

COMPOSITE OVERWRAPPED PRESSURE VESSEL (COPV) LIFE TEST

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ABSTRACT

Recent attention has been focused on how NASA and its commercial partners have been placing less emphasis on testing and have become more dependent on analytical methods when evaluating design margins for fracture-critical components. Of high concern is the possible misuse of such analytic models for thin-walled metallic liners for composite overwrapped pressure vessels (COPVs).

The NASA Engineering and Safety Center (NESC) has initiated an assessment to understand the limitations of linear-elastic fracture mechanics (LEFM) computational methods used to predict fatigue crack growth rate behavior of small cracks in thin metal liners for COPVs. It has been observed that fabrication of some thin metallic liners results in a wide variation in microstructure morphology, which results in varying microscale crack growth mechanisms. The ultimate goal is to develop and demonstrate a test-based methodology validating the safe-life requirements for COPVs with thin, elastically responding metal liners where LEFM methods are not appropriate.

MOTIVATION

There is growing concern within NASA that technology gaps are leading to the use of Durability and Damage Tolerance (D&DT) tools beyond their capabilities for both analysis and test¹. Many are still using continuum based LEFM in a noncontinuum regime. In these cases global properties may not apply and damage growth processes are dependent on local environments. Therefore it is essential to understand local Properties, local environments and to develop new noncontinuum methods. Fig. 1 illustrates the important relationships of length scale with D&DT engineering practices and continuum mechanics based methods.

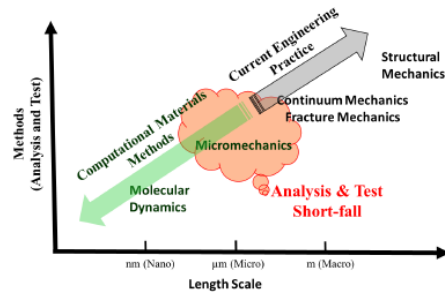


Figure 1. D&DT analysis and test methods as a function of length scale.

For COPV's one must also consider fracture control safe-life requirements. For COPVs with elastically responding liners the initial crack is based on the largest crack that can be missed by the non-destructive evaluation (NDE) inspection. The undetected crack (part-through surface crack) is assumed to exist at the "most unfavorable location" with respect to the applied stress and material properties. The "most unfavorable" crack must be shown analytically to be able to survive 4 lifetimes. Safe-life testing can be performed in lieu of analysis (4 lifetimes are still required). For COPVs with plastically responding liners. No generally accepted elastic/plastic analytical method is available. Therefore, testing is the only acceptable method of demonstrating safe-life (4 lifetimes are still required).

So the fracture control concern is that LEFM assumptions at some point will become violated as the liner thickness is reduced. The question that needs to be answered is if the current theories that define the LEFM limitations relative to thickness (e.g., crack depth + plastic zone < remaining ligament, 5 to 10 grains in the remaining ligament) are valid? The ultimate question to be answered is if better guidelines be developed to quantify when the use of LEFM is invalidated by decreasing thickness (influenced by applied stress, yield stress, and microstructure)?

COPV LIFE TEST ASSESSMENT

The NESC has approved an assessment title "COPV Life Test". The current practice is to use LEFM computational methods to demonstrate safe-life of elastically responding liners while test is used to demonstrate safe-life of plastically responding liners.

The intent of this assessment is to develop test data to understand the limitations of the LEFM computational methods used to predict fatigue crack growth rate behavior of small detectable cracks in thin metal liners for COPVs. The ultimate goal is to develop and demonstrate a test-based methodology validating the safe-life requirements for COPVs with thin, elastically responding metal liners where LEFM methods are not appropriate. The test methodology used in this assessment reflects the AIAA S-081² safe-life demonstration requirements for plastically responding liners.

For this assessment three commonly used COPV liner materials will be examined: 6061-T6 aluminum, Titanium 6Al4V and Inconel. Sheet alloys in various thicknesses for each alloy will be used. A spun formed 6061-T6 aluminum liner will also be used for microstructural and fatigue crack growth tests and for the COPV demonstration test. To date only testing on the aluminum sheet materials and liner have started. Attempts are being made to secure additional materials from known liner materials.

