RING AND PLUG SPECIMEN

CHOICE OF SAMPLE AND MATERIALS

An aluminum shrink-fit ring and plug was chosen as the known residual stress specimen for several reasons. First, this specimen has a closed form solution for the residual stresses, and the stress distribution is relatively simple: the stresses are constant in the plug, and only a function of radial position in the ring. Second, the ring and plug specimen has appeared routinely in the literature as a test specimen for evaluating residual stress measurement techniques, e.g., (Gnaupel-Herold *et al*., 2000). Third, this type of specimen provides the full range of biaxial stress states for testing. In the ring near the interface, σ_θ is positive and σ_r is negative. Near the outer edge of the ring the stress state is nearly uniaxial since σ_r goes to zero. In the plug, the stress state is equi-biaxial, $\sigma_\theta = \sigma_r$. Therefore, with one specimen it is possible to demonstrate the ability of a given technique to measure three stress states.

Aluminum 2024-T351 was chosen as the material for the ring and plug. The 2024 alloy is readily available, well characterized, and has good yield strength characteristics. The T3 temper refers to a solution heat treatment, cold working to improve strength, followed by natural aging to ensure stable properties. The T3*51* designation refers to plate that has been stress relieved after processing by uniaxial stretching to 1.5-3.0% strain. After this stretching, residual stresses on the order of 1-2 ksi (6.8-13.6 MPa) are expected to exist in the material (Prime, et al., 1999). The modulus used for this material was E=73.08 GPa, Poisson's Ratio [illegible] and yield strength of 290 MPa.

DIMENSIONS AND ASSEMBLY PROCEDURE

The specimen was nominally a 4" (101.6 mm) diameter ring, with a 2" (50.8 mm) diameter hole in the center and a corresponding 2" plug. The ring/plug diametrical interference was approximately 0.005" (0.127 mm). The components were 0.5" (12.7 mm) in the Z axis.

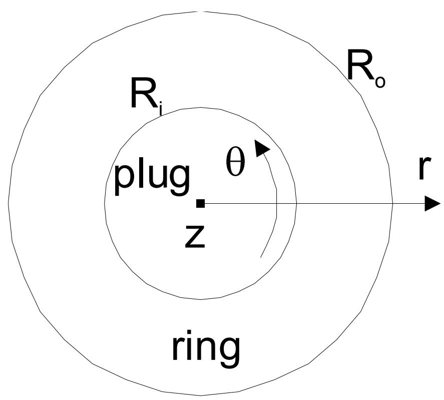

Figure 1. Ring and plug assembly sketch. Z axis is out of the page.

For assembly, the plug was cooled to liquid nitrogen temperature (-160 °C) leaving approximately 0.0038" (0.0965 mm) clearance with the room temperature (20 °C) ring. Clear vacuum assembly grease was used to lubricate the interface and minimize any friction between the surfaces. Figure 2 shows the locations of the gages, six of which measured the radial strain component and two of which measured hoop strains. The gages were placed on the ring near the plug interface where the strains are the highest. One gage would be sufficient to uniquely determine the stress state, however, using multiple gages allow one to confirm that the stress state is axisymmetric, and to establish uncertainty bounds on the stresses.

CALCULATION OF STRESS

There are three independent measurements to establish the actual amount of stress in the ring and plug:

- The measured interference (i.e., difference between ring I.D. and plug O.D.) measured before the assembly.
- The measured strain on the ring, from the time the plug is inserted until temperature equilibrium is reached.
- The measured change in the O.D. of the ring.

All three techniques have been tested, and all three have their benefits and disadvantages. For overall accuracy and, we recommend the use of multiple strain gages, with corroborating interference measurements made. For cost efficiency we recommend measurement of the interference and ring OD change using a CMM. Figure 2 shows 8 strain gages installed on the ring prior to assembly, with 6 oriented to measure radial stress and 2 to measure hoop stress.

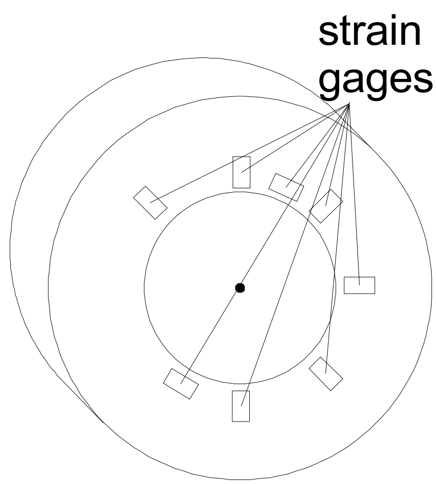

Figure 2. Strain gages locations on ring and plug

The stress state of the ring and plug can be calculated (Shigley and Mitchell, 1998) by first calculating the pressure

$$p = \frac{E\delta}{2R_i}\frac{\left(R_o^2 - R_i^2\right)}{R_o^2} \quad (1)$$

which is taken as positive, and δ is the radial interference between the ring and plug. In the plug the stress is equal to the pressure in the radial and angular directions. In the ring, the stress is:

$$\begin{aligned} \sigma_r &= \frac{pR_i^2}{R_o^2 - R_i^2}\left(1 - \frac{R_o^2}{r^2}\right) \\ \sigma_\theta &= \frac{pR_i^2}{R_o^2 - R_i^2}\left(1 + \frac{R_o^2}{r^2}\right) \end{aligned} \quad (2)$$

Equation 2 can be combined with the usual elastic relations to give ε (p,r), which can be inverted to give p(ε,r) and thus the strain gages applied to the surface of the sample can be used to calculate the pressure. A typical ring and plug was measured with eight strain gages as shown in Figure 2 gave an average value for the interference pressure of p=8.27±0.45 ksi (57.0 MPa ± 3.1). The measured strains also confirmed that the stresses were axisymmetric to within the precision of the measurements. For the same sample, the measured interference between the ring and the plug before assembly using a manual dial indicator was 0.0023" ± 0.0003" (0.058 mm ± .0076 mm), which gives a calculated value of p=9.19 ksi ± 1.16 (63.4 Mpa ± 8.0). Also, the change in outer diameter of the ring after assembly was measured as 0.0019" ± 0.0006" (0.048 mm ± 0.015 mm), which gives a calculated value of p=7.47 ksi ±2 (51.5 Mpa ±13.8).

