Damage process of additively manufactured stainless steel 316L under tensile loading in the presence of process-induced defects

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ABSTRACT

This study first investigates the damage process, including initiation and progression for as-built stainless steel 316L components in the presence of internal and surface imperfections during tensile loading in a temporal domain, using X-ray computed tomography (XCT). Then, a numerical approach based on the coupled continuum damage mechanics (CDM) and plasticity model is introduced to perform systematic investigations for assessing the strength of the AM components in the presence of inevitable process-induced imperfections. The results of this study provide further information leading to distinguishing between imperfections and defects and defining acceptance limits for internal and surface defects. Defining acceptance limits for induced process-related defects during AM processes is crucial to paving the road for replacing metal AM components with conventionally produced parts in different industries.

EXPERIMENTAL INVESTIGATION

- Direct metal laser sintering is employed to produce the hourglass-shaped round specimens manufactured vertically with the tensile axis.
- The initial CT scan was performed from the intact specimen (red rectangle) to characterize the internal defects population and surface roughness characteristics.
- The CT scan was performed to monitor the pores' evolution, damage initiation and progression under tensile loading at two stages, after yielding, and close to the tensile strength.

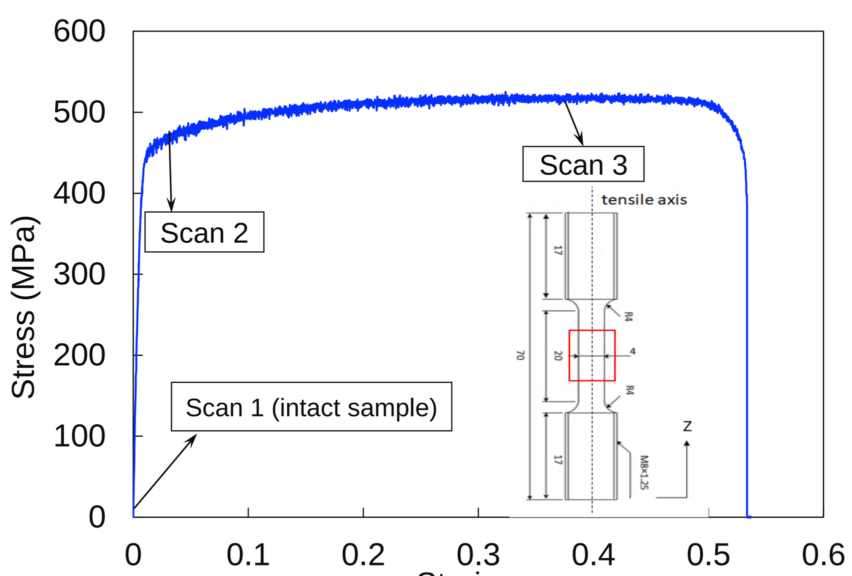


Fig. 1. Tensile stress-strain behavior of the specimen, and stress levels where XCT imaging is carried out.

COUPLED CDM AND PLASTICITY MODEL

- In metal AM components, internal defects and surface roughness cause stress concentration.
- Stress concentration leading to plastic strain localization and material degradation in the vicinity of pores and surface notches.
- The coupled CDM and plasticity model is used to study the material's damage behavior and to simulate the interaction of the internal and surface defects under tensile loading.
- The introduced coupled damage and plasticity model is implemented in the ABAQUS software by the user material (UMAT) subroutine.
- The results of damage behavior using the simulation for several locations around the specimen have been compared with those experimental results.

