Received: 30 January 2020 | Accepted: 31 January 2020

DOI: 10.1002/mdp2.158

REPORT

WILEY

Analysis of acoustic emission entropy for damage assessment of pearlitic ductile cast irons

Danilo D'Angela[1] | Marianna Ercolino[1] | Costanzo Bellini[2] | Vittorio Di Cocco[2] | Francesco Iacoviello[2]

[1]School of Engineering, University of Greenwich, London, United Kingdom

[2]Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino, Italy

Correspondence
Costanzo Bellini, G. Di Biasio, 43, 03043 Cassino (FR), Italy.
Email: costanzo.bellini@unicas.it

Funding information
University of Greenwich, Grant/Award Numbers: Seedling 2016/2017, REF 2017/2018, REF 2018/19

Abstract

The paper shows the preliminary results of uniaxial tension tests on a pearlitic Ductile Cast Iron (DCI) by using the Acoustic Emission (AE) technique as well as the Scanning Electron Microscope (SEM) analysis. The experimental tests demonstrate the damage initiation and evolution occurring within the graphite nodules produce AE activity. The evaluation of the Shannon Entropy of the AE data is found to promising for the assessment of DCIs.

KEYWORDS

Nodular iron, Structural integrity, Acoustic emission

1 | INTRODUCTION

Ductile Cast Irons (DCIs) have a microstructure quite peculiar for the massive presence of spheroidal graphite nodules embedded within the iron matrix. They have a good castability as well as they are comparable to low-carbon steels in terms of mechanical performance.[1,2] The matrix of DCIs governs the overall mechanical properties, whereas the presence of the graphite nodules mainly affects the damage evolution.[3] Recent studies found multiple and complex damaging micromechanisms occurring within the DCIs.[1-5] Such mechanisms are mainly affecting the nodules, which do not simply behave as mechanical *voids*, as it was traditionally considered. The matrix microstructure was also found to influence the significance of such mechanisms. Such findings are questioning the knowledge of the materials as well as the reliability of the existing modelling approaches. There are some DCIs that have not been extensively investigated, e.g., pearlitic and austenitic ones.

DCIs are used in structural components of several engineering systems, such as pipelines and wind turbines.[6,7] In many cases, such systems are extremely critical for the public safety and international economy, and they require to be monitored during their lifetime. Non-Destructive Testing (NDT) is often used for this purpose,[8,9] even though the complexity of the damage evolution in DCIs makes challenging the health monitoring of such materials. Acoustic Emission (AE) testing[10] is among the most advanced NDT techniques aimed at the damage assessment of engineering systems during their lifetime. The technique is based on the generation of acoustic waves due to localised structural damage. The processing/analysis of such waves and their features allows identifying the occurring of the damage. Few past studies proved that AE testing can be a reliable technique for the damage assessment of DCIs.[10,11,12] The Information Entropy of the AE data evaluated using the Shannon formulation[13] has been recently used to assess fatigue and fracture damage in metals.[14-16] However, this approach has never been applied to DCIs.

The paper shows the preliminary results of AE tests on pearlitic DCI under uniaxial tension. The damage micromechanisms are identified by means of Scanning Electron Microscope (SEM) analysis. A novel approach is used by evaluating the Shannon Entropy of the AE data in order to identify both the onset and the evolution of the damage in (pearlitic) DCIs. The approach is finally proposed for the application to health monitoring of DCIs.

2 | MATERIAL AND METHODS

A fully pearlitic DCI (EN GJS700–2)[17] was tested under tensile loading by means of microtensile specimens (Figure 1.a) with high nodularity. Strain control was applied with a rate equal to 0.2 s^{-1}. The tests were performed using a tensile holder in order to perform the *step-by-step* Scanning Electron Microscope (SEM) analysis.[1,2,16] AE testing was performed along with the mechanical tests using two simultaneous AE systems (*1283 USB Node*). Two ultra-low noise pre-amplified sensors (*PK15I*) detected the AEs; they had a resonance frequency equal to 150 kHz, operating within 100–450 kHz. The software *AEwin*™ was used to process and visualise the AEs in real-time. The whole AE testing equipment was produced by Mistras Group LTD UK. Mock tests were carried out in order to define the main parameters for the AE testing, also taking into account previous applications.[13] Amplitude threshold was set equal to 45. Figure 1.b shows the testing set-up. *Sensor 1* was located on the support box of the tensile holder (close to the specimen), and *sensor 2* was located on the inferior support of the testing machine. The location of sensor 1 was aimed to minimise the noise and maximise the signals Amplitude, whereas the location of sensor 2 was chosen to minimise the signals Amplitude and maximise the noise. The Shannon Entropy of the AE data (S_E) was evaluated using Equation (1).[12,14] In particular, the probability mass distribution vector at the i^{th} time step, i.e., $\boldsymbol{p_i}$, is defined in Equation (2), where n_i and Σn_i are Counts and cumulative Counts related to the i^{th} time step, respectively.

