DUCTILE FRACTURE OF SS-304L MICROTUBE UNDER COMBINED AXIAL FORCE AND INTERNAL PRESSURE

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Abstract

The fracture behavior of the stainless-steel SS-304L is assessed by loading microtubes of 2.38 mm diameter under combined axial force and internal pressure, using a custom apparatus. The force/pressure ratio is controlled in the experiments, to generate different biaxial stress paths that are proportional or nearly proportional. The results from the experiments are used to calibrate the non-quadratic anisotropic yield function Yld2004-3D. Then, finite element (FE) models of the microtubes are created after incorporating the anisotropic material modeling framework, and compared with the experiments to establish their fidelity. The FE models are then used to probe the fracture behavior under the proportional loading. The failure modes of the microtubes are different depending on the stress state being axial- or hoop-stress-dominant. It is found that the structural instabilities that precede necking are different and appear at different levels of strain. The strains at the onset of fracture, as determined by probing the FE model, reveal significant fracture anisotropy, that can be possibly also attributed to the specimen geometry, beyond the material processing.

1. Introduction

Ductile fracture is one of the basic mechanisms of material failure. Thus, establishing the fracture envelope of a material is of interest for both component and process design. Studies have shown the dependence of the fracture locus on the specimen geometry, the through-thickness gradients, and non-linear loading. Oftentimes, the fracture locus is a correlation between the equivalent plastic strain and stress state at fracture. In this study, the ductile fracture behavior of SS-304L microtube is investigated using experiments and analysis. Depending upon the stress paths followed, the microtubes deform into an axisymmetric bulge, having curvatures in both hoop and meridional directions. Due to this, a membrane stress state similar to shells with double curvature is induced.

The proportional experiments are used to calibrate the non-quadratic anisotropic yield function Yld2004-3D. Since fracture is of interest, finite element (FE) models of the microtube experiments are created after incorporating the calibrated material model. Then, the FE models are used to probe the fracture parameters, i.e., stress triaxiality, Lode angle, and equivalent strain inside the tubes, and establish the fracture locus.

2. Experimental results

The experiments were conducted on SS-304L microtubes with outside diameter and wall thickness nominal dimensions of 2.38 mm and 0.15 mm respectively. The microtubes were loaded under axial force and internal pressure using a custom apparatus with a mesoscale tensile stage (μTS) from Psylotech, with 2 kN force and 1034 bar capacity. The apparatus can apply axial force and internal pressure in a fully coupled way. In these experiments, the force/pressure ratio was kept constant. As as result, biaxial stresses along proportional loading paths were applied to the microtubes throughout loading, almost until failure. During the experiments, the full strain-field of the test-section was acquired using the 3D Digital Image Correlation (DIC) method, using the VIC-3D commercial system.

The fifteen stress paths with nominal stress ratios, i.e., $\sigma_\varphi:\sigma_\theta$ = -2:5, -1:5, -1:10, 0:1, 1:4, 1:2, 4:5, 1:1, 10:9, 5:4, 4:3, 2:1, 3:1, 6:1, 1:0, from the experiments are shown in engineering and true stress space as in Fig. 1. As seen in the figure, most of these stress paths are proportional or nearly-proportional. However, due to the high ductility of the material, some of the constant force/pressure experiments resulted in excessive bulging and thus they deviated significantly from proportionality. The failure modes of the tube vary depending upon the stress path followed. For axial-stress-dominant paths, the tubes ruptured circumferentially, while for hoop-stress-dominant paths, the tubes failed by bursting along a generator.