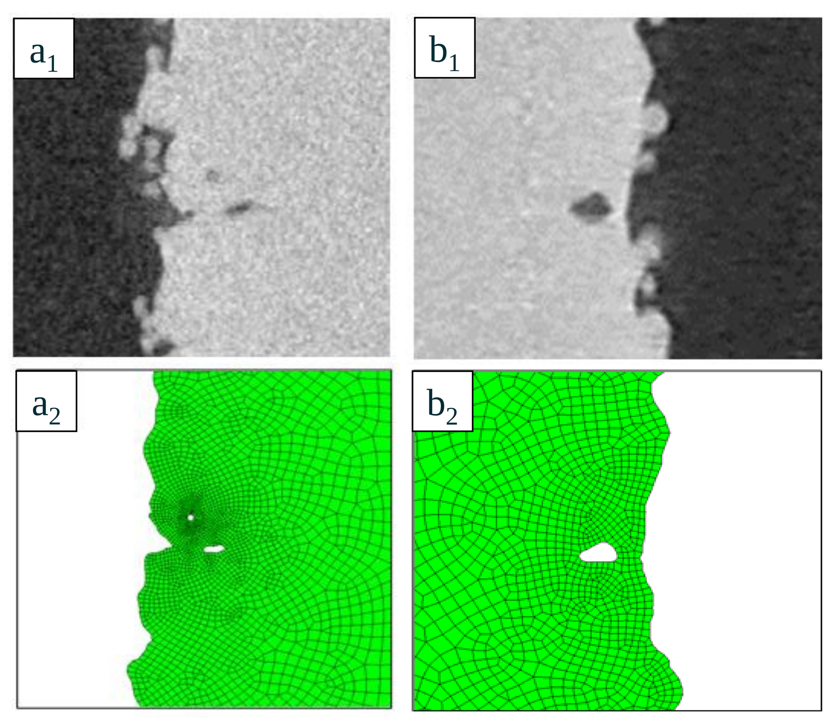
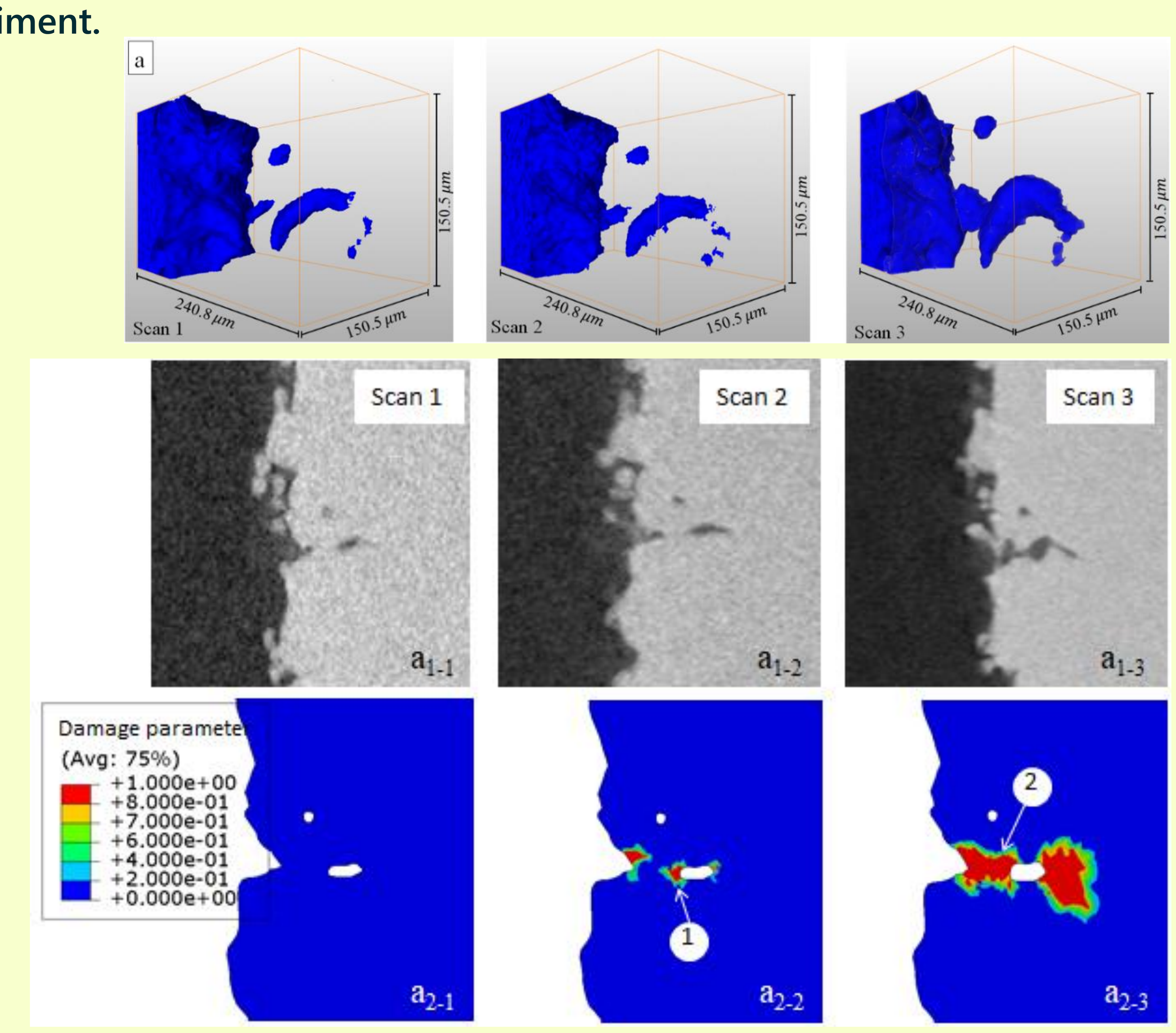