The first task for this assessment was to perform a microstructural comparisons and small-scale testing of 6061-T6 sheet materials versus the spun formed liner. A coupon will be designed which simulate a bi-axial stress field. The expected outcome for these tests is that the materials will be characterized and any deviation from the LEFM behavior will be summarized with recommendations for modeling improvements identified, if required. A quantification of the grain size distributions within the liner and at various location of the spun-formed liner will be performed. A direct measure of the inherent error in the LEFM-based damage tolerance models will be provided through comparison with the small-scale specimens that more closely mimic in-service loads and geometries.

Materials characterization tests for various thicknesses of the three sheet material alloys will be performed. Included will be uniaxial tensile tests where measured loads will be compared to both global strain and local strain using differential interference contrast (DIC) methods. These tests will be performed on traditional samples and using the coupons that simulate a bi-axial stress field. Uniaxial long crack fatigue crack growth tests measuring cycle and crack length will be performed. For these tests da/dN versus ΔK will be calculated and compared to the NASGRO database. The expected outcomes from these tests will be: (1) uniaxial tensile behavior for global and local finite element analysis (FEA) of sheet material, (2) baseline fatigue crack growth rate behavior for sheet material for comparison with NASGRO database and (3) comparison of small-scale and long-crack growth data noting deviations from LEFM models.

Fatigue crack testing will also be performed for each

sheet material. 15 L-T and 15 T-L surface crack uniaxial fatigue crack growth rate coupons will be tested per material.

Uniaxial deep notch coupons that simulate biaxial conditions, identical to previous tests, will be machines. Six each for the L-T and T-L orientations. Electrical discharge machining (EDM) notches to the center of the coupons (size: 0.02 inch long by 0.01 inch deep). At a select stress level and stress ration the number of cycles to nucleate a crack and the number of cycles to reach the desired crack length will be measured.

Surface crack fatigue crack growth rate tests will be performed with no autofrettage cycle applied and with an autofrettage cycle applied. For these tests the end of the pre-crack will be marked using Sharpie® ink. Cycling will be stopped prior to the crack breaking through. Each fracture surface will then be examined using a scanning electron microscope (SEM). The initial and final crack size and shape will be measured. Comparisons to surface crack measurements and crack depth estimates will be performed.

The expected outcomes of these fatigue tests are: (1) precracked coupon specimens for crack growth rate testing, (2) fatigue crack growth rate behavior for elastic conditions without an autofrettage cycle, and (3) fatigue crack growth rate behavior for elastic conditions following an autofrettage cycle. Considerations of both tensile yielding at autofrettage pressure and compressive yielding during the subsequent depressurization will be made.

Concurrent with this testing the preliminary design of the test COPV will be performed. Data from the fatigue testing will be used to determine the liner thickness and wrap configuration. The COPV will have a maximum design pressure (MDP) of 4,000 psi, an autofrettage of approximately 12,500 psi and approximately 80% yield at MDP. The goal of the design is to hoop strain endpoints and number of cycles for each test. This includes Liner hoop strain at autofrettage pressure, liner hoop strain at zero pressure after autofrettage and liner hoop strain at MDP after autofrettage and unloading.

NASGRO coupon predictions will be performed. Fatigue crack growth rate behavior (da/dN vs. ΔK) from either the NASGRO database or test data or a combination of the two will be used. NASGRO fatigue crack growth predictions for each surface crack test will be made with comparisons to predicted measurements. The expected outcome for these comparisons are: (1) a fatigue crack growth rate model for the material used in the coupon and COPV tests, (2) LEFM NASGRO predictions of fatigue crack growth behavior, and (3) an evaluation of the thickness where LEFM predictions are invalid.

