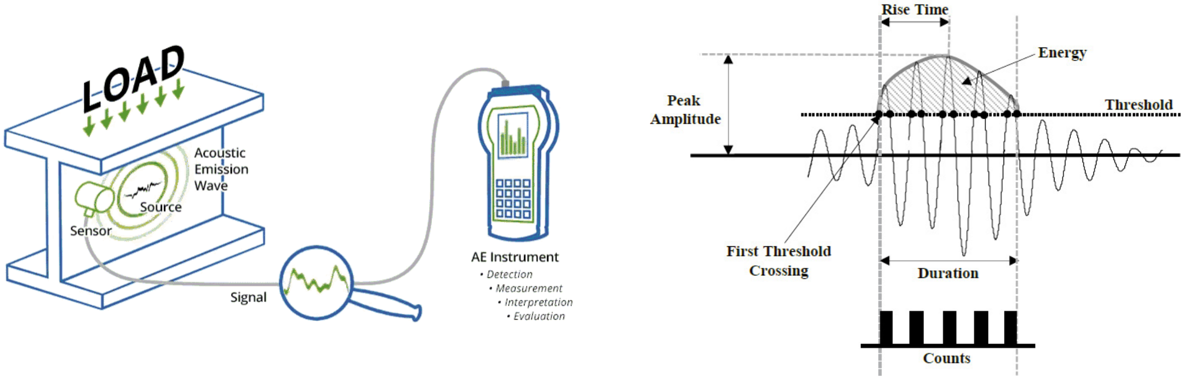
et al., 2010; Iacoviello et al., 2008). The matrix of DCIs governs the mechanical properties of the material, whereas the graphite nodules were recently found to play a key role on the damage evolution and the failure mechanisms (Bellini et al., 2019; Di Cocco et al., 2013, 2010; Iacoviello et al., 2008). DCIs are typically widely used in civil, industrial, and mechanical engineering for critical systems such as pipelines, wind turbines, and engine components (Bellini et al., 2019; Hubner et al., 2007). DCI components are often subjected to repeated loading, and in many cases, they are prone to fatigue crack propagation (e.g., (Iacoviello et al., 2016, 2013)). The assessment of fatigue cracking in DCI elements can be challenging given the complex microstructure of the material (Di Cocco and Iacoviello, 2017), as well as the reduced size of the cracks that are typically associated with fatigue crack propagation. Traditional monitoring based on visual inspection and destructive testing is typically expansive, and it can be inefficient.

AE testing (Balageas et al., 2006; Di Benedetti, 2012; Grosse and Ohtsu, 2008; Schultz, 2014; Unnorsson, 2013) is the among the most advanced methods the for non-destructive damage assessment of structural elements (Fig. 1.a) (Iturrioz et al., 2014). AE waves are the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material (ASTM International, 2001). This release of energy is typically caused by damage or degradation within the structure. The direct/indirect analysis of the main features of the AE waves (*AE features,* Fig. 1.b) allows to localize and identify the occurring damage, according to the *parameter-based approach* (Grosse and Ohtsu, 2008). Several studies investigated the acoustic activity associated with fracture and fatigue in metal components (e.g., (Aggelis et al., 2011; Al-jumaili, 2016; Bassim et al., 1994; D'Angela and Ercolino, 2019)). However, only few studies applied AE testing for the assessment of DCIs (Carpenter and Zhu, 1991; Kietov et al., 2018; Sjögren and Svensson, 2005), demonstrating that the analysis of the AE features potentially provides information about the ongoing damage. There are cases in which the traditional AE analysis is not efficient for damage evaluation. Microstructural complexity and noisy testing environment are typical conditions in which more refined methods may be needed for a reliable evaluation (Al-jumaili, 2016; D'Angela and Ercolino, 2019; Kahirdeh and Khonsari, 2016). The information Entropy of the AE data was recently found to be robustly correlated to the damage evolution in metallic components under fracture and fatigue (D'Angela and Ercolino, 2019; Kahirdeh and Khonsari, 2016, 2015; Yun and Modarres, 2019). This approach is still at an early stage of development, and it has not been applied yet for the fatigue assessment of DCI. The present study reports the preliminary results of AE tests on fully pearlitic DCI microtensile specimens under fatigue tension loading. The information entropy of the AE data is evaluated by using the early formulation by Shannon (Kahirdeh and Khonsari, 2016; Shannon, 1948). Novel damage correlations are finally proposed.



(a) (b)

Fig. 1. AE testing: (a) technique application scheme (by MISTRAS Limited), and (b) main AE features (Ercolino et al., 2015).