Fig. 2. Real microstructure and FE modeling of two different possible cases in the unloaded state.

RESULTS

- Results of the simulations depict that the damage initiation (e.g., points 1 Fig. 3a2-2 and 3b2-2), and damage evolution, including the interaction of surface defects and internal defects (e.g., points 2 and 4 in Fig. 3a2-3, 3b2-3 are correspond to what occurs in the experiment.



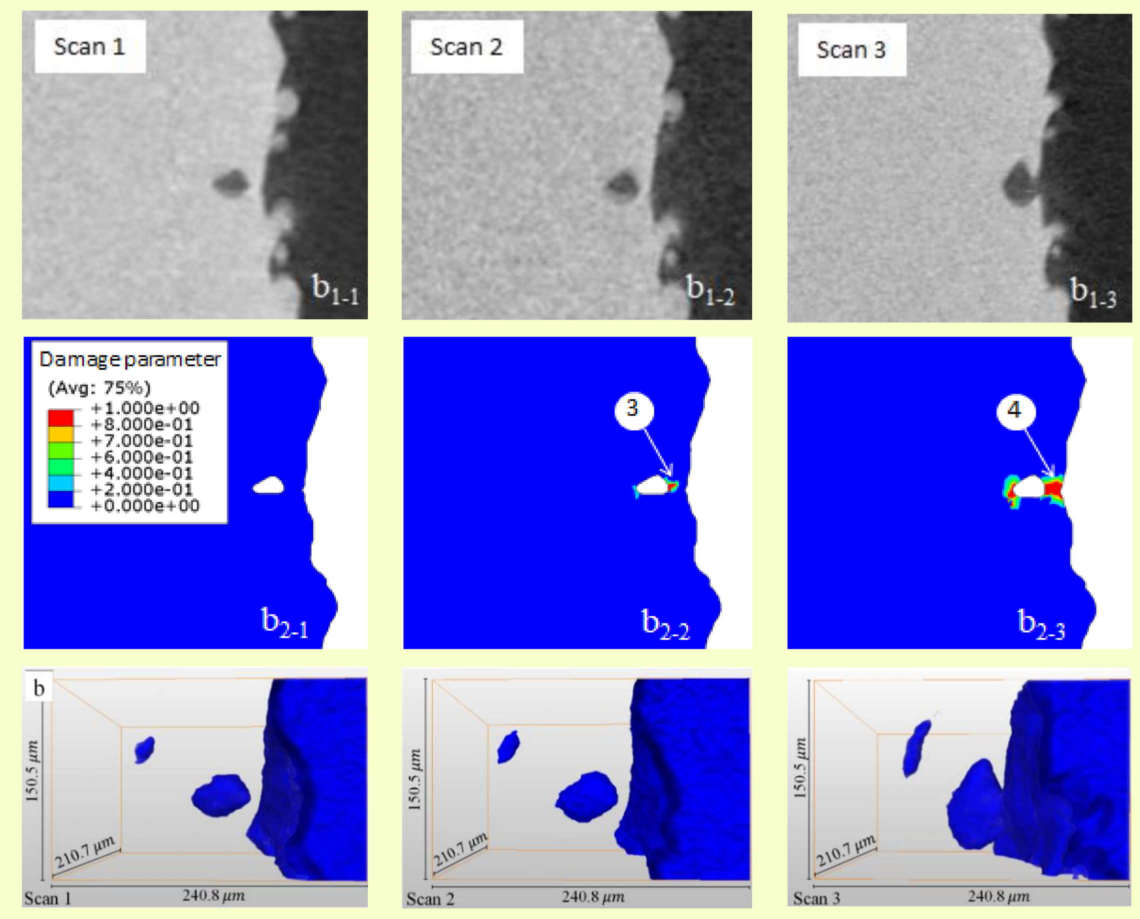


Fig. 3. XCT images and FE simulation results showing damage parameter during tensile testing for two different possible cases: $(a_{(1-1)-(2-3)})$ a pore close to the sharp notch, $(b_{(1-1)-(2-3)})$ a pore close to the smooth notch, and 3D XCT images.