Liner to COPV activities will then proceed. An

evaluation of 15 liners for thickness uniformity will be done, selecting the 6 most uniform for chem-milling. The liner will then be chem-milled to the thickness determined in earlier tests. Up to 10 EDM notches to each liner will be added at specified locations (size: 0.02-inch long by 0.01-inch deep). The outer surface will be polished as necessary. The liners will then be pre-cracked using hoop stresses previously determined. These tests will be done hydrostatically. NASGRO will be used to estimate number of cycles applied. Eddy current NDE will be used to characterize initial condition. Crack lengths will then be measured at appropriate intervals using eddy current. Pre-cracking will stop when an appropriate number of cracks achieve the desired length, but before the longest crack is 20% longer than the desired length. At this point the COPV liners will be wrapped. A COPV with cracks will then be tested. An autofrettage pressure cycle followed by 4 MDP pressure cycles will be performed. DIC strain measurements will be made and compared to FEA design. An evaluated will be made for techniques for obtaining the magnitude of the strain on the ID of the liner after autofrettage and MDP cycling. The expected outcome for the these tests are: (1) notched liners of the appropriate thickness, (2) liners with fatigue cracks nucleating from notches and/or naturally occurring defects, and (3) strain measurements for validation of the FEA COPV model.

COPV testing will then proceed. Pressure testing will be done applying an autofrettage pressure cycle and the appropriate number of MDP pressure cycles. Post-test examination will be performed. The COPVs will be cut in half (away from any notches) and composite overwrap removed. Eddy current NDE will be performed of the ID surface to search for naturally nucleating cracks if appropriate. After cutting out the area around each known crack and the fracture surface will be examined with an SEM measuring initial crack size and shape, crack size and shape after autofrettage and crack size and shape at failure. The expected outcomes for these tests are: (1) The average crack growth rate behavior for outer diameter (OD) (and possibly ID cracks) between the autofrettage marking and the end of the subsequent fatigue region (2) a procedure for full-scale COPV testing.

Finally NASGRO COPV predictions will be performed. The fatigue crack growth rate behavior will be defined (da/dN vs. ΔK) from either NASGRO database or test data or a combination of the two. NASGRO fatigue crack growth predictions will be made for each crack in each COPV. Comparisons will be made to predicted measurements. The expected outcome for this activity is an evaluation of the NASGRO LEM fatigue crack growth life predictions for COPVs with thin liners.

INITIAL RESULTS

Liner microstructure variation

Metallographic specimens were removed from various locations of the 6061-T6 spun formed liner. As shown in Fig. 2 the grain size varied throughout the bottle. Larger grain sizes were observed in samples taken from the domes, where a greater amount of heat and deformation were needed to create the liner's shape. In the cylinder regions smaller grain sizes were observed. The mid cylinder grain size was similar to that found in rolled 6061-T6 sheet (Fig. 3). But comparing the spun formed to rolled differences were observed. The spun formed liner's microstructure followed the flow lines of the spin forming process and had a random texture. The rolled sheet had elongated grains and a rolled texture. Also, the distribution of secondary phase particles was noticeably different between the two materials.

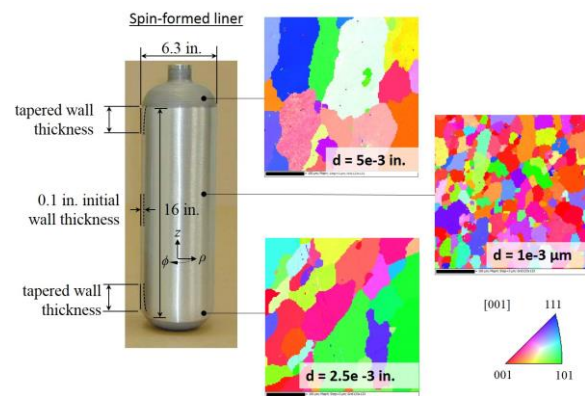


Figure 2. Liner Microstructural variation

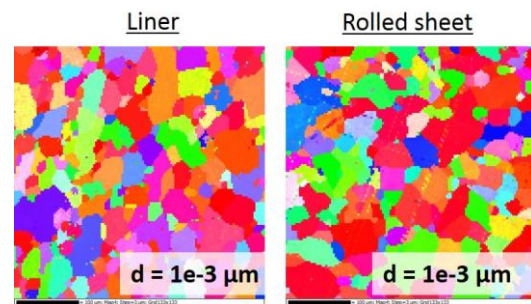


Figure 3. Comparison of microstructures from the midsection of the spun formed liner to rolled sheet

