LA-UR-03-8629

Approved for public release; distribution is unlimited.

Title: EXPERIMENTAL PROCEDURE FOR CRACK COMPLIANCE (SLITTING) MEASUREMENTS OF RESIDUAL STRESS

Author(s): Michael B. Prime (ESA-WR)

Submitted to: http://www.lanl.gov/residual/

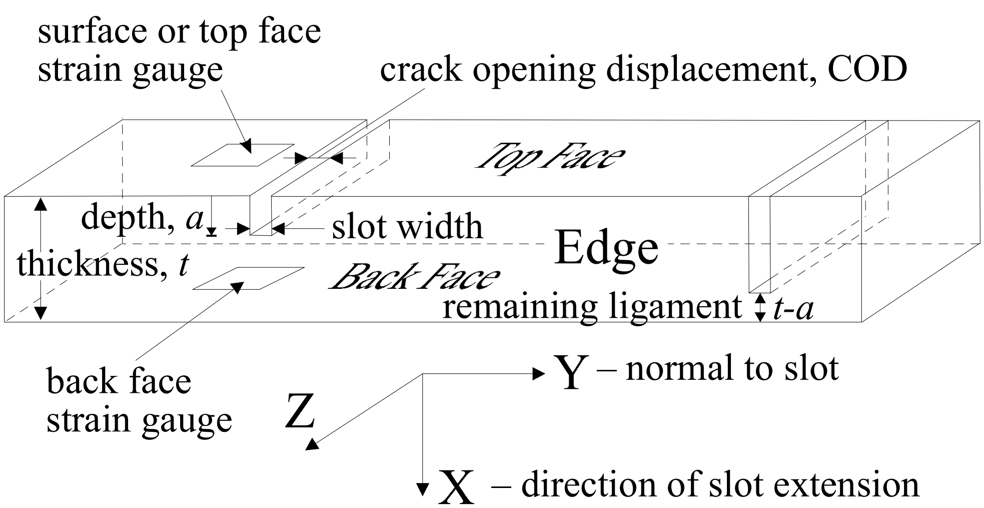
Experimental Procedure for Crack Compliance
(Slitting) Measurements of Residual Stress

Michael B. Prime
Los Alamos National Laboratory
Engineering Sciences and Applications Division

Reference: M. B. Prime, "Experimental Procedure for Crack Compliance (Slitting) Measurements of Residual Stress," LA-UR-03-8629, Los Alamos National Laboratory Report, 2003.

To provide feedback, email me at prime@lanl.gov . Check http://www.lanl.gov/residual/ for the latest version of this document and more resources and information. Thanks to C. Can Aydiner at Caltech and Mike Hill and Matt Lee at U.C. Davis for helpful comments.

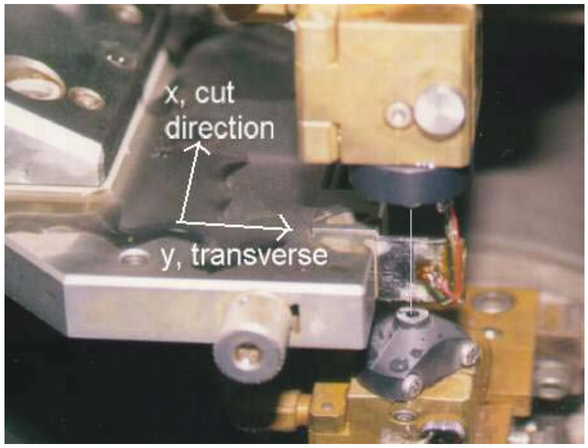
Read this whole procedure through *before* the test. Some of these things need to be decided before you start the test. This document is meant to describe one way to successfully obtain slitting data. It is not the only way to get good data.



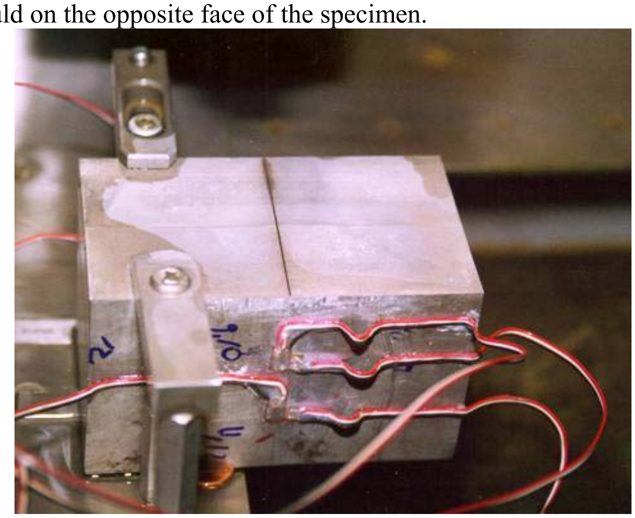
Terminology for Crack Compliance

1. Fixture
   a. Clamp the specimen on one side of the cut, leaving the other side free (hanging out into the EDM tank).
   b. The specimen should be oriented such that the appropriate specimen faces are square relative to the wire. Care should be taken so that the cut depth will be uniform along the length of the cut.
   c. Clamp securely enough to keep the specimen from moving under the force of the water jet agitation. Don't over-tighten.
   d. The strain gage(s) should preferably be on the free side. The path from the cut to the gages needs to be free to expand.

e. Samples:



This figure shows a specimen just ready to test. The visible gage is a "top" gage and if there were a back gage, it would on the opposite face of the specimen.