- The effective distance leads to the interaction between the sharp notch on the surface profile and the internal defect smaller than the smooth notch case.
- The stress values in the region between the surface notch and the internal defect are higher in the case of the smooth notch. Therefore, the damage initiation happens earlier than the sharp notch.

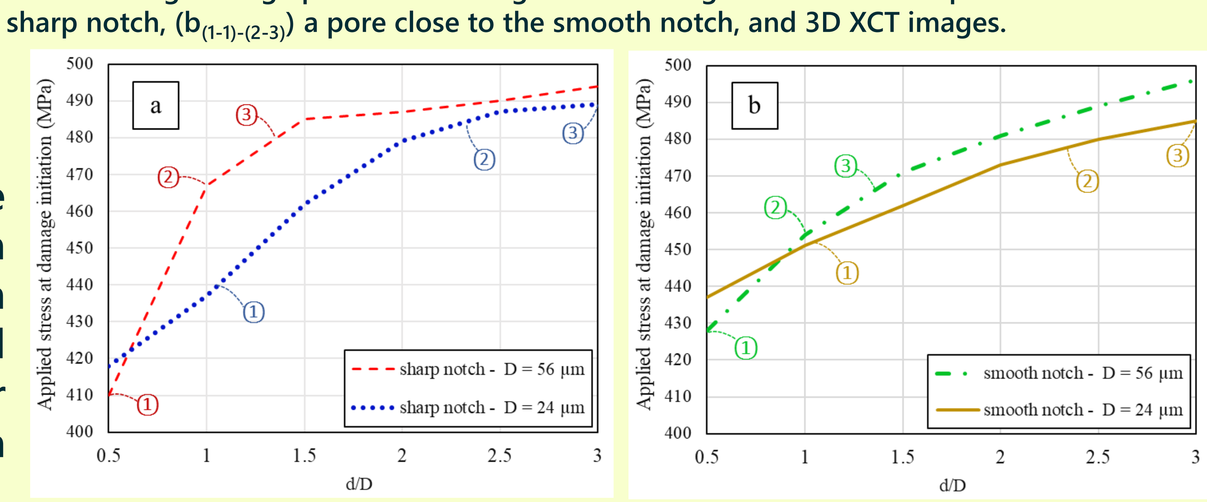


Fig. 4. Applied stress causing damage initiation in different edge distances to the pore's diameter ratio (d/D) for two maximum and average values of the pore's equivalent diameter in the presence of (a) sharp notch (b) smooth notch with different pore sizes.

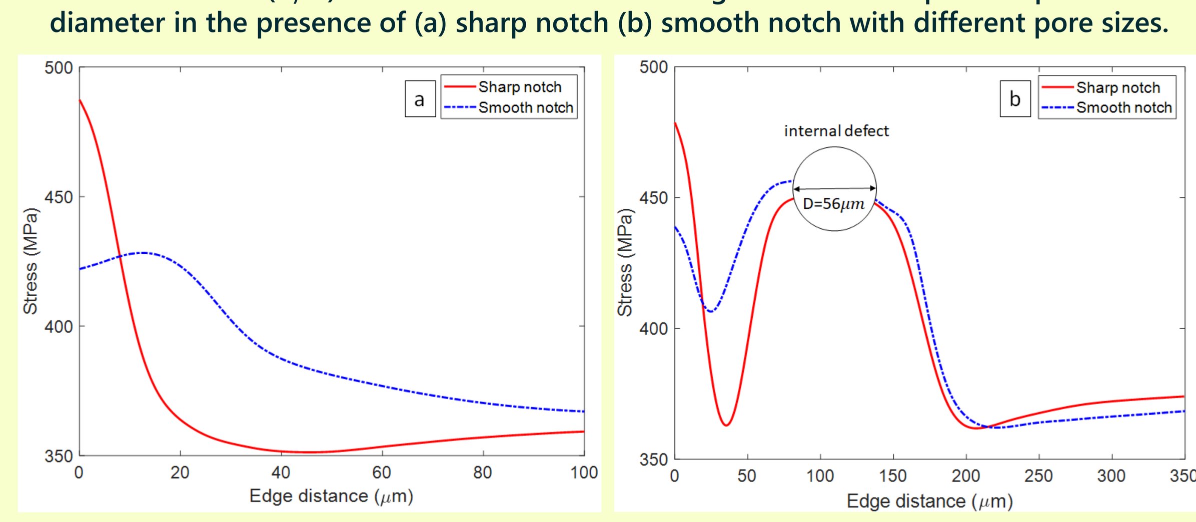


Fig. 5. The von-Mises stress distribution in the vicinity and away from the sharp and smooth notches (a) without the internal defect and (b) with the internal defect.