Small-scale testing: Specimen design and fabrication

Small-scale specimens are cut from both the spun formed line and sheet material using Electrical Discharge Machining (EDM). The liner was cut from two sides and samples covered the length of the bottle were removed in both the radial and circumferential directions (Fig 4.). These coupons were 0.032 inches thick. Similar coupons were removed from a 0.090 inch thick sheet. Half of these coupons were milled to 0.032 inch thick.

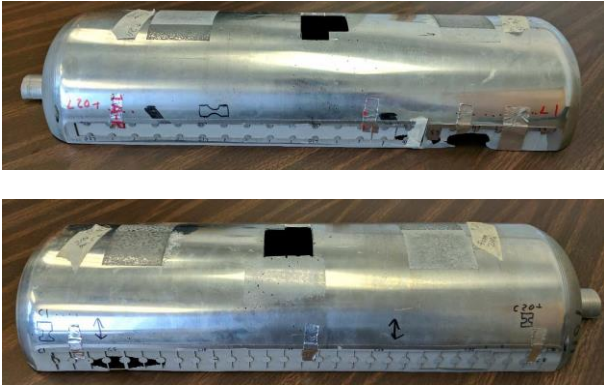


Figure 4. Coupon locations and orientations from the spun formed liner

The small-scale test specimens were specifically design to create a 2 to 1 stress state. This specimen design is shown in Fig. 5 and testing results shown in Fig. 6.

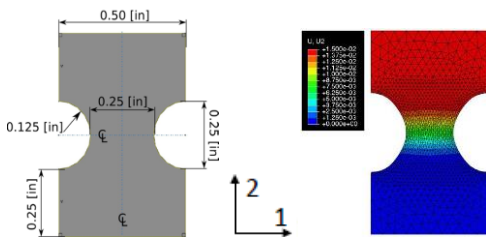


Figure 5. Coupon designed to create a 2:1 stress state

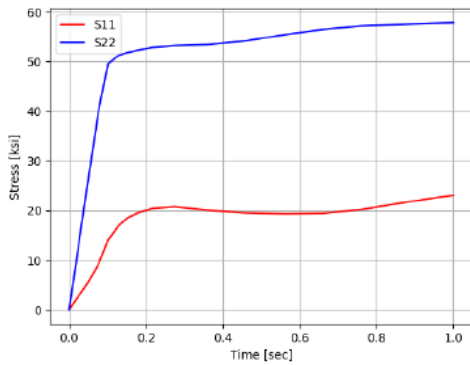


Figure 6. Test results demonstrating a near 2:1 stress state

Tensile testing of the small scale specimens found similar results between the spun formed and sheet materials. As shown in Fig. 7 the sheet materials (A3 and B3) enveloped the test results from the spun formed material.

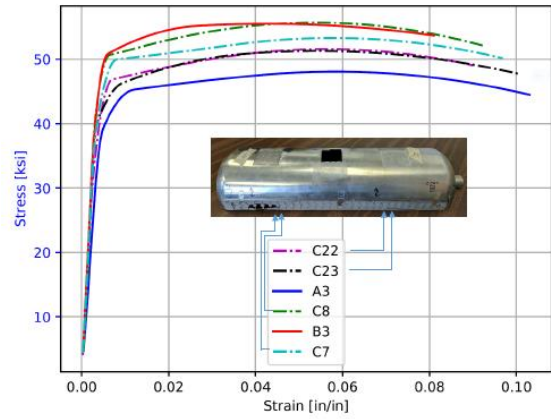


Figure 7. Tensile behavior of provided sheet and liner material

Small-scale testing: Fatigue crack growth rate comparison

Fatigue testing of the small-scale coupon was performed on specimens removed from various sections of the spun formed liner and from sheet material. A Plasma Focus Ion Beam notch was inserted as a starter notch then fatigue cycles were applied at a constant load. Fig. 8 shows a cross section of a fatigue specimen with a micrograph inserted to show the relationship of the large grain samples.

