Ductile Fracture Prediction in Metals: Applications for Pipelines

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1. Research Problem

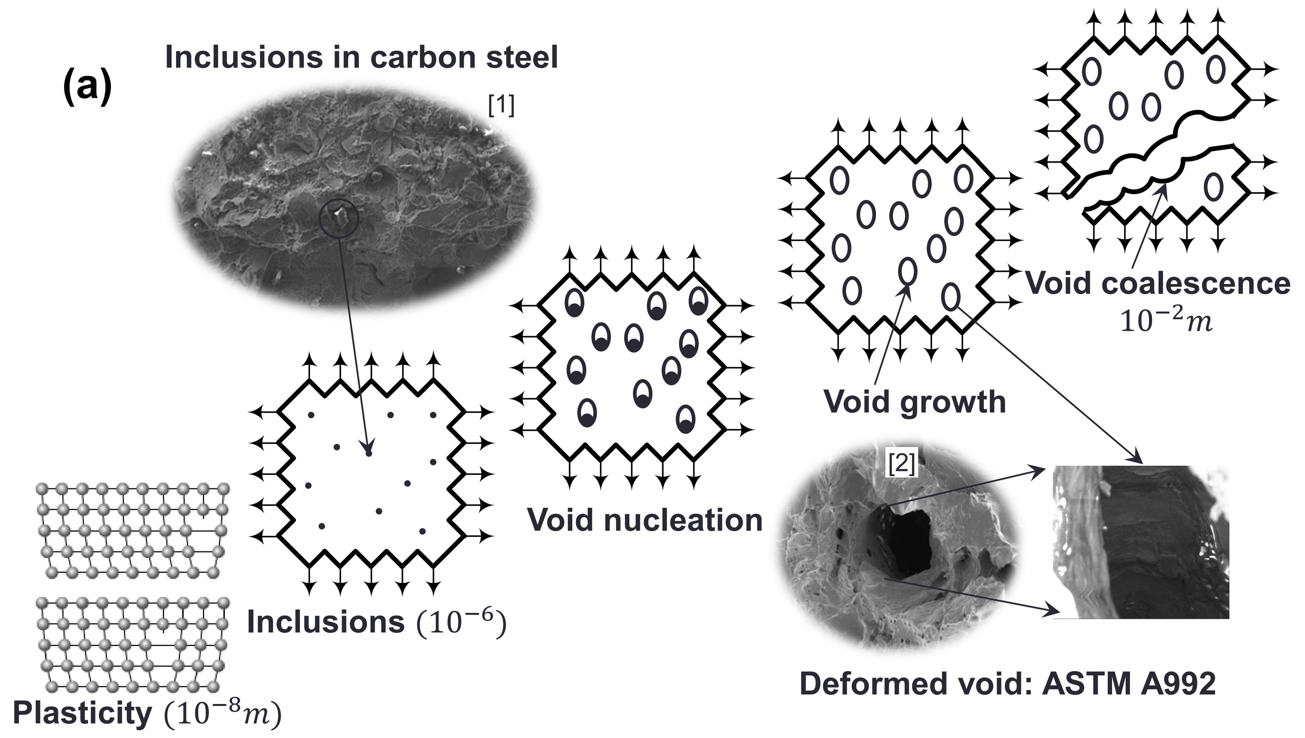
Material/ Weld/ Equipment failure/ fracture is the reason for 32% of pipeline accidents in the past two decades. Fracture in metals and welds is governed by the inherent defects and stress concentration.

2. Research Objectives

(a) to experimentally characterize the microvoid statistical attributes at the instance of fracture by employing microscopy on the fracture surfaces of steel; (b) to quantify the relationship between the experimentally extracted microvoid features at the instance of fracture, and state of stress and strain; and (c) validate obtained relationship to predict ductile fracture in structural steels.

3. Background

Several existing models predict the fracture strains by tracking material scale damage as a function of stress and strain states. The fracture model parameters are usually not directly calibrated from void growth observations although void growth leads to ductile fracture.