2. Materials and methods

Microtensile specimens (Fig. 2) made of a fully pearlitic DCI EN GJS700-2 (Table 1) were subjected to cyclic uniaxial tension loading. The material had a nominal strength equal to 700 MPa. The graphite elements of the tested material were characterized by a nodularity higher than 85%, having a volume fraction equal to 9 – 10 %. Three specimens were tested under cyclic loading under the following loading conditions:

- test C1: incremental σ_{max} = {200, 300, 400, 500, 600, 700} MPa, and σ_{min} = 100 MPa
- test C2: σ_{max} = 700 MPa, and σ_{min} = 350 MPa (R = 0.5
- test C3: σ_{max} = 700 MPa, and σ_{min} = 70 MPa (R = 0.1)

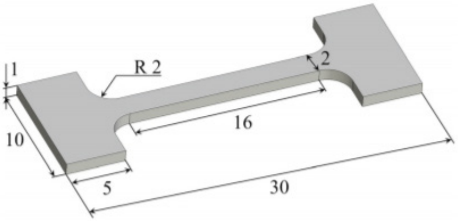


Fig. 2. Geometry of the microtensile specimens (in mm) (Iacoviello et al., 2008).

Table 1. Chemical composition in wt% for (fully) pearlitic DCI.

C	Si	Mn	S	P	Cu	Mo	Ni	Cr	Mg	Sn
3.59	2.65	0.19	0.012	0.028	0.004	0.004	0.029	0.061	0.060	0.098

The specimen deformation was controlled by a Linear Variable Differential Transformer (LVDT). Two miniature load cells (10 kN each) were used to measure the applied load on the specimen. The Shannon formulation (Kahirdeh and Khonsari, 2016; Shannon, 1948) was used to evaluate the information Entropy of the AE data (S_E), according to Equation 1. The probability mass distribution vector $\boldsymbol{p_i}$ is defined in Equation 2, where n_i and Σn_i define AE counts and cumulative AE counts (e.g., Fig. 1).

$$S_E = -\sum_{i=1}^{N} p_i \log_2(p_i) \tag{1}$$

$$\mathbf{p_i} = \left\{\frac{n_1}{\Sigma n_i}; \frac{n_2}{\Sigma n_i}; \dots; \frac{n_i}{\Sigma n_i}\right\};\ \Sigma n_i = \sum_{k=1}^{i} n_k \tag{2}$$

3. Results and Discussion

The three tests showed significantly different evolution of the AE activity, which is only described in the paper for the sake of brevity. A very small amount of activity was detected over test C1 if compared to both tests C2 and C3. Almost all the AE events related to test C1 were detected prior or just prior to the failure occurring, whereas an almost continuous activity was exhibited for tests C2 and C3. Despite the difference in number and evolution of the acoustic events, some similarities were identified among the tests, e.g., in terms of the characteristic values of the AE features. The number of counts related to the pre-failure stage of C1 test was significantly larger than the one related to C2 and C3 tests. On the contrary, in these latter cases, the activity associated with the pre-failure stage did not present evident differences if compared to the AE detected over the whole tests. Tests C2 and C3 presented a very similar number of total events, which was an order of magnitude larger than the one related to test C1. The amplitude of the AE signals was not larger than 50 up to the pre-failure stage for all cases. In the (very) last stage, large amplitudes were detected. Extremely large values were detected for test C1 (80 –100 dB), whereas large values were associated with test C3 (70 – 80 dB), and relatively low amplitudes with test C2 (50 – 60 dB).

The basic AE analysis allowed to qualitatively identify the ongoing damage, e.g., AEs were detected over the increasing damage, and significant activity having large amplitude (and other characteristic features) was emitted prior or just prior to the failure. However, the damage correlations were qualitative, or rather weak. And, the only robust criteria (related to the incipient failure) did not trigger the failure with large time-advance. Therefore, the basic analysis of the AEs was confirmed to be inefficient for field health monitoring of structures under fatigue loading.