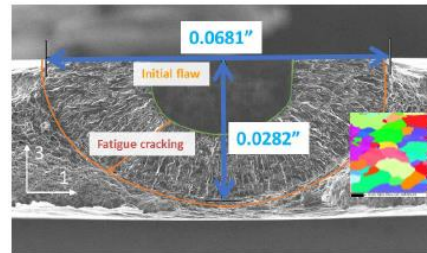


Figure 8. Small-scale fatigue specimen

The fatigue results were plotted da/dN verses ΔK . Fig 9. shows a comparison of results from a liner coupon removed from the large grain dome region verses sheet materials. Very similar fatigue crack growth rates were noted. Fig. 10 shows a comparison of the fatigue crack growth rates from the same dome coupon to a sample removed from the smaller grain mid cylinder. In this case a dramatic difference between the two samples was observed with the smaller grain size material having a crack growth rate approximately 10 times faster than the large grain size material. Subsequent examination found the small grain size fracture to be intergranular while the large grain size material failure transgranularly.

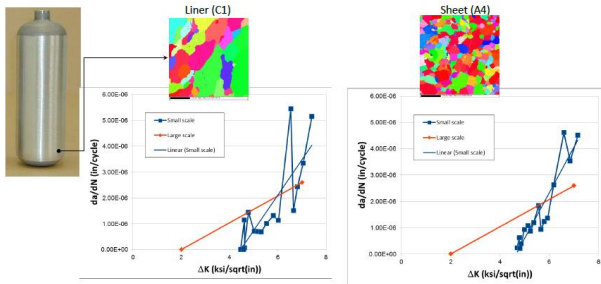


Figure 9. Comparison of fatigue crack growth rates between large grain liner material and rolled sheet material

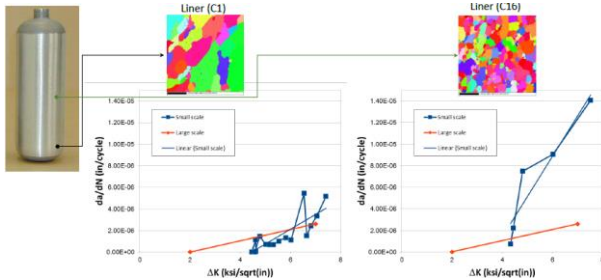


Figure 10. Comparison of fatigue crack growth rates between large grain and smaller grain liner materials

In summary, microstructure variations are too significant for testing on rolled sheet to be a viable certification method for spin-formed liners. Validation of LEFM requires more than plasticity/continuum limitations. Microstructure variation may, for certain conditions, have a stronger influence than plasticity/continuum effects (and may influence Elastic Plastic Fracture Mechanics (EPFM) parameters as well). The two liner examined had significant microstructure variation, which appears (with the limited amount of data generated to-date) to have a significant effect on crack growth rates. Neither (traditional) LEFM nor EPFM models consider length scales that can capture the observed microstructural variation.

Material characterization

For 6061-T6 sheet material baseline tensile and crack growth rate behaviour was performed. The tensile behaviour of 0.032 inch material and the crack growth behaviour of 0.090 inch material are shown in Fig. 11.