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

$$\boldsymbol{p_i} = \left\{ \frac{n_1}{\Sigma n_i}; \frac{n_2}{\Sigma n_i}; \ldots; \frac{n_i}{\Sigma n_i} \right\} \tag{2}$$

3 | RESULTS AND DISCUSSION

An approximately linear elastic response was observed up engineering stress equal to about 600 MPa, with an engineering strain equal to about 6%. After this limit, a gradual stiffness decrease was observed up to the ultimate strength (about 750 MPa). The failure was reached just after the ultimate tensile strength in some cases (engineering strain about 10%); in other cases, it occurred after a short softening branch (engineering strain about 12%). The SEM analysis identified the combination of three elementary damaging micromechanisms, similarly to the ones found in ferritic DCI,[1] i.e., *onion-like*, *disgregation*, and *matrix-nodule debonding* mechanisms. The onset of the damage mechanisms was quite dispersed over the material response, ranging from 450 MPa to 700 MPa. More than 75% of the mechanisms initiated

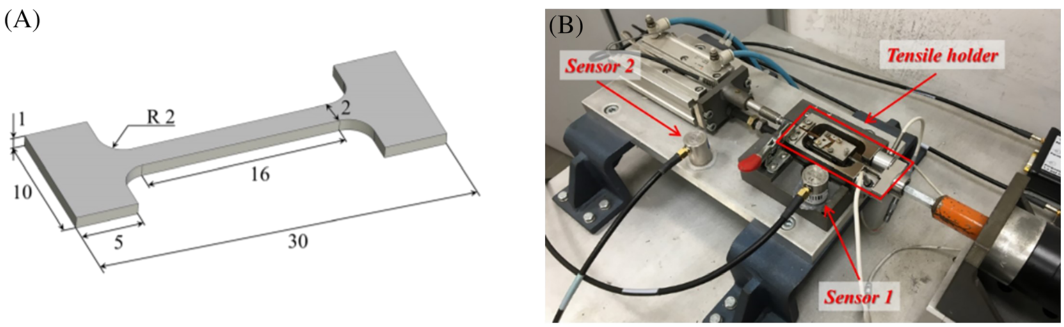

FIGURE 1 (a) Geometry of microtensile specimens, and (b) testing set-up

between 550 and 650 MPa. The damaging mechanisms always started prior to the beginning of the elastic–plastic range, and in many cases, during the early elastic stage. This was not observed in a ferritic DCIs,[1] where the nodule damage only initiated during the plastic stage. It was not possible to identify a clear pattern of the sequence of the elementary mechanisms. However, multiple mechanisms are often observed within the same nodules. Figure 2 shows the post-failure results of the SEM analysis of the graphite nodules investigated during the tests. In particular, Figure 2.a shows a nodule in which both matrix-nodule debonding and disgregation mechanism occurred. Figure 2.b shows a case of multiple occurring of all mechanisms. Overall, disgregation mechanism usually started after another mechanism (often as the latest), as it was found for ferritic DCI.[1] The matrix-debonding mechanism was found to be often occurring in pearlitic DCI, differently from ferritic DCI, where it was seldom observed.[1] Crack initiation was also observed within the matrix at higher levels of stress (e.g., yielding stage); such cracks tended to propagate during the plastic stage leading to the failure of the specimen.

