Why the Slitting and Contour Methods Have Unusual Spatial Resolution Capabilities for Residual Stress Measurements

M. B. Prime

Los Alamos National Laboratory, Los Alamos, New Mexico 87545 USA

prime@lanl.gov

Abstract. The incremental slitting and contour methods have relatively unique capabilities to measure spatial variations of residual stress with good spatial resolution. For the slitting method, that means fine spatial resolution of a one-dimensional through-thickness stress profile. For the contour method, it is the measurement of a two-dimensional stress map that is unique. This talk will present examples illustrating the how recent advances have improved these capabilities. For example, the slitting method was able to resolve a stress profile in a shot peened Ti-6Al-4V coupon that showed both the gradients in the thin shot peened layer and the low magnitude balancing stresses through most of the thickness of the specimen. Contour method measurements in a multipass girth weld demonstrate the ability to measured fine details associate with the weld start and stop. There are specific experimental mechanics reasons that explain these unique capabilities compared to other relaxation methods, which will be presented.

Introduction

Residual stresses are the stresses present in a part free from external load, and they are generated by virtually any manufacturing process [1, 2]. They can be particularly insidious because they are ubiquitous, offer no external evidence of their existence, and they are difficult to predict or measure [3]**.** All measurements have advantages for residual stress measurements [2]. The slitting [4] and contour [5] methods have relatively unique abilities to measure residual stresses with good spatial resolution.

Slitting

The incremental slitting method [4], previously known as the crack compliance method, can measure a one-dimensional profile of residual stress with excellent spatial resolution through the entire thickness of a specimen. A previously unpublished example is presented here that demonstrates some of the unique capabilities of slitting. A Ti-6Al-4V coupon, 6.45 mm thick and 38 mm wide, was shot peened on both faces. A strain gage was bonded on one face of the coupon, and wire EDM with a 100 μm diameter brass wire was used to cut from the opposite face towards the strain gauge in 51 μm increments. Figure 1 shows that the measured strains have excellent sensitivity, with the strain reaching 9 $\mu\varepsilon$ at only 51 μm cut depth. Figure 2 shows the through-thickness stress profile, which not only resolves the high gradients in the shallow shot-peened layer but also shows the low-magnitude balancing tensile stresses well into the part. The stress profile was calculated from the strain using the pulse-regularization method [6], which is the only method that can resolve such a profile with both high gradients and uniform stress regions. Measuring such a profile would be a challenge for any other method. In fact, the slitting method could have likely also resolved the symmetric peening stresses on the other face of the coupon if a thicker wire was used to make a wider slit. As it was, the slit closed on itself because of the compressive stresses, stopping the measurement.

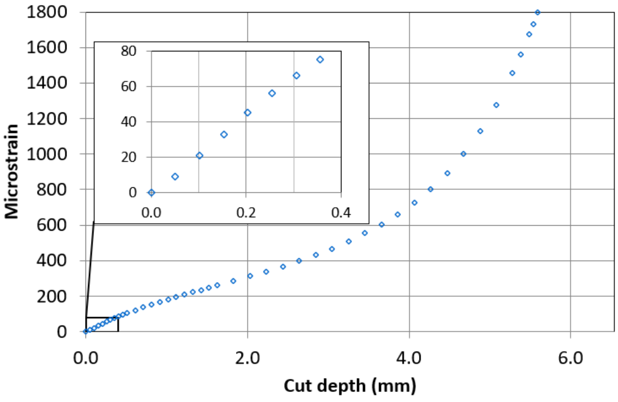

Figure 1. Strains measure during incremental slitting of a shot peened Ti-6AL-4V coupon sown excellent sensitivity.

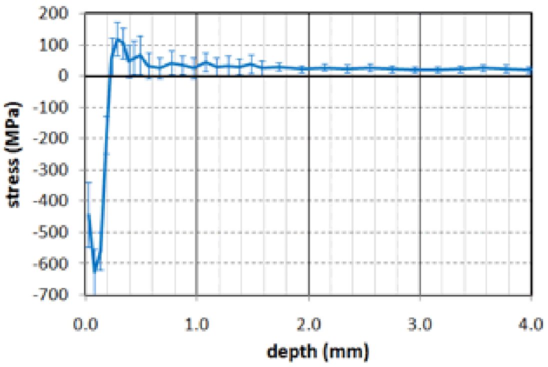

Figure 2. The through-thickness stress profile, resolves the high gradients in the shallow shot-peened layer and also shows the low-magnitude balancing tensile stresses well into the part.

