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The synergistic action of hydrogen embrittlement mechanisms in steel: HELP + HEDE model

Oral - online presenter: Milos B. Djukic [1]

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Abstract

The deleterious hydrogen effects and provoked degradation of mechanical properties of steel are expressed in diverse forms and often in opposite ways, including both softening and hardening phenomena, depending on three main factors: material, mechanic, and environmental [1]. Although the huge complexity of hydrogen-steel and hydrogen-deformation interactions during hydrogen embrittlement (HE) has been extensively investigated, still there is no agreement regarding the true nature and trigger HE mechanism and recently confirmed synergistic action of multiple mechanisms [2]. Simultaneous action in a cooperative manner of the hydrogen-enhanced localized plasticity (HELP) and hydrogen-enhanced decohesion (HEDE) mechanisms (HELP + HEDE model) of hydrogen embrittlement were detected and fully confirmed experimentally to be active, depending on the local concentration of hydrogen in steel [2-7], and not only through simulation and modeling. The recently proposed HELP + HEDE model of HE by Djukic et al. [2-4] is based on the correlation of mechanical properties to SEM microscopy fractography analysis of fracture surfaces in the presence of simultaneous action in a cooperative manner of the HELP and HEDE mechanisms of HE depending on the local concentration of hydrogen. Recently we further summarized that both the HELP and HEDE mechanism (according to the HELP + HEDE model for HE in steel [3,4], proposed by Djukic et al. in 2015/2016) and their synergistic action are responsible for the degradation of material's resistance to the crack propagation in low carbon steel [5]. The unified HELP + HEDE model for HE in steel [2,5] presented in this invited lecture, is based on the specific fracture modes at various global hydrogen concentrations, both above and below the critical hydrogen concentration, depending on the dominant HE mechanism during the synergistic action mode of both HELP and HEDE mechanisms. The proposed unified HELP + HEDE model and structural integrity model for the synergistic action of hydrogen embrittlement mechanism [2-6] are recently widely accepted to be operative in various metallic materials including steels, iron, nickel alloy, and aluminum alloys, and should enable enhanced predictive maintenance of industrial component systems. This lecture also provides recent results and the

current state of the art in understanding in an overview-form of critical discussion about the synergistic action and interplay of HE mechanisms in steel, experiments, and models. We further hope that this lecture can spark new research and advanced experiments and thereby accelerate progress toward technological solutions to the still unresolved hydrogen embrittlement problem [7].

[1] B.N. Popov, J-W. Lee, **M.B. Djukic**, *Chapter 7 - Hydrogen Permeation and Hydrogen Induced Cracking*, in: Handbook of Environmental Degradation of Materials, Third Edition, edited by Myer Kutz, 2018, William Andrew, Elsevier (2018), pp. 133-162. https://doi.org/10.1016/B978-0-323-52472-8.00007-1

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[3] **M.B. Djukic**, V. Sijacki Zeravcic, G.M. Bakic, A. Sedmak, B. Rajicic, *Hydrogen damage of steels: A case study and hydrogen embrittlement model*, Engineering Failure Analysis, **58** (2015), pp. 485-498. https://doi.org/10.1016/j.engfailanal.2015.05.017

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[5] M. Wasim, **M.B. Djukic**, T.D. Ngo, *Influence of hydrogen-enhanced plasticity and decohesion mechanisms of hydrogen embrittlement on the fracture resistance of steel,* Engineering Failure Analysis **123** (2021), p. 105312. https://doi.org/10.1016/j.engfailanal.2021.105312

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Short Bio - Milos B. Djukic, Associate Professor

Dr. Milos B. Djukic, Associate Professor at the University of Belgrade, Faculty of Mechanical Engineering, Department of Engineering Materials and Welding, Belgrade, Serbia, is a specialist in the field of hydrogen embrittlement, materials and corrosion science, and the mechanical behavior of materials. He has more than 20 years of teaching and research experience and is the author/co-author of 5 books, 5 book chapters, 1 patent, 71 refereed scientific papers in international journals, 120 papers published in conference proceedings and journals and more than 200 studies, reviews, reports, and expertise for industrial partners.

His new book (co-authored with Prof. Branko Popov) entitled: "Hydrogen Embrittlement Theory and Prevention of Hydrogen Damage in Metals and Alloys, 1st Edition" will be published in 2021 by Elsevier. The book chapter (co-authored with Prof. Branko Popov and Prof. Jong Won Lee), entitled: "Hydrogen Permeation and Hydrogen-Induced Cracking" in the "Handbook of Environmental Degradation of Materials, 3rd Edition" was published by Elsevier in 2018.

Since 2014 he is an external peer reviewer for scientific projects for the following European scientific agencies: Research Foundation Flanders, Belgium, National Science Centre, Poland, and the Dutch Research Council, Netherlands.

He was a keynote speaker on the hydrogen embrittlement topic at the Materials Science and Engineering 2018 Conference, Darmstadt, Germany. He was also an invited speaker at the 13th International Conf. on Diffusion in Solids and Liquids in Austria, and at the CORROSION 2015 Conference, Dallas, USA. Recently, in 2021, he gave an invited talk - hydrogen embrittlement topic on the HYDROGENIUS, I2CNER, and HydroMate Joint Research Symposium on Hydrogen Materials Interactions 2021, Kyushu University, Japan, and during the 1st Corrosion and Materials Degradation Web Conference, Session 5 - Corrosion Assessment and Management, 17 May, 2021 organized by MDPI.

He was an external Ph.D. thesis examiner, topic hydrogen embrittlement, at the University of Queensland, Australia, and ISAE-ENSMA, Université de Poitiers, France. He is a member of the editorial board of eight international journals: International Journal of Hydrogen Energy, Frontiers in Materials, Metals, Coatings, Journal of Pipeline Science and Engineering, Frattura ed Integrità Strutturale, European Journal of Materials and Mechanical Engineering, and Structural Integrity and Life. He has 231 verified editor records and 119 reviews for 42 international journals including top journals like Science, Acta Materialia, Scripta Materialia, and Materials Science and Engineering: A.

In 2017 and 2018 he was a co-chair and chair of the two special symposia on hydrogen embrittlement topic during the 14th International Conference on Fracture - ICF14 (symposium co-chair: "Fatigue and Fracture in Aggressive Environments: Mechanisms and Risk Assessment" - Hydrogen Embrittlement Topic) held on Rhodes island, Greece, and during 22nd European Conference on Fracture - ECF22 (symposium chair: "Recent Advances on Hydrogen Embrittlement Understanding") held in Belgrade, Serbia.

In 2019, he was a Managing Guest Editor of Engineering Fracture Mechanics Journal, special issue titled: "Recent Advances on Hydrogen Embrittlement Understanding and Future Research Framework" (https://www.sciencedirect.com/journal/engineering-fracture-mechanics/special-issue/10HVJ5LL55F).

In 2021/2022 he is a Managing Guest Editor of Journal of Natural Gas Science and Engineering, special issue on "Corrosion and Stress Corrosion Cracking in the Natural Gas and Oil Industry" (https://www.journals.elsevier.com/journal-of-natural-gas-science-and-engineering/call-for-papers/special-issue-on-corrosion-and-stress-corrosion-cracking).

In 2021/2022 he is an organizer of the thematic symposium entitled: "TC10B Hydrogen Embrittlement, The Current State of the Art in Hydrogen Embrittlement Understanding" on the 23rd European Conference on Fracture - ECF23 which will be held from June 27 - July 1, 2022, in Funchal, Madeira, Portugal (https://www.ecf23.eu/thematic-symposia/).

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