The damage of the nodules and the matrix interfaces was qualitatively correlated to the AE features. Sensor 1 detected discontinuous stages of the acoustic activity, whereas sensor 2 detected continuous AE activity having significantly lower Energy, Counts, Amplitude and Duration. The values of such AE features were essentially constant during the tests. No significant AE activity was detected by sensor 2 prior or just prior to the failure, differently from sensor 1. Therefore, the signals detected by sensor 2 can be considered as sourced by the testing equipment as a noise disturbance (e.g., continuous machine vibration), whereas the AEs related to Sensor 1 can be assumed caused by the damage of the specimen.

Figure 3 shows the time evolution of both Amplitude A and cumulative Counts N related to sensor 1 for three representative tests. The acoustic activity was observed at three stages of testing time t: (1) $10 \leq t \leq 20$ s, (2) $37 \leq t \leq 53$ s, and (3) $t \geq 60$ s. Stage 1 corresponded to low engineering stresses (220–250 MPa), stage 2 to the pre-yielding stage (500–650 MPa), and stage 3 to the incipient failure. More than half of the total number of AE events was detected over stage 2 (i.e., pre-yielding stage), corresponding to the initiation of most of the damaging mechanisms within the nodules. Few AE events with much higher Amplitude and Counts occurred just prior to the failure in all tests; AE activity was also detected quite earlier than the failure (about 9 s earlier) in one case out of three.

The analysis of the traditional AE features allowed to assess both onset and evolution of the microdamage, even though only qualitative correlations have been identified. Most of the AE activity occurred during stage 2, when the damage within the nodules began, and when the material response exhibited the stage between the elastic limit and the plastic response. The AE activity occurring just prior to the failure is probably due to the propagation of the matrix cracks (higher Amplitude and Counts) that is leading the specimen to the fracture. The findings strengthen the reliability of the correlation between the actual damage and the AEs.

Figure 4 shows the results of the Shannon Entropy evaluation up to the specimen failure (last point of the curves). The Entropy has approximately the same trend for all tests: after a sub-vertical branch, its slope over time ($\delta (log_{10}\Sigma S_E)/\delta t$) gradually decreases as the damage evolves, up to the failure, where the tangent is sub-horizontal. As a matter of fact, the onset of most of the permanent damage corresponded to stage 2, corresponding to the convergence of all the different curves, and to very reduced values of $\delta (log_{10}\Sigma S_E)/\delta t$.

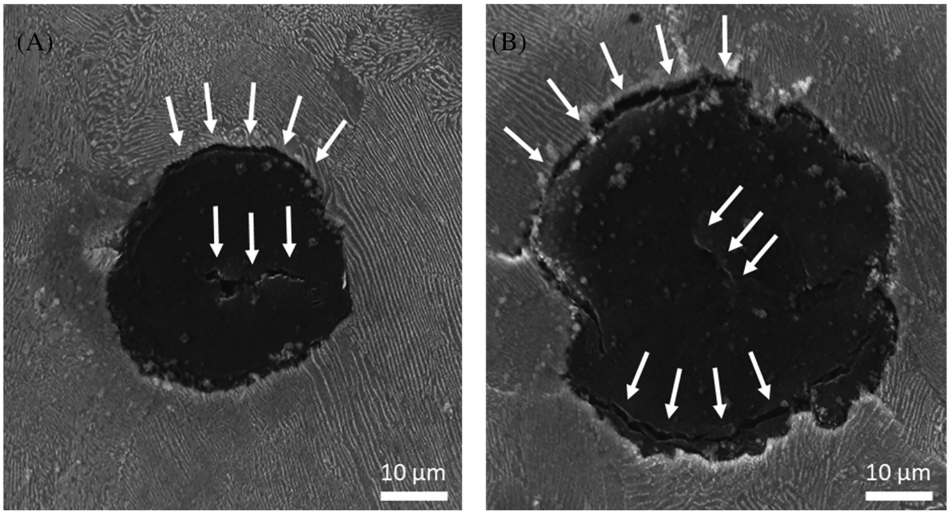

FIGURE 2 SEM analysis of damaging mechanisms occurring in a pearlitic DCI: (a) matrix-nodule debonding together with disgregation mechanisms, and (b) combination of onion-like, disgregation, and matrix-nodule debonding mechanisms