This figure shows a specimen that has already been cut. The visible gages are back gages. The cut started on the far side of the specimen.

2. Alignment (transverse, y). Careful alignment of the cut to the strain gages is preferred, although it not required because compliance functions for actual gage locations can always be calculated with FEM. The below procedure can be used with transparent gage coatings or if a scribe mark is used to show the location of alignment arrows on a strain gage. Alternately, one may prefer to use a convenient datum on the part for alignment when opaque coatings are used on the gage.
    a. For a through-thickness measurement, start with the cut centered on the back face gage. Move the EDM wire around to the back of the specimen. Align the wire with the alignment arrows on the strain gage. Set the zero for the y-direction coordinate of the EDM machine. Move the wire back to the front of the specimen and to y=0.
        i. If you used an opaque waterproof coating, you will not be able to see the alignment arrows. Before applying such a coating, mark the location of the alignment arrows on the specimen such that they will be visible after coating.

   ii. If you have a top gage, now follow below instructions to position wire close to top gage. If you move *y* more than ½ of the active length of the back gage, you have violated assumptions about location of back gage, and you may have errors if you use calibration coefficients based on the cut being centered on the gage.

b. For near-surface measurements, the cut should generally be as close to the gage as possible. Move the wire (*x*-direction) until it is nearly touching the surface. Move the wire (*y*-direction) as close to the gage as possible without it having to cut through waterproofing or glue during the cutting. Record the y-distance that you have moved the wire since it was centered on the back gage. Set the zero for the *y*-direction coordinate of the EDM machine in case there is a need to re-locate this position.
c. Make sure that the wire will not have to cut through glue or waterproofing on the front face or the edges of the specimen. Trying to cut through non-conductive material can cause the wire to break.

3. Set zero for cut depth.
   a. It is important to know how deep your cuts are. Unfortunately, wire EDM will overcut (the cut is wider than the wire), so the cut will be slightly deeper than the wire position.
   b. The best way to zero the cut depth will depend on the EDM machine. So combine the advice in this checklist with the knowledge of the machine operator to determine the best approach.
   c. Some machines can "touch off" on the surface *without cutting* and use electrical contact to determine the surface location. You may wish to set the *x*-direction zero now using this feature. You may need to wait until the water tank is filled. If you set the zero this way, it does not account for the overcut, and the cut depths will be greater than the *x* value given by the EDM machine.

4. Set strain gages to zero.
   a. Although you will re-zero after filling the water tank, now is a good time to set the strain gages to zero.

5. Fill tank, re-zero gages
   a. Fill the water tank. If the EDM machine uses jets instead of a tank, consider turning them on at his point.
   b. Observe the strain readings. An initial change in strain upon submersion (maybe 10-30 $\mu\varepsilon$) is normal. The readings should stabilize within a few minutes. Continued drift is indicative of poor waterproofing or poor thermal compensation in the gages.
   c. Record strain changes and then re-zero the gages (or just use readings as a zero value).
   d. Depending on the EDM machine, there may be a good way to set the zero for the cut depth now. Ask the operator, and set the zero if it is appropriate.

6. Cutting

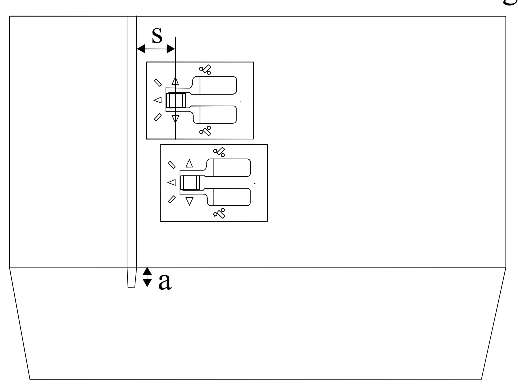
a. You do not want to put in any stresses during the cutting. You want to use “skim cut” or “finishing cut” settings on the EDM machine. A normal high-precision EDM job will make use of a rough cut to get the basic shape, and a series of skim or finishing cuts for precision and a good surface finish. The same settings that give a good surface finish tend to put in very low stresses. You will have to try to find the manufacturers settings for your situation. On a Mitsubishi machine, I use the “EPAK” for a “skim 1” or “skim 2” cut. Testing on a spare piece of material can tell you if a particular setting might be problematic (causing wire breakage, not cutting, etc.)
b. You need to decide how deep to make your incremental cuts. Some judgment is required. Too many increments does not hurt as far as the results, but can make your test take way too long. Increments need to be smaller (by at least factor of 2) than the spatial stress variations you want to resolve. For a through-thickness measurement, something like 30-40 increments is generally sufficient with 50 being better. For near surface measurements, you want your increments to be just large enough that the strain change between increments is significant. A good rule of thumb is increments no smaller than half of the wire diameter.
c. Program in a "dwell" of maybe 10-15 seconds at end of the cut increment to make sure that cut front is straight. Here, dwell means that the wire location is held still at the final cut depth, but it is still cutting.
d. After each increment, take the strain readings. There needs to be no power to the wire so that no stray voltages interfere with the strain gage. Turn on the strain gage box, and wait for the strain reading to stabilize to within 1-2 microstrain. Once it does, wait one more minute to be sure.