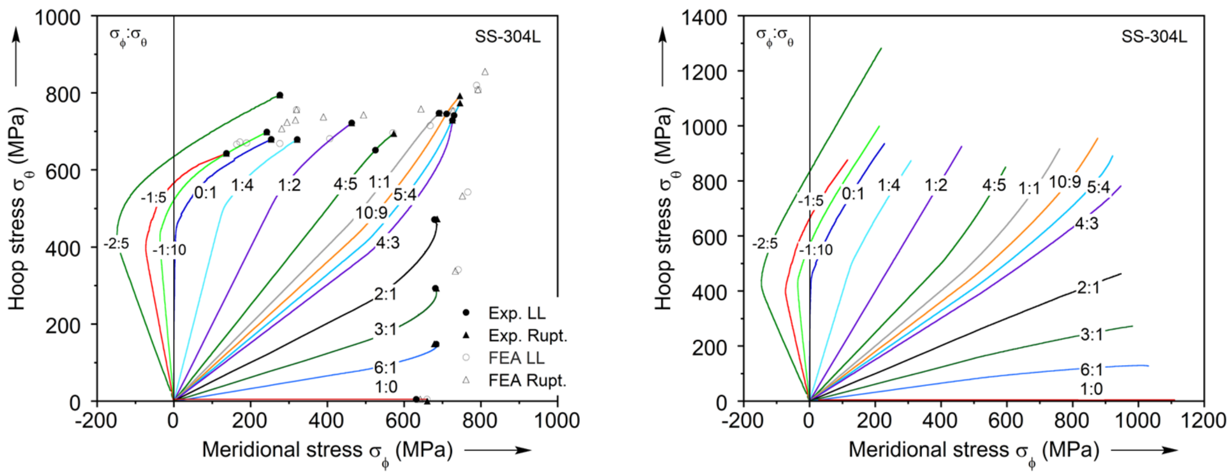

Fig.1 – Stress paths from experiments: (a) Engineering stress space, (b) True stress space..

3. Finite element modeling

The FE models of the microtube experiments were developed in the nonlinear code Abaqus/Standard ver. 6.13-3 using the material modeling framework described above. The microtube is meshed with solid, linear, reduced-integration elements (C3D8R). The internal cavity of the tube is meshed with hydrostatic elements (F3D4 and F3D3) to reproduce the volume-control inflation of the microtubes during the experiments. A local imperfection in the form of an axial or circumferential groove of reduced thickness is added in the model, to simulate failure for the hoop-stress and axial-stress dominant paths respectively. These imperfection orientations are selected based on the failure modes observed in the experiments. The predictions of the FE models are compared to the behavior observed during the microtube experiments. The FE predictions match reasonably well with the experiments in terms of average stress-strain curves and nominal strain paths.

4. Ductile fracture behavior

The fracture parameters, i.e., triaxiality, Lode angle parameter, and equivalent plastic strain are extracted from a material point adjacent, but outside of the imperfection region at mid-thickness of the tube using the FE models. The loading paths are found to be reasonably proportional, for all stress paths examined in this work. The stress triaxiality remains relatively constant for most of the paths, while it is evolves somewhat for the paths in the second quadrant. This deviation of proportionality can be attributed to the change in overall tube geometry during the deformation. The effect of orientation-sensitive loading paths can be seen for the microtubes due to the wide range of triaxialities studied here. The loading paths, and thus the strains at fracture from the axial-stress dominant paths are found to be much higher than those for the hoop-stress dominant paths, revealing the anisotropic nature of fracture behavior of the tubular specimen.

5. Summary and conclusions

The ductile fracture behavior of SS-304L microtubes was investigated using experiments and analysis. The microtubes were loaded until fracture under a combined effect of axial force and internal pressure using a custom apparatus. The experiments were used to calibrate Yld2004-3D nonquadratic, anisotropic yield function in order to incorporate the plasticity modeling in the FE simulations. The predictions from the FE simulations were compared to the experiments to establish the fidelity of the numerical models. The FE models were then used to obtain the fracture parameters, i.e., triaxiality, Lode angle parameter, and equivalent plastic strain to study the fracture behavior of the microtubes. The proportional results show that the loading paths maintain constant triaxiality and Lode angle parameter for most of the paths along with the orientation sensitive loading, indicating an anisotropic nature of the fracture behavior.