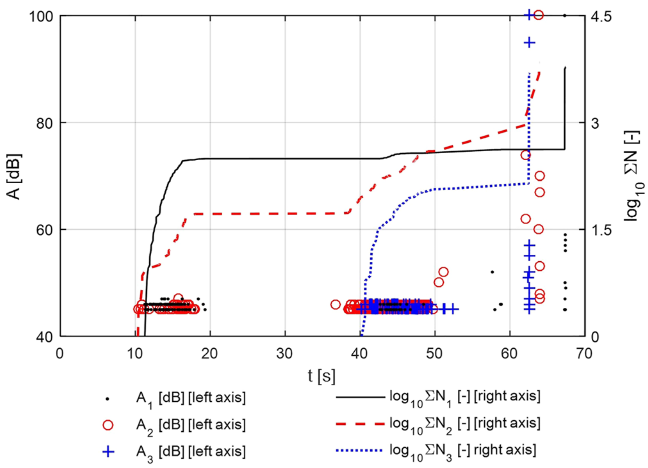

FIGURE 3 Amplitude A vs Time t together with logarithmic cumulative Counts $log_{10}\Sigma N$ vs Time t

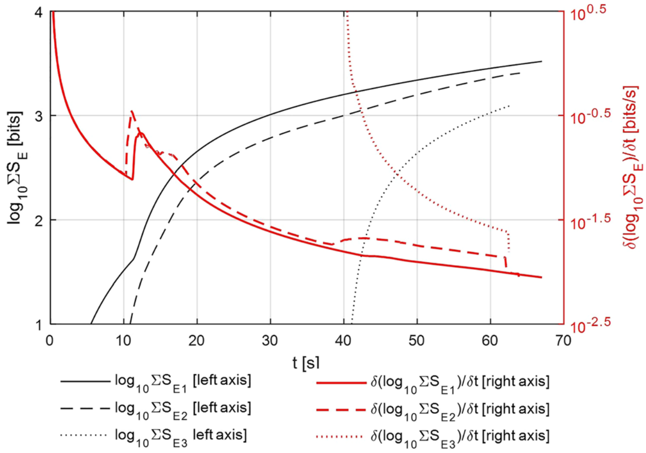

FIGURE 4 Logarithmic cumulative Shannon Entropy $log_{10}\Sigma S_E$ vs Time t together with the variation over time of the logarithmic cumulative Shannon Entropy $\delta\ (log_{10}\Sigma S_E)/\delta t$ vs Time t

A similar Entropy trend was already found by D'Angela and Ercolino,[13] who performed fatigue crack propagation tests on Nickel steel compact tension specimens. Indeed, the pattern of the Acoustic Entropy was already proven to be not significantly depending on the specific material/testing case.[14] Shannon Entropy was confirmed to be damage-sensitive even in the case of (pearlitic) DCIs. Entropy evaluation is not potentially affected by bias or analyst decisions (e.g., closed-form equation considering standard AE features), and it can be easily evaluated during the AE testing process. Therefore, the presented approach could be potentially used for health monitoring of structural components.

4 | CONCLUSIONS

The paper reported the preliminary results of Acoustic Emission (AE) tests performed on a pearlitic Ductile Cast Iron (DCI) under uniaxial tensile loading. The characterisation of the occurring damaging mechanisms was performed by means of the Scanning Electron Microscope (SEM) analysis. The analysis of the traditional AE features allowed to detect the onset of the damage occurring within the graphite nodules. The Shannon Entropy of the AE data was found to be correlated to the damage evolution. The presented approach was proven to be promising for the implementation for health monitoring purposes. However, further data analysis should be performed to strengthen the findings, as well as further tests should be performed to consider alternative case studies.

ACKNOWLEDGEMENTS

The authors wish to thank the University of Greeniwich for providing fundings for this research. In fact, AE testing equipment was funded by Seedling 2016/2017, REF 2017/2018, and REF 2018/2019 (Dr Marianna Ercolino, University of Greenwich).

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHORS CONTRIBUTION

The project was conceived by all the authors, DDA, CB and VDC performed the experiments and wrote the paper, FI and ME revised the manuscript.