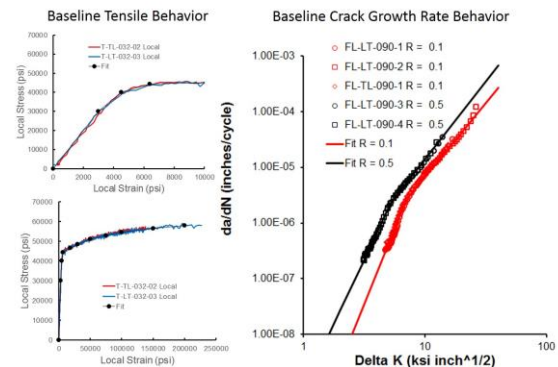


Figure 11. Baseline 6061-T6 sheet tensile and crack growth rate behavior

Finite element analysis (FEA)

Before testing, a FEA simulation of crack mouth opening displacement (CMOD) was performed. Nine different crack growth rates were simulated using both liner elastic and elastic-plastic FEA. From this analysis it was shown that separation of the elastic and elastic-plastic curves grew with an increase of the stress to yield stress ratio (S/Sy). Fig. 12 shows this separation as three different S/Sy ratios for 0.09 sheet material.

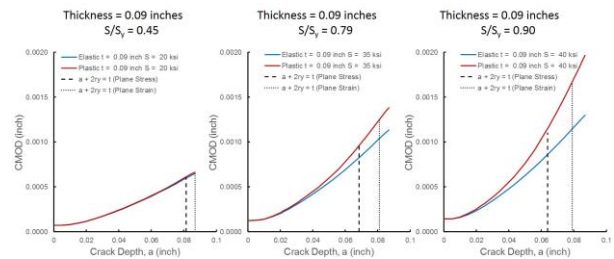


Figure 12. Finite element analysis results

FEA estimates were also performed of the progression of the plastic zone and the growth of dimples on the back face of the test specimen, as shown in Fig. 13.

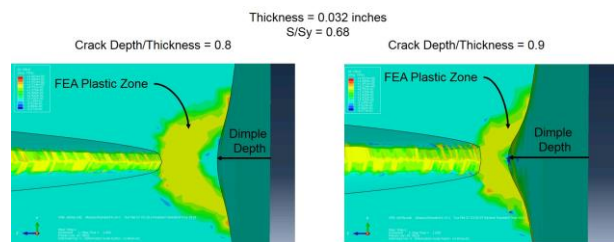


Figure 13. FEA estimates of plastic zone and back face dimple

Surface crack fatigue testing

Surface crack fatigue specimens were created first by EDM notching the center of a 2 inch wide dogbone coupons (~0.02 inches long and 0.01 inches deep). Precracking was performed with the same load as will be used in the fatigue crack growth test (~0.04 inches long). The crack front was marked with a Sharpie pen while at max load and letting the ink wick to the crack front. Fatigue cycling was performed while measuring the CMOD. After cycling the crack was broken open to reveal the crack front prior to breakthrough, Fig 14.

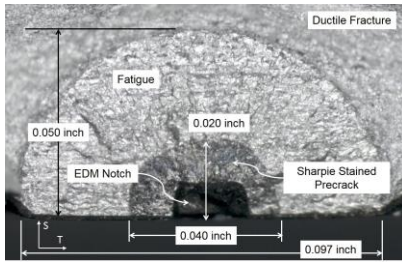


Figure 14. Crack front marking

As shown in Fig. 15, DIC was used to measure the strains and displacements of the crack surface. The CMOD was measured from displacements 0.02 inches above and below the center of the crack. Fig. 16 shows a plot of CMOD measurements during fatigue cycling.