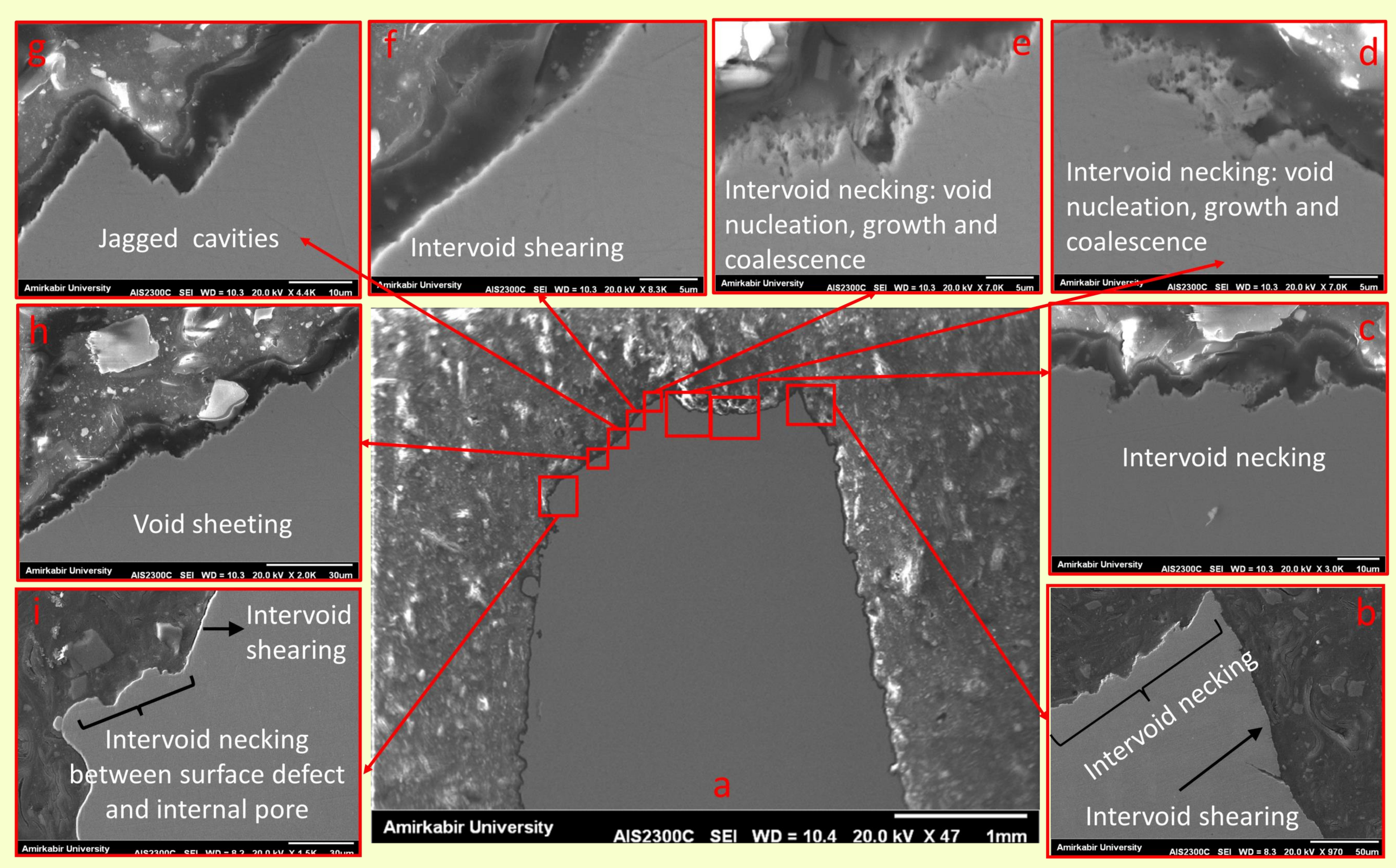


Fig. 6. Detailed SEM images of the specimen's cross-section of the fractured surface in the transverse direction showing different failure mechanisms, intervoid necking, intervoid shearing, and void sheeting.