ORCID

Costanzo Bellini https://orcid.org/0000-0003-4804-6588
Vittorio Di Cocco https://orcid.org/0000-0002-1668-3729
Francesco Iacoviello https://orcid.org/0000-0002-9382-6092

REFERENCES

1. Di Cocco V, Iacoviello F, Cavallini M. Damaging micromechanisms characterization of a ferritic ductile cast iron. *Eng Fract Mech*. 2010;77:2016-2023. https://doi.org/10.1016/j.engfracmech.2010.03.037
2. Iacoviello F, Di Bartolomeo O, Di Cocco V, Piacente V. Damaging micromechanisms in ferritic–pearlitic ductile cast irons. *Mater Sci Eng A*. 2008;478:181-186. https://doi.org/10.1016/j.msea.2007.05.110
3. Iacoviello F, Di Cocco V, Rossi A, Cavallini M. Fatigue crack tip damaging micromechanisms in pearlitic ductile cast irons. *Fatigue Fract Eng Mater Struct*. 2015;38:238-245. https://doi.org/10.1111/ffe.12215
4. Di Cocco V, Iacoviello F, Rossi A, Cavallini M, Natali S. Graphite nodules and fatigue crack propagation micromechanisms in a ferritic ductile cast iron. *Fatigue Fract Eng Mater Struct*. 2013;36:893-902. https://doi.org/10.1111/ffe.12056
5. Iacoviello F, Cocco VD, Cavallini M. Fatigue crack propagation and overload damaging micromechanisms in a ferritic-pearlitic ductile cast iron: stress intensity factors using a new semi-analytical method. *Fatigue Fract Eng Mater Struct*. 2016;39:999-1011. https://doi.org/10.1111/ffe.12443
6. Hubner P, Schlosser H, Pusch G, Biermann H. Load history effects in ductile cast iron for wind turbine components. *Int J Fatigue*. 2007;29:1788-1796. https://doi.org/10.1016/j.ijfatigue.2007.01.012
7. Kleiner Y, Rajani B, Krys D. Performance of ductile iron pipes. I: characterization of external corrosion patterns. *J Infrastruct Syst*. 2013;19:108-119. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000097
8. Yao Y, Tung S-TE, Glisic B. Crack detection and characterization techniques-An overview. *Struct Control Health Monit*. 2014;21:1387-1413. https://doi.org/10.1002/stc.1655
9. Liu Z, Kleiner Y. State of the art review of inspection technologies for condition assessment of water pipes. *Measurement*. 2013;46:1-15. https://doi.org/10.1016/j.measurement.2012.05.032
10. Grosse C, Ohtsu M. *Acoustic emission testing*. Berlin: Springer Berlin Heidelberg; 2008. https://doi.org/10.1007/978-3-540-69972-9.
11. Sjögren T, Svensson IL. Studying elastic deformation behaviour of cast irons by acoustic emission. *Int J Cast Met Res*. 2005;18:249-256. https://doi.org/10.1179/136404605225023117
12. Kietov V, Henschel S, Krüger L. Study of dynamic crack formation in nodular cast iron using the acoustic emission technique. *Eng Fract Mech*. 2018;188:58-69. https://doi.org/10.1016/j.engfracmech.2017.07.009
13. Shannon CE. A mathematical theory of communication. *Bell Syst Tech J*. 1948;27:379-423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x
14. D'Angela D, Ercolino M. Acoustic Emission Entropy as a fracture-sensitive feature for real-time assessment of metal plates under fatigue loading. *Procedia Struct Integr*. 2019;18:570-576. https://doi.org/10.1016/j.prostr.2019.08.201
15. Kahirdeh A, Khonsari M. Acoustic Entropy of the materials in the course of degradation. *Entropy*. 2016;18:280. https://doi.org/10.3390/e18080280
16. Kahirdeh A, Khonsari MM. Energy dissipation in the course of the fatigue degradation: mathematical derivation and experimental quantification. *Int J Solids Struct*. 2015;77:74-85. https://doi.org/10.1016/j.ijsolstr.2015.06.032
17. Iacoviello F, Di Cocco V, Rossi A, Cavallini M. Pearlitic ductile cast iron: damaging micromechanisms at crack tip. *Fratt Integrità Strutt*. 2013;7:102-108. https://doi.org/10.3221/IGF-ESIS.25.15

How to cite this article: D'Angela D, Ercolino M, Bellini C, Di Cocco V, Iacoviello F. Analysis of acoustic emission entropy for damage assessment of pearlitic ductile cast irons. *Mat Design Process Comm*. 2020;2:e158. https://doi.org/10.1002/mdp2.158