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Experiments and Predictions of Large Deformation and Failure in Thermomechanical Loading Environments

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The response of 304L stainless steel to combined mechanical and thermal loadings is studied to enable the development of validated computational simulation methods for predicting deformation and failure in coupled thermomechanical environments. Experimental coupling was accomplished on axisymmetric tubular specimens that were mechanically loaded by internal pressurization and thermally loaded asymmetrically by side radiant heating. Mechanical characterization experiments of the 304L stainless steel tube material was completed for development of a thermal elastic-plastic material constitutive model used in the finite element simulations of the validation experiments. The design and implementation of the experimental methodology and results of preliminary experiments were presented at 2010 SEM Annual Conference [1, 2].

The experiments were designed to have well-defined, controlled thermal and mechanical boundary conditions that could be accurately represented in the simulations. Experimental parameters studied include geometrical features, applied temperature rates, pressurization rates, maximum temperature and pressure, time at temperature and phasing of the thermal and mechanical loading. Specimens were made from 89 mm (3.5 in.) diameter 304L stainless steel tube with a wall thickness of 6.35 mm (0.25 in.), an overall length of 355 mm (14 in.) and a reduced wall thickness in sections of variable length. Specimens were instrumented with twenty-three Type K intrinsic thermocouples at locations around the circumference, mainly concentrated in the high heat region directly in front of the heat source, as shown in Figure 1. Full-field thermal measurements, applied internal pressure and specimen mechanical response were continuously monitored during the experiments and were used as direct input into the finite element simulations of each experiment. Specimen deformation and dimensional changes were measured in-situ with optical photography methods. A photograph of an instrumented specimen during an experiment is shown in Figure 2. The heat shroud is shown on the left surrounded by an insulating ceramic board, the shroud was heated by a double bank of quartz lamps. The specimen was internally pressurized using nitrogen gas. Both temperature and pressure were computer controlled to any ramp profile desired. Overall axial force and displacement were controlled using MTS Flextest controller of the 220 Kip test frame.

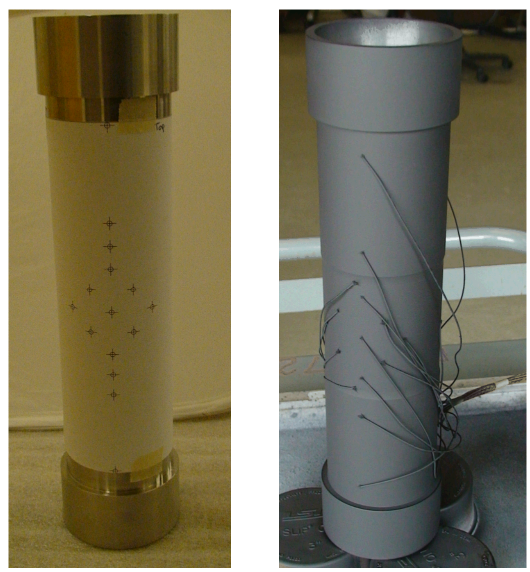

Fig. 1. Thermocouple placement on 304L stainless steel tube specimens.

The results from specimen #10 are shown in Figures 3 and 4. The center temperature of the specimen was ramped at 30 degrees/minute from room temperature to 650C. Once this temperature was reached it was held and the specimen was pressurized at a rate of 72 psi/minute until failure occurred at 645 psi. At failure, the specimen split vertically first, followed by horizontal splitting. Results from specimen #8 are shown in Figures 5 and 6. The temperature and pressure were ramped simultaneously, at 30 degrees/minute and 36 psi/minute, until failure occurred at 650C and 640 psi. In a similar experiment, specimen #9 was ramped at the same temperature rate, but at twice the pressure ramp rate. In that case, specimen failure occurred at 325C and 730 psi. Several variations of temperature and pressure ramp rate were imposed, as well as heating to various hold temperatures prior to pressurizing. A photograph of several of the failed specimens is shown in Figure 7. In each case, the pressure, displacement, axial load and full-field temperature data was used as direct input into the finite element simulation of the experiment. Figure 8 shows an example of the simulation results for specimen #2 which had similar applied temperature and pressure profiles to specimen #10. Using the full-field thermomechanical loading data as input along with a tearing parameter based determination of failure [3], prediction of failure times have matched the experimental results very closely.