7. Problems during cutting.
   a. Wire breakage. EDM wires occasionally break, especially when using a thin wire. If the wire breaks, stop and take a strain reading. You may need to move the wire head out of the cut region to re-thread it. Make sure you will be able to re-locate the wire correctly. After re-threading, re-fill the water tank, wait for the gages to stabilize, and take another reading. Without cutting, if that is possible, move the wire close to the maximum depth that was previously cut.
      i. If the slot has begun to narrow (cutting into compressive stresses), you may not be able to move the wire to its previous location. Try re-threading the wire at the cut tip. As a last resort, you may have to cut your way back in or else the wire will break. If you cut some more material from the top of the cut, you may change the cut-to-gage distance, and you will not be able to measure it accurately after the cut. See below.
   b. Cut closure. With high compressive stresses and a low elastic modulus, the cut may close. This violates the crack compliance assumptions and will give bad results. You have to open the slot. Often, it works better to cut your way back in from the surface rather than trying to cut back out, but it is not certain. If you have a top gage and cutting back in will change the cut-to-gage distance, then try to photograph or measure the cut-to-gage distance so that you can use the already obtained data from the top gage.

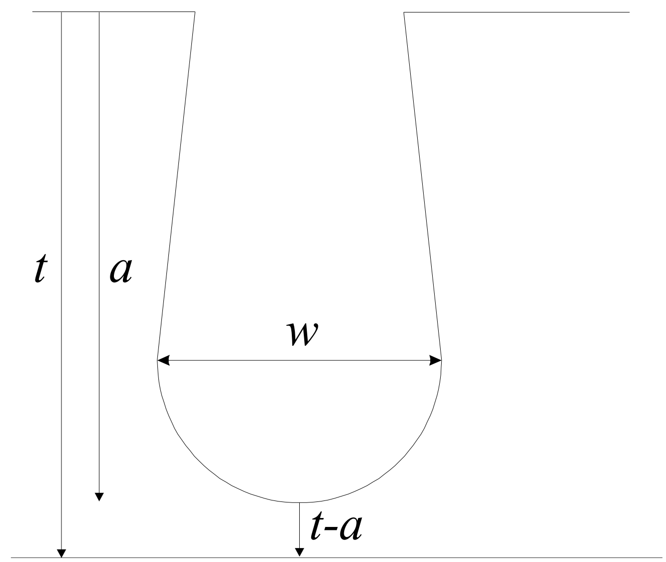
c. Crack propagation. Under rare circumstances cutting into tensile stresses, the crack may propagate on its own. Sorry, but your test is over.

8. When to stop.
   a. You usually do not want to cut the part in two. First of all, you won't get any usable data from the last cut. Second, you will not be able to measure the final slot depth to check if your assumed zero for cut depth is correct.
   b. You can generally get usable data through 95-98% of the specimen thickness. As you approach the back face, the strain readings will become less stable. Eventually, the strain will reflect the specimen weight as well as the released stress. You can check if the weight is a factor by lifting the free end of the specimen with your finger. Only lift with a force about the same as the specimen weight, and make sure the machine isn't cutting. If the strain changes significantly, it is time to stop. If the readings are unstable, stop. If you reach 98% of the thickness, stop.

9. Post-test.
   a. You want to take some dimensional measurements. Most of these can be best taken using a microscope with an instrumented stage for moving the part.
   b. On the top face, measure the distance from the closer edge of the cut to the alignment arrows that mark the center of the strain gage pattern:



c. Turn the specimen on its side. Measure the width of the cut. The width is best taken near the bottom of the cut. Near the top, residual stresses have likely caused the slot to open or close from its initial width.



d. Measure the cut depth from the top surface to the bottom of the slot. For an EDM round-bottomed slot, you want the very bottom.
e. If appropriate, measure the remaining ligament, the distance from the bottom of the cut to the back face.
f. Flip the specimen over to the other edge and repeat c,d,e. Use the average value from the two sides in later calculations. The differences should not be large or else the cut depth was not uniform along the length of the cut.
g. For through-thickness measurements, use a micrometer to measure the specimen thickness in the region of the cut.

10. Data adjustment
    a. Use the various dimensional measurements to determine your actual cut depths. The cutting *increments* of the EDM machine should be sufficiently precise, so you just need to adjust the zero to match your measurements of final slot depth, remaining ligament, etc.
    b. If necessary, subtract off initial values to get correctly zeroed strains.