We also measured the apparent residual stresses in the parent material. This measurement will actually include both the residual stress in the parent material and the "apparent" stress caused by the drilling. This measurement is crucial in understanding the measurements on the ring and plug, but we find that for aluminum, with drilling at 15,000 rpm, there is no measureable effect on the stress. Since it is expected that the rolling direction will have a significant effect on residual stress, the ring and plug rolling directions were aligned during assembly.

SAMPLE RESULTS

As an example, we measured the stress in the plug of an assembled system, where both CMM measurement of the interference and strain gaging had been done. CMM measurements were made at 4 diametrical locations, and the average interference used to calculate a stress. A 10-element strip gage with radial grids was applied, and 8 of the grids connected, and the average value of the pressure calculated at the various radii were used to get an average stress. These are the solid green and purple lines in Figure 3.

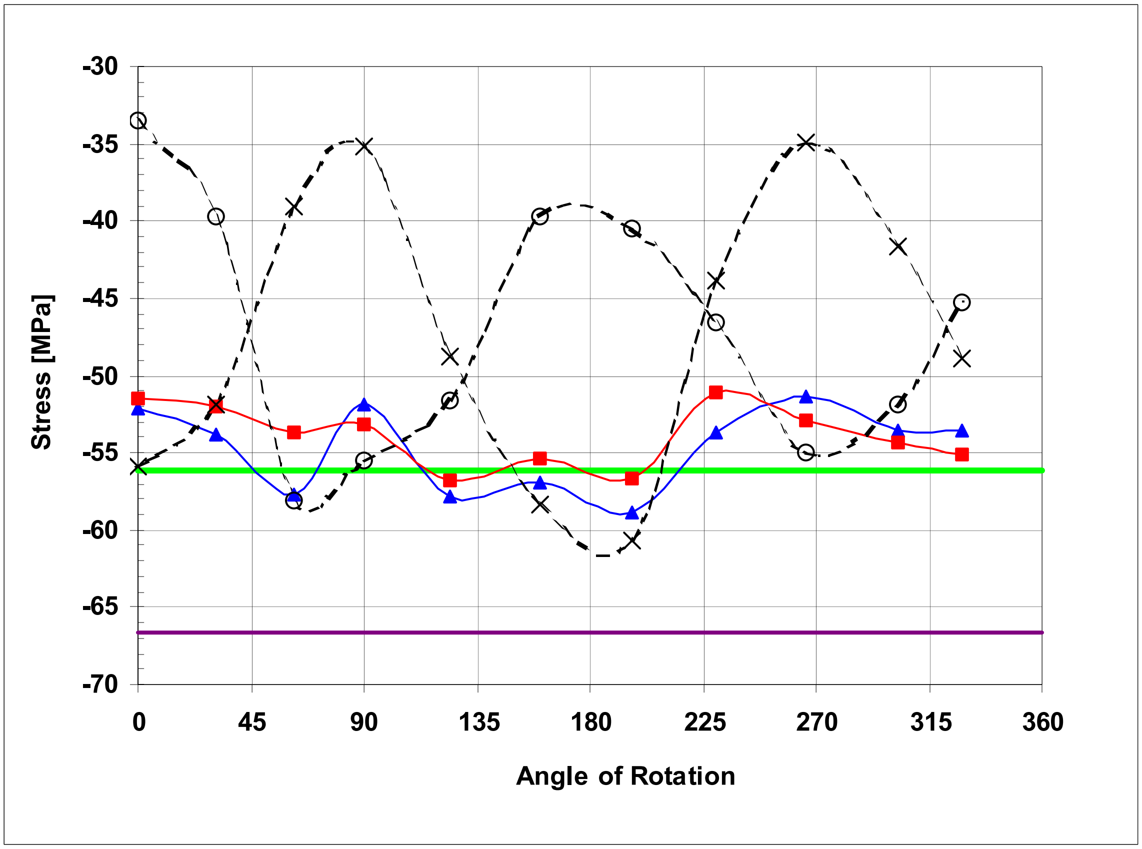

Figure 3. Stress in the plug as a function of angle from rolling direction. Dashed lines are raw data, red and blue are after adjusting for rolling stress, green line and purple lines are calculated values based on strain gage and interference measurement, respectively.

Multiple measurements were made on the sample using the ESPI hole drilling technique. The drill and measuring equipment remained stationary, while the sample was rotated about 30 degrees between each measurement, for a total of 11 measurements. The holes were all drilled at the same radius from the center of the plug, and results for both planar components of stress were plotted as a function of angle at which the rolling direction is oriented with respect to the horizontal. As shown in the graph of Figure 3, the raw stresses follow a very cyclic pattern, as would be expected if the residual stress is a function of the rolling direction. A total of 10 holes were then drilled in an as-received sample of 2024 aluminum, and an average stress of 2.8 ksi in the rolling direction, and –0.7 in the transverse direction was found. When these values were subtracted from the measured results, the answers look much more biaxial, and fairly near the value expected based on the strain gage measurement. Note that the CMM measurement seems to over-predict the stress, which might be expected due to surface roughness that can accommodate some compression without contributing to the overall stress.