Contour

The contour method [5] is relatively unique in its ability to map two-dimension variations in residual stress over a specimen's cross section. The specimen is cut in two using wire EDM. The surface height map, i.e., contour, of the opposing surfaces created by the cut is measured. Once the two are averaged, the result is used to calculate the original residual stresses normal to the cut using an elastic finite element model. An example is presented here to demonstrate some of the unique capabilities of contour. The samples were small, thick-walled steel pressure vessels. They were constructed by joining two halves using a five pass Gas Tungsten Arc Weld. Each specimen was cut in half through the center of the circumferential weld. Figure 3 shows that the contour method was able to resolve local variations in the axial stress caused by transients at the start and stop of the weld. Moving the weld stop away from the start showed that the main effects came from the weld stop not the start. Such fine two-dimensional stress details would be challenging to resolve with other techniques.

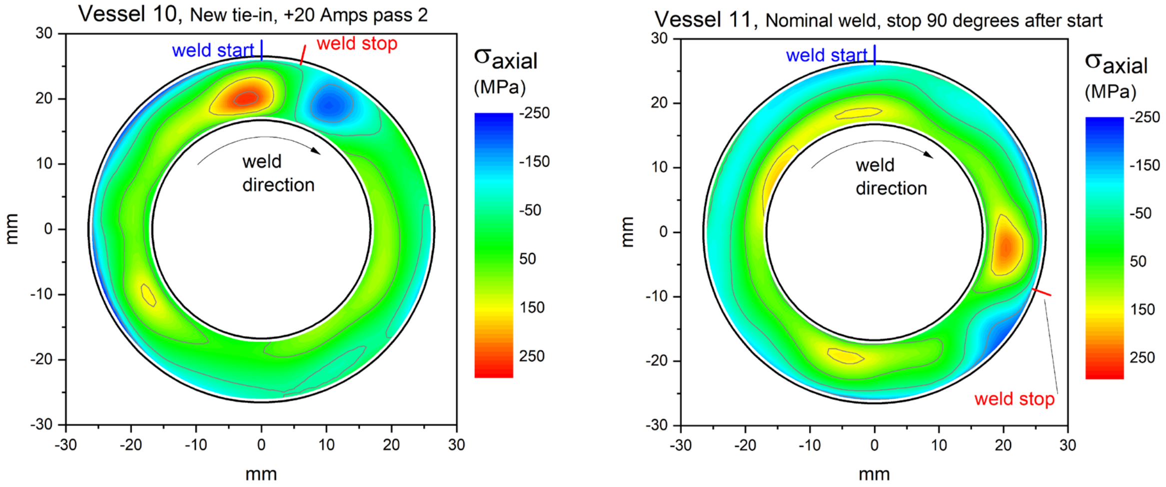

Figure 3. In a multipass circumferential weld, the contour method was able to resolve local stress variations caused by the transients at the start and stop of the weld.

Conclusion

The mechanics of the measurement methods explain why slitting and contour have unique spatial resolution capabilities compared to other methods like hole drilling. For the slitting method, the unusual sensitivity through the entire thickness of a part occurs because the specimen deforms in the equivalent of a crack opening mode. This allows the part to deform significantly in bending even for deep cuts. As a contrasting example, the hole in hole drilling is constrained by surrounding material and deforms very little at the hole gets deeper. The contour method can measure a full two-dimensional stress map for a different reason. The measurement of the contour, a shape as compared to a displacement, allows the measurement to occur *directly at the location of full stress relief*, the cut surface. Other methods measure deformations on a pre-existing free surface where one can take the reference measurement prior to stress relief. Measuring directly at the location of stress relief gives unique sensitivity to two-dimensional stress variations and a simpler inverse problem to solve. (These mechanics concepts will be illustrated during the presentation.) Of course, the same mechanics that gives the advantages also can be a source of uncertainty or bias. For the slitting method, the large deformations can cause local yielding, which can cause errors in the measurement. For the contour method, the measurement of a shape instead of a displacement makes the measurement very sensitive to the details of making the cut and the required assumption of a uniform cut width.

References

[1] Withers, P. J., and Bhadeshia, H. K. D. H., 2001, "Residual stress. Part 2 – Nature and origins," *Materials Science and Technology*, **17**(4), pp. 366-375.
[2] Schajer, G. S., 2013, Practical residual stress measurement methods, John Wiley & Sons, Chichester,WestSussex, UK.
[3] Schajer, G. S., Prime, M. B., and Withers, P. J., 2022, "Why Is It So Challenging to Measure Residual Stresses ?," *Experimental Mechanics*, **62**(9), pp. 1521-1530.
[4] Hill, M. R., 2013, "The Slitting Method," Practical Residual Stress Measurement Methods, G. S. Schajer, ed., John Wiley & Sons, Ltd, pp. 89-108.
[5] Prime, M. B., and DeWald, A. T., 2013, "The Contour Method," Practical Residual Stress Measurement Methods, G. S. Schajer, ed., John Wiley & Sons, Ltd., Chichester,WestSussex, UK.
[6] Schajer, G. S., and Prime, M. B., 2006, "Use of Inverse Solutions for Residual Stress Measurements," *Journal of Engineering Materials and Technology*, **128**, pp. 375-382.