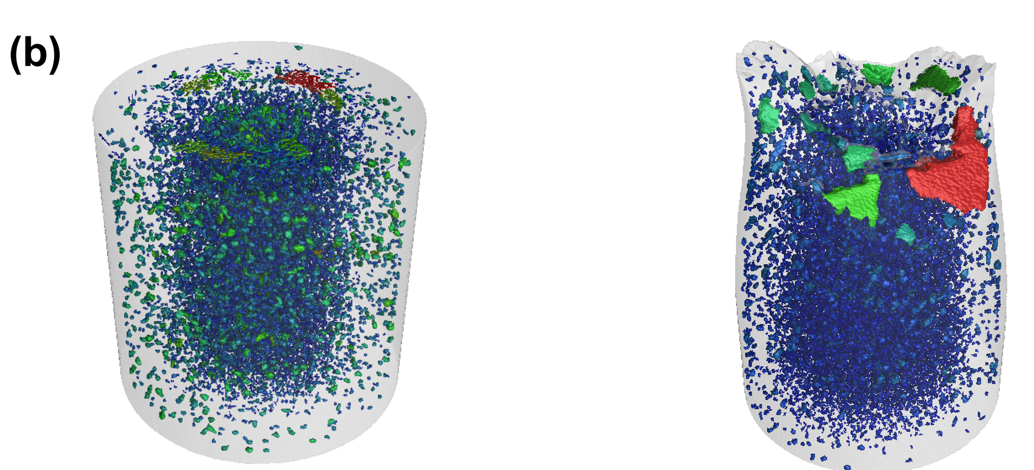


Fig 1: (a) multiscale mechanism leading to fracture in structural steels; and (b) coalesced voids in additive manufactured 17-4 steel

4. Experimental Methodology

Assumptions

1. Voids at coalescence are approximately spherical.
2. Each fracture surface contains approximately one-half of the spherical void.

Experimental Procedure

- Conduct uniaxial tension tests on circumferentially notched steel specimens (C –notch used in present study)
- Observe fracture surface under a microscope and divide into 5 regions (Figure 2)
- Capture microscopic images of all the 5 regions (Figure 2)
- Select two 75 μm × 75 μm sample areas on each of the micrographs (Figure 3)
- Randomly select 25 microvoid areas from each sample area
- Compute area of microvoids using image analysis software ImageJ

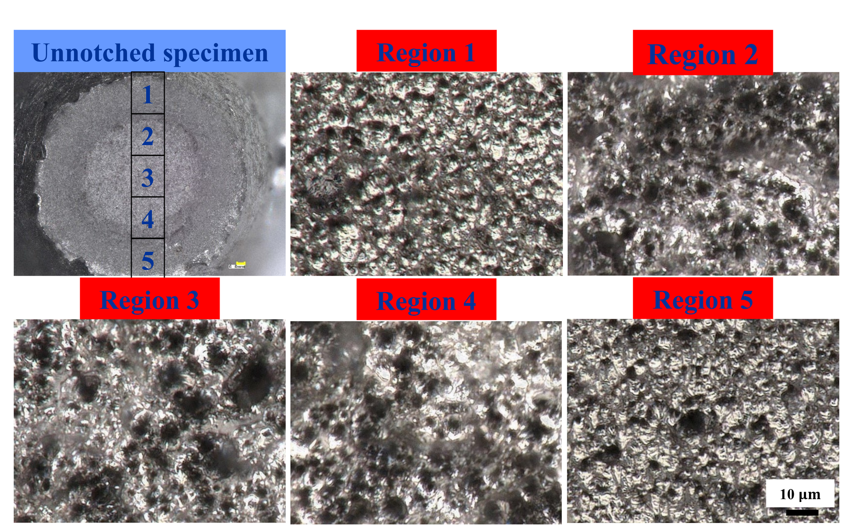


Figure 2: Typical micro-scale fracture images of 17-4PH stainless steel unnotched specimen

