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STATISTICAL SIMULATION OF FRACTURE TOUGHNESS IN SEGREGATED RPV STEEL USING DEEP-LEARNING-BASED RANDOM FIELD GENERATION AND HIGH-FIDELITY FEA MODELING

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Abstract
Charpy impact tests are used in the nuclear industry to certify forging processes. However, the results of these tests may exhibit a strong variability in the context of large metal parts manufactured by Framatome. Preliminary studies have shown that the steel is highly heterogeneous at the millimeter scale in certain areas of forged parts. These heterogeneities are surmised to be the main cause of the variability observed in the results of impact tests. The aim of this study is to qualify and numerically quantify the effect of these heterogeneities on the distribution of fracture energies thanks to an innovative computational approach featuring deep learning to generate 3D realizations of the mechanical properties from sparse experimental results, and high-fidelity modeling of brittle fracture in heterogeneous Charpy specimens.

1. Introduction

Segregated zones are present in particular near the inner surface side of nuclear reactor pressure vessel (RPV) made from plain ingots of A508 class 3 steel. Those zones, characterized by an enrichment in alloying elements and impurities, are in charge of a high scatter in fracture toughness at low temperatures. Consequently, a significant quantity of material exhibits low fracture energies, or low points.

Experimental observations indicated that micro-segregation plays a critical role in fracture at low energies: fractographic investigations have shown that the rupture was initiated in the segregated zones. Thus, the goal of the study is to take advantage of experimental data, *i.e.*, 2D micrographs of segregation areas similar to the one presented in Figure 1-a., tensile tests data, quasi-static Charpy tests data, chemical concentration profiles and micro-hardness mappings to i) construct a 3D model of the morphology of those segregations as presented in the Figure 1-b., c. and d., ii) characterize the local mechanical behavior of the heterogeneous material and finally iii) perform 3D elastoplastic with large deformations finite element computations of the Charpy impact tests on multiple realizations of the microstructure using the local approach of fracture.

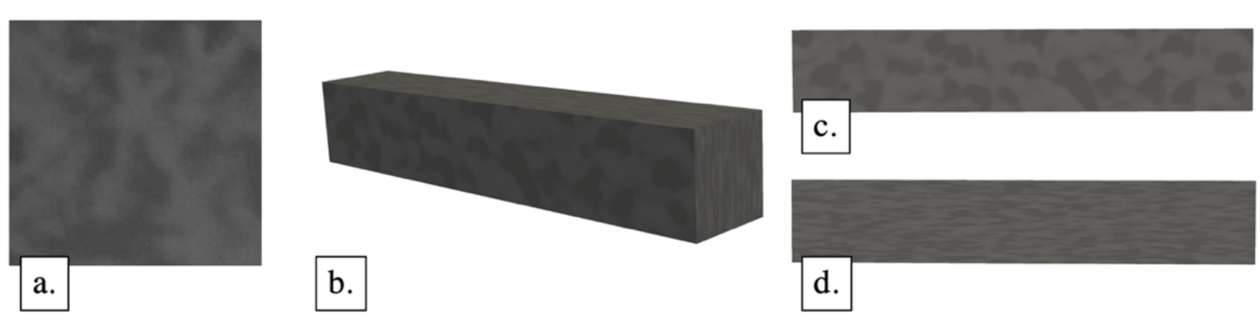

Fig.1 – (a.) 20x20 mm^2 experimental micrograph of a piece of segregated material. (b.) 55x10x10 mm^3 synthetic material generated by the WGAN-GP informed by two points correlation geostatistics from the previous 2D experimental data. (c.) visualization of one face of the synthetic volume with “dendrites” morphology. (d.) visualization of one lateral face of the synthetic volume with “bands” morphology.

2. Methodology

In order to achieve the objectives listed in the introductory part, several tools were developed:

a. The first part of the study was dedicated to the development of a deep neural network in order to generate a 3D field of the microstructure from a set of 2D experimental micrographs. The used architecture is an improvement of the SliceGan [Kench et al.,2021], which is one of the first networks allowing the generation of 3D volumes from 2D datasets to our knowledge. We solved some major numerical artifacts in the generated volume and improved its quality by proposing a new objective function for the training of the network.
b. The second part of the study was focused on the characterization of the segregated region. We took advantage of our large experimental dataset in order to calibrate deformation and fracture models. In particular, we choose a local approach to fracture based on weakest-link statistics (model of Beremin [Beremin et al.,1983]). We developed a program in order to attribute those characteristics to quadrature points within our finite element mesh as depicted in Figure 2-a., b., and c.
c. In the last part, we performed multiple simulations of the Charpy impact test with different realizations of microstructures. The purpose of those multiple simulations was to make a statistical distribution of fracture energies as depicted in Figure 2-d.

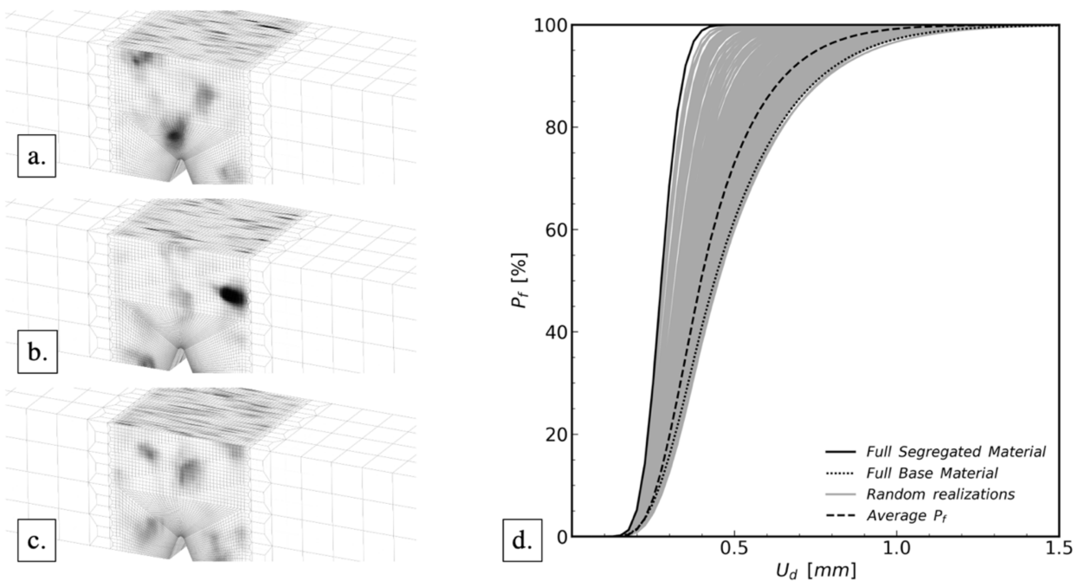

Fig.2 – (a.), (b.) and (c.): Finite element mesh with a random realization of microstructures generated by our neural network. For each gauss point, the dark spots represent the degree of local segregation. (d.): Distribution of the failure probabilities using the Beremin model on a set of 1000 microstructures simulated with a maximal imposed displacement U_d equal to 1.5 mm.

Acknowledgements

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