Fig. 2. Thermomechanical test specimen during experiment

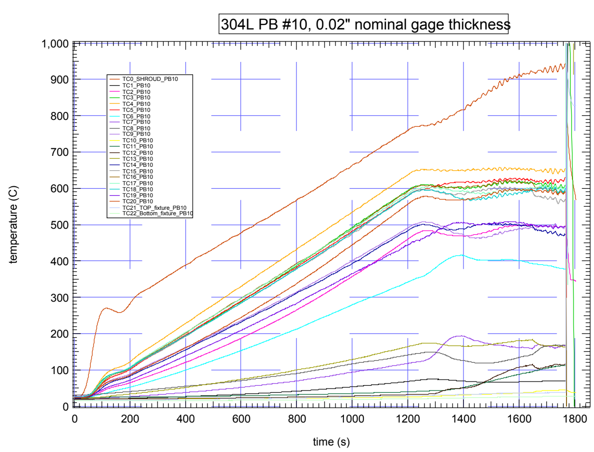

Fig. 3. Temperature measurements from specimen #10

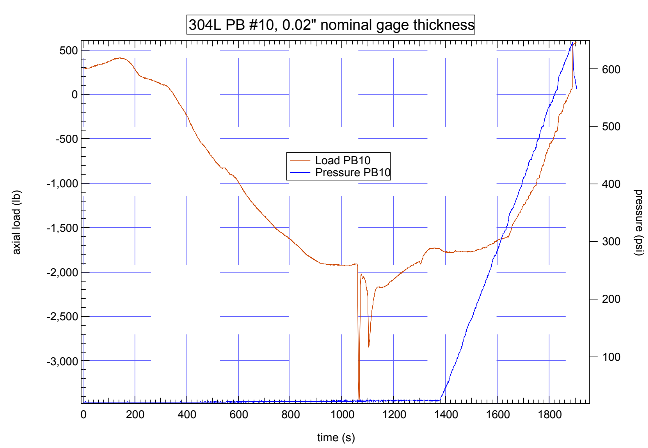

Fig. 4. Applied pressure and axial load response of specimen #10

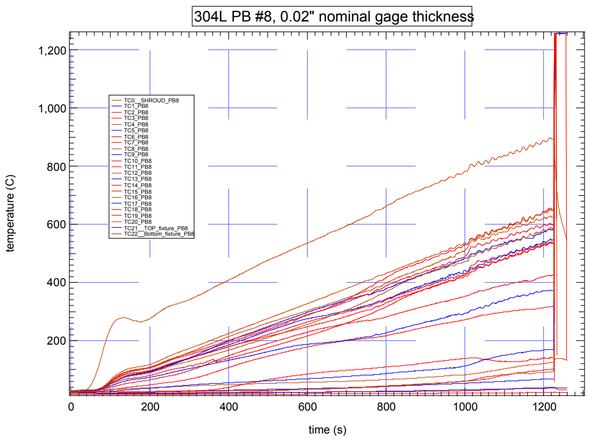

Fig. 5. Temperature measurements from specimen #8

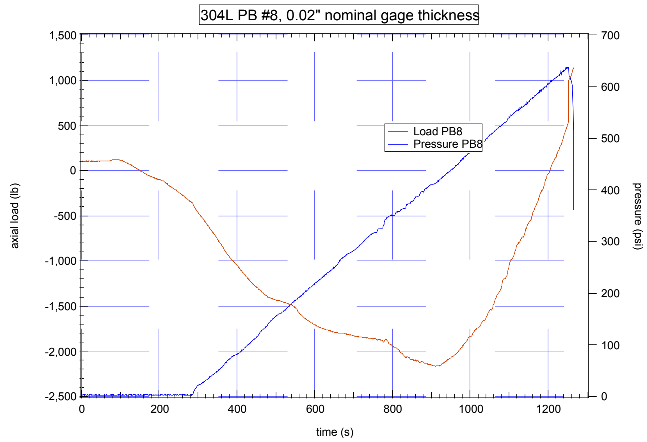

Fig. 6. Applied pressure and axial load response of specimen #8

Fig. 7. Specimens failed under various thermomechanical loading conditions

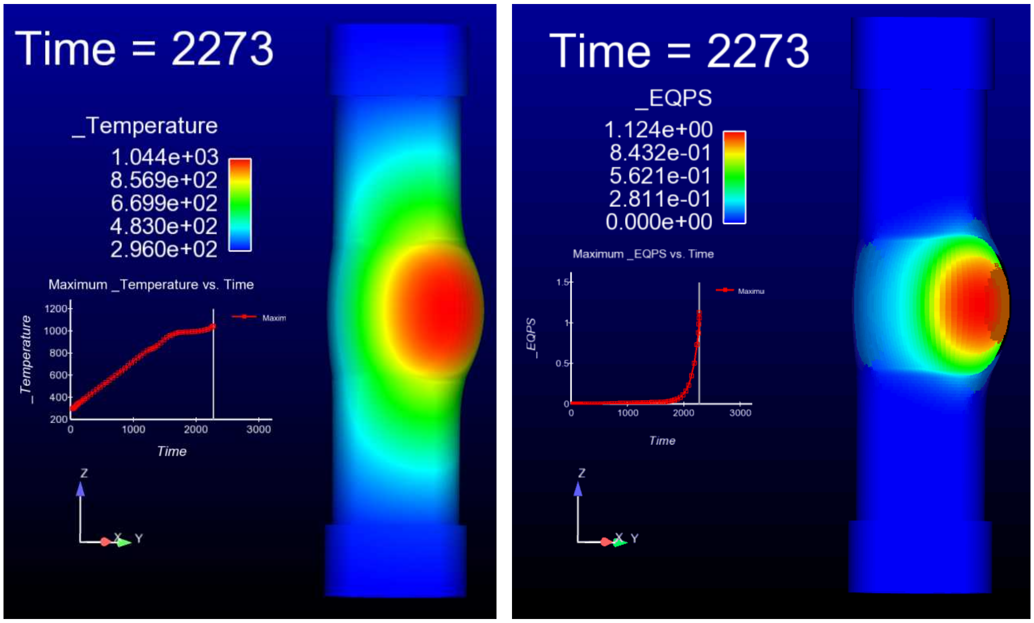

Fig. 8. Thermal-mechanical simulation using measured thermal field mapped onto finite element model of specimen

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