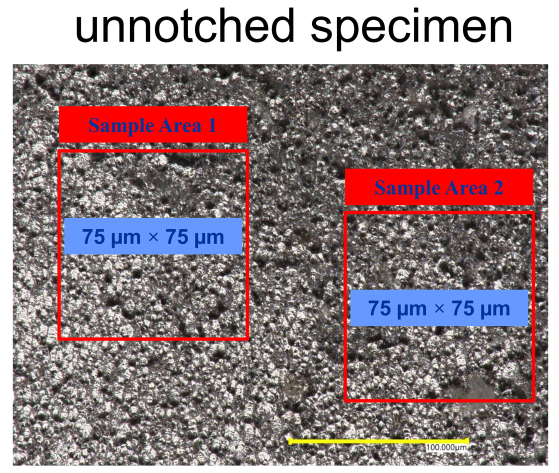


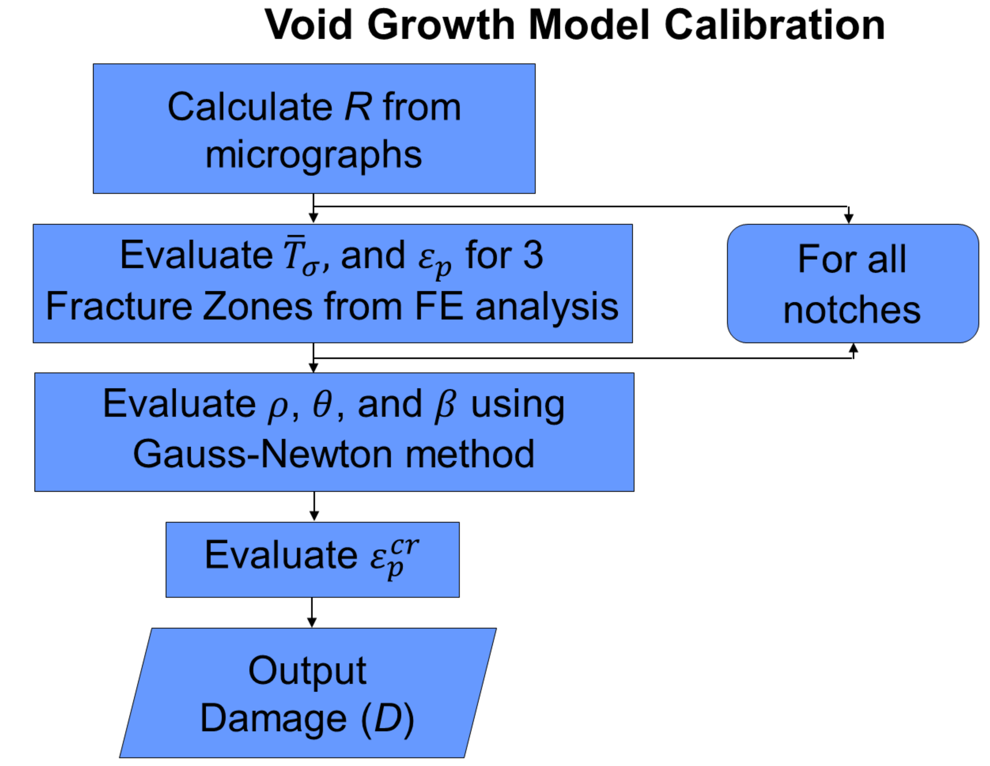
Figure 3: Sample areas in a micrograph

Void Growth Model $ln(R) = \rho + \theta\, exp(\beta T_\sigma)\varepsilon_p$

R: Radius of voids; ρ: Natural logarithm of initial void radius; T_σ: Stress triaxiality; ε_p: Plastic strain

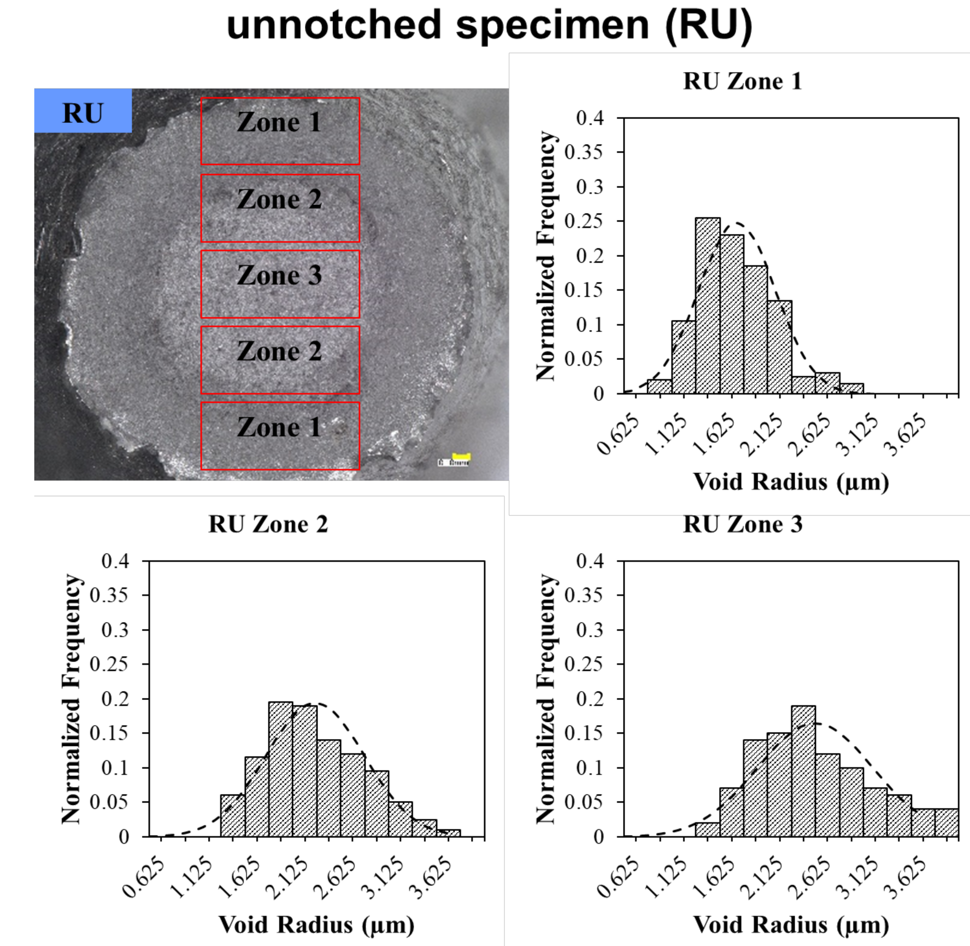
Failure Criterion $\text{Damage (D)} = \varepsilon_p - \varepsilon_p^{cr} = \varepsilon_p - \alpha\, exp(-\beta T_\sigma) > 0$