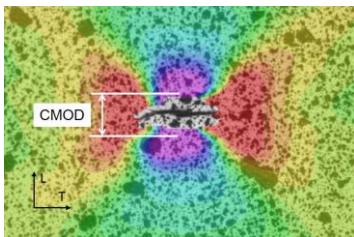


Figure 15. CMOD measurement location

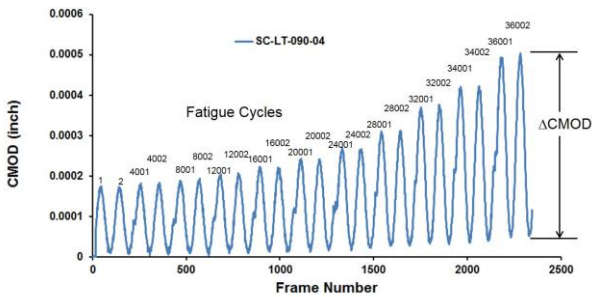


Figure 16. CMOD measurements

The crack depth is known at the end of precracking (Sharpie stain) and the start of ductile fracture. The measured delta CMOD and known crack depths was then plotted as a function of the measured crack depth. The test data was then plotted versus the elastic and elastic-plastic FEA results. Plastic zone limits were then revealed. Fig. 17 shows a plot for the 0.090 inch material showing a deviation from LEFM behaviour at crack depths greater than approximately 0.080 inches.

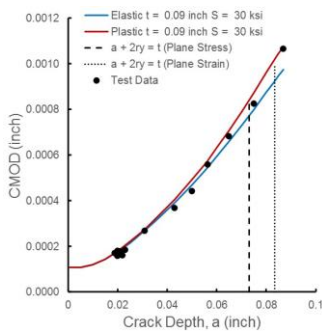


Figure 17. FEA and measured delta CMOD (30 ksi, $t=0.090$ inch)

The back face strain and dimpling was recorded using DIC. Fig. 18 shows the growth of the back face strain as a crack approaches the back face for a 0.090 inch sample.

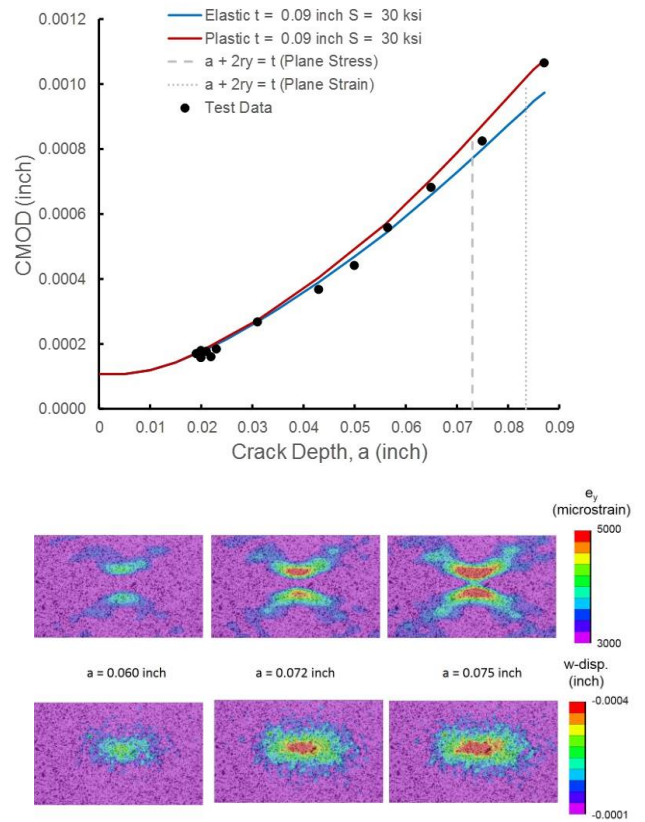


Figure 18. Back face strain and dimpling (30 ksi, $t=0.090$ inch)

In summary, the experimental and analytical techniques developed are sufficient to address the applicability of LEFM assumptions. Experimental measurements suggest that LEFM assumptions can be violated for surface cracks in 0.09 inch thick materials. Back face strains indicate ligament yielding occurs at smaller crack lengths than predicted by theoretical plastic zone calculations. CMOD measurements suggest that crack tip conditions are more severe than predicted by LEFM. Measured crack growth rates were unconservative relative to LEFM predictions at crack lengths smaller than predicted by theoretical plastic zone calculations.

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2. AIAA S-081A (2006) Space Systems – Composite Overwrapped Pressure Vessels (COPVs).