Fig. 3 shows logarithmic cumulative Shannon AE Entropy ΣS_E vs normalized time on the right axis, along with the engineering strain ε vs the normalized time on the left axis. The normalized time was defined by the actual testing time divided by the failure time. The AE Entropy curves are quite similar for the different tests despite the different AE features in terms of both time evolution and characteristics values. The shape of the Entropy curves is quite regular, and it identifies three sequential stages: (a) a sub-vertical branch, (b) a gradual *knee*, and (c) sub-horizontal branch (*plateau*). Two aspects associated with the Entropy evaluation are potentially relevant for health monitoring implementation: (1) the slope of the Entropy curves decreases as the fatigue damage increases, and (2) the Entropy values at the incipient failure is very similar for the different tests. Two damage indexes can be developed according to the damage correlations identified through the experimental testing. The slope of the Entropy curve can be associated with the evolution of the fatigue damage, and the Entropy value might be compared to threshold values for the prediction of the incipient failure. Similar qualitative Entropy trends were identified by other authors (e.g., (Kahirdeh and Khonsari, 2016; Yun and Modarres, 2019)), and similar damage criteria were found with regard to fatigue crack propagation tests performed on metallic Compact Tension (CT) specimens (D'Angela and Ercolino, 2019, 2018). As a final comment, the slope of the Entropy curve can be reasonably preferred to the Entropy threshold value as a damage index; this can be justified by both for its univocal interpretation, and as well as experimental robustness (D'Angela and Ercolino, 2019).

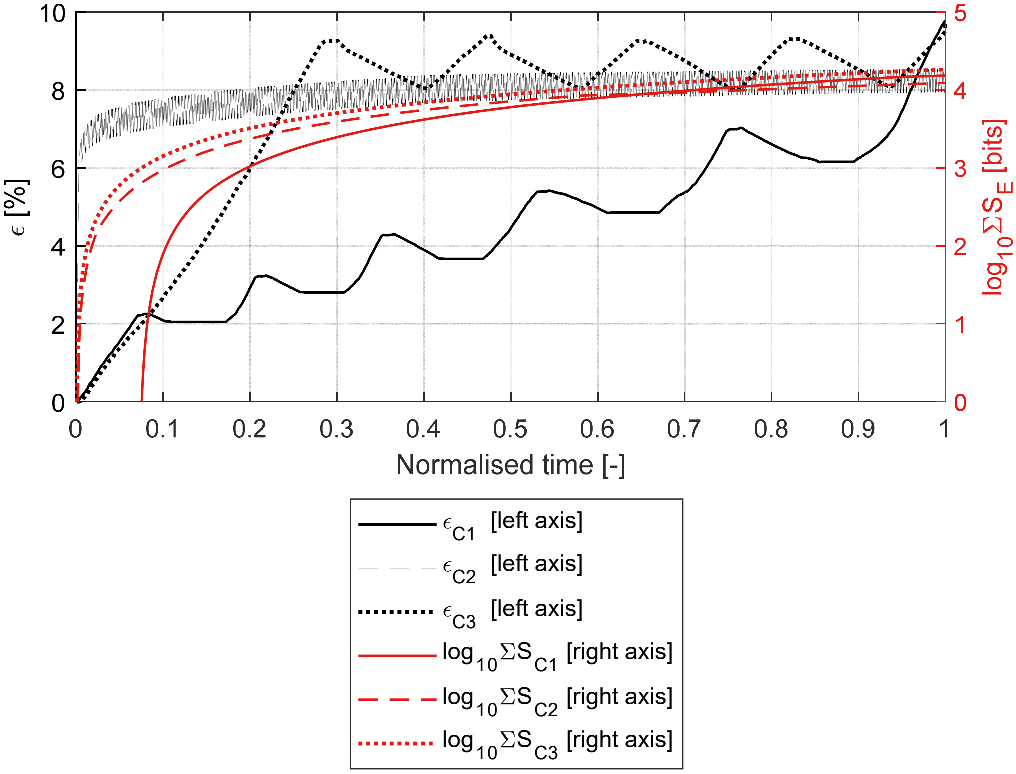


Fig. 3. Engineering strain ε vs normalised time (left axis) and logarithmic cumulative AE Entropy ΣS vs Normalised time (right axis) for the tests C1, C2, and C3.

4. Conclusions

The paper presented the preliminary results of AE tests on pearlitic DCI microtensile specimens subjected to fatigue tension loading. The basic AE features were qualitatively correlated to the damage evolution. However, the traditional

AE analysis was found to be weak or inefficient for the assessment of the fatigue damage in the investigated materials. Conversely, the Shannon Entropy of the AE data was proven to be clearly correlated to the damage evolution, and informative of the incipient failure conditions. Two promising damage indexes were finally suggested for the structural health monitoring implementation. The study cannot be considered to be exhaustive for the few tests performed, and for the peculiar application. Further studies should be performed in order to strengthen the findings, as well as to extend the proposed assessment approach to other materials and applications.

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