Void Growth Model Calibration



5. Microvoid Data and Fracture Prediction Results

Sample microvoid statistics for reference unnotched specimen (RU)

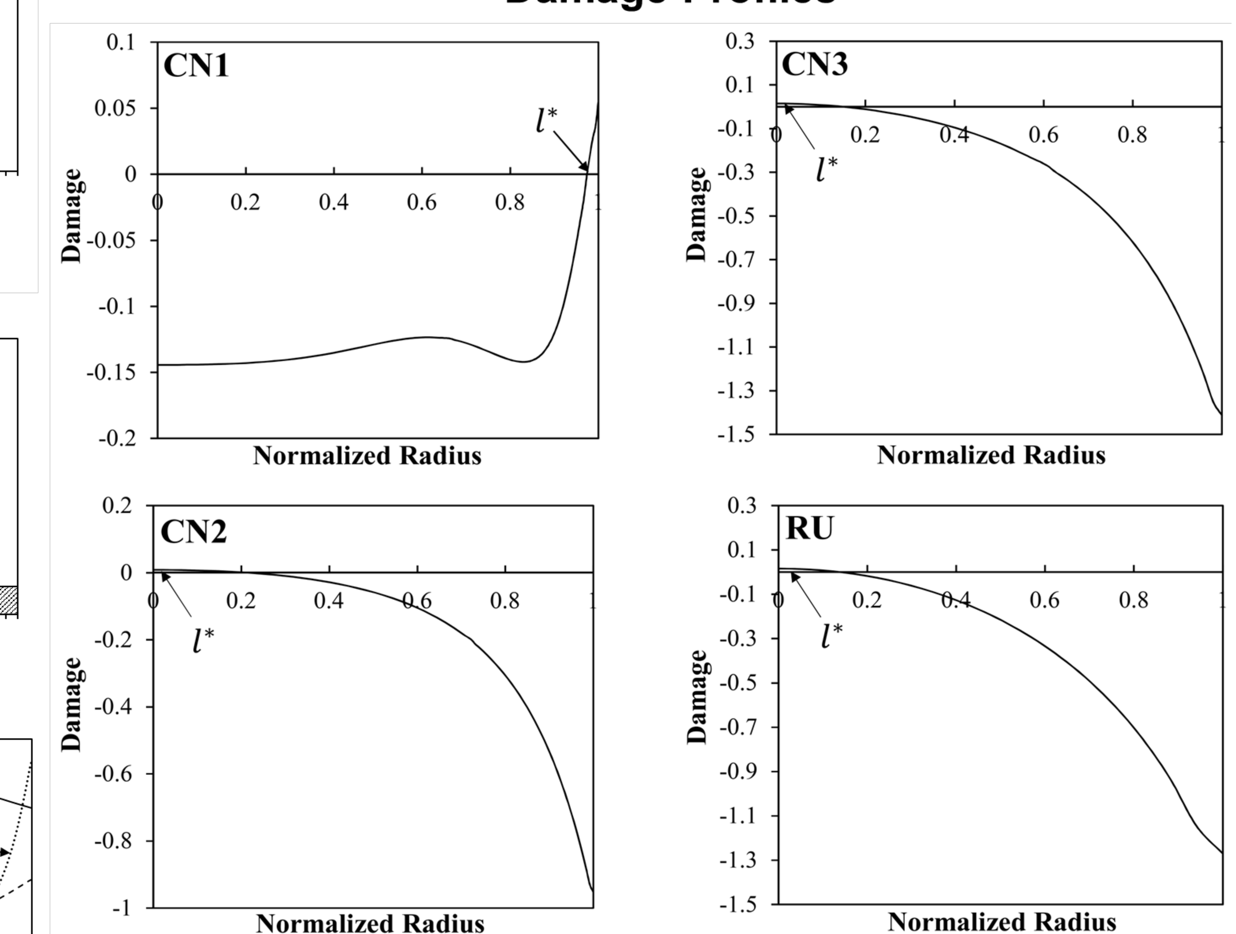


Failure Criterion for 17-4PH stainless steel

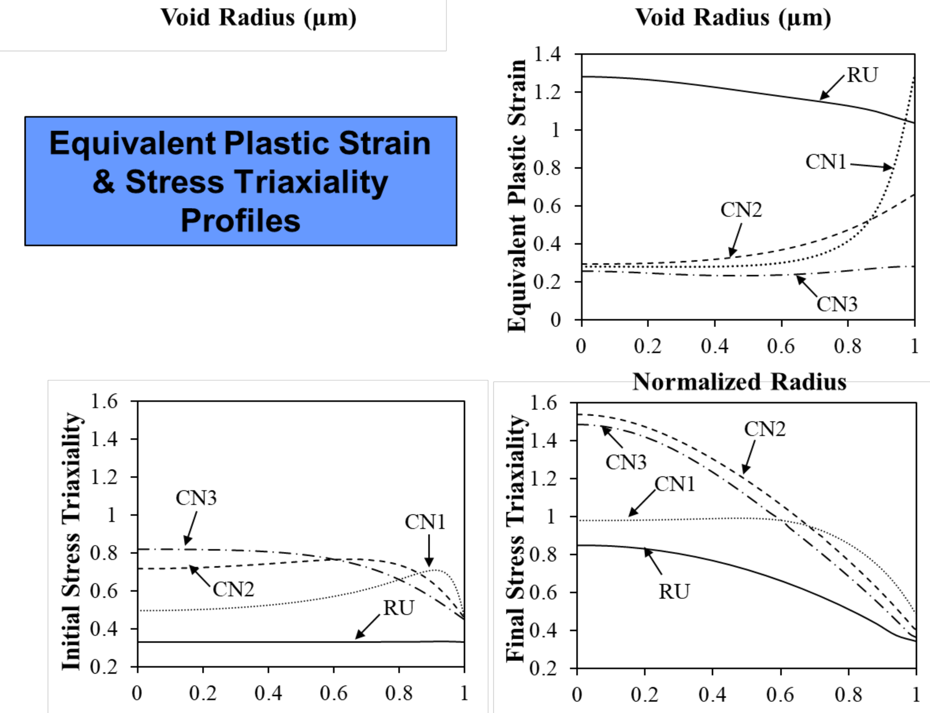
$$\text{Damage(D)} = \varepsilon_p - 3.51\exp(-2.15T_\sigma)$$

Characteristic length: $l^* = 50\mu\text{m}$

Damage Profiles



Equivalent Plastic Strain & Stress Triaxiality Profiles



Comparison of Experimental and Predicted fracture deformations

Material	Specimen	Δ_{exp} (mm)	Δ_{Pre} (mm)	Diff (%)
17-4 PH	RU	2.69	2.3	11.1
	CN1	1.28	1.28	0.0
	CN2	0.8	0.72	10.0
	CN3	0.47	0.45	4.4

1. Microvoid radii on the fracture surfaces range between 0.89 μm to 3.91 μm.
2. Void sizes obeyed normal distribution, & 95 percent of the void radii fell between 0.95 μm to 3 μm.
3. The relationship between the experimental void size and states of stress and strains provided conservative estimates of fracture strains with ~10% maximum error.

6. Acknowledgments

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7. References

1. **R. Yellavajjala**, & Khandelwal, K. (2014). A triaxiality and Lode parameter dependent ductile fracture criterion. Engineering Fracture Mechanics, 128, 121-138.
2. Dey S., **R. Yellavajjala**, and Ulven C. (2023). "Experimental Evaluation of Microvoid Characteristics and their Relationship with Stress and Strain for Ductile Fracture", (accepted for ASCE Journal of Materials in Civil Engineering).

8. Public Project Page

https://labs.engineering.asu.edu/dams/