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Residual Stresses in a Bi-Material Laser Clad Measured Using Compliance

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Abstract

In this research we used the compliance method to measure residual stresses in a laser-clad layer and the underlying substrate. Surface strains were measured as a slot was incrementally introduced using wire electric discharge machining (EDM). The elastic modulus of the layer, a copper alloy, was about 85% greater than that of the base material, an aluminum alloy. Because of this large difference in elastic constants, a new solid mechanics solution was needed in order to apply the compliance method accurately. The stress profile was also measured using x-ray diffraction and electrochemical layer removal. Results from the two techniques were compared. Additionally, the error caused by using an older single material solution was shown to exceed 50% for stresses measured near the interface.

1. Introduction

The compliance, or crack compliance, method [1,2] involves incrementally introducing a slot into a part containing residual stress. Strain gauges on appropriate surfaces measure strain at each increment of slot depth. These measured strains are used to solve for the residual stresses that originally existed. Compliance has successfully profiled residual stress variation with depth in surface regions as thin as 100 μm [3] and through parts as thick as 166 mm [4]. The primary advantage of the compliance method is that it can resolve stress variation with depth better than other methods.

Clad surface layers are increasingly used in engineering applications. They