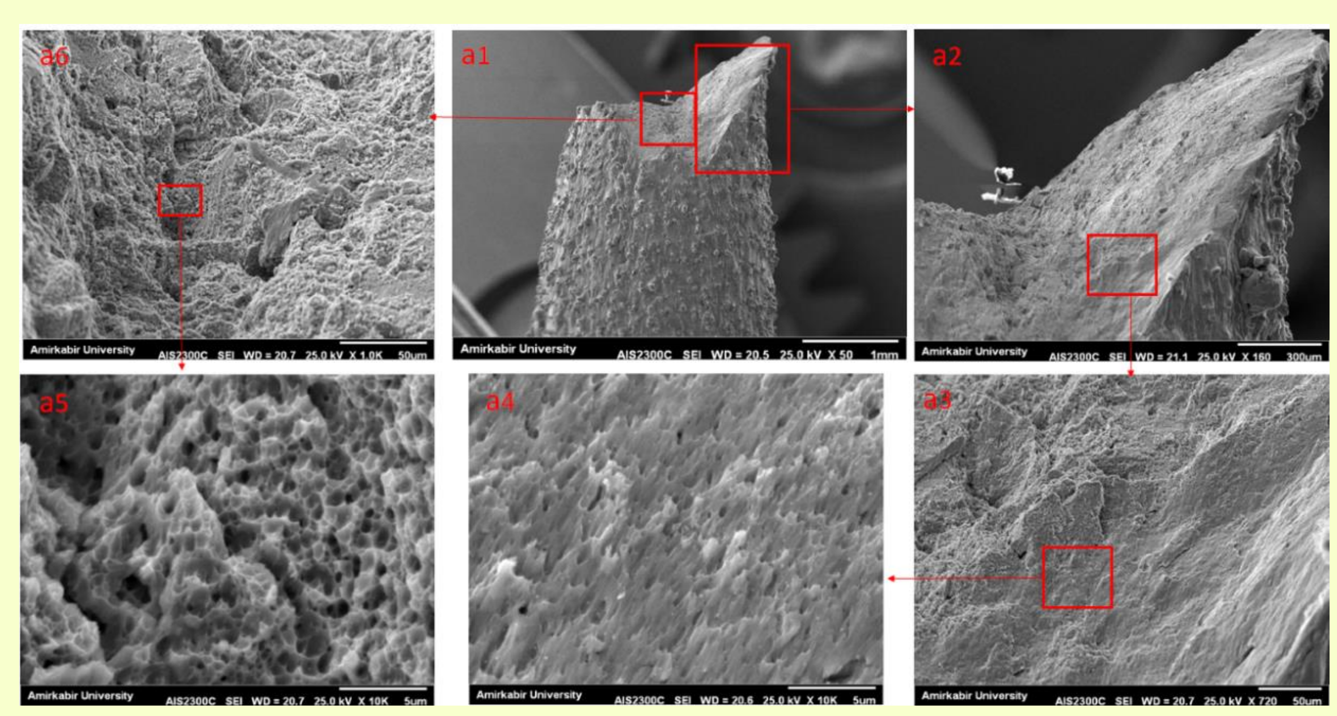


Fig. 7. Detailed SEM images from the $(a_1$-$a_6)$ front and $(b_1$-$b_9)$ top view of the fractured specimen.

CONCLUSION

- FE simulations with introduced coupled damage and plasticity model can accurately capture both the sites and the mechanism of ductile failure compared to experimentally observed.
- In the presence of sharp and smooth notches as surface defects on the surface profile with different shapes, the required stress for damage initiation for the bigger pore is lower than for the smaller one for pores at short distances from the notch.
- By increasing the edge distance, the effect of pore size on the initiation of damage in the presence of the surface defect decreases, and this reduction is higher in the case of sharp notches.
- The intervoid necking mechanism mainly controls the interaction of the internal and surface defects and internal defects in close proximity. Therefore, this mechanism leads to damage initiation, and the other mechanisms of intervoid sheeting and intervoid shearing are active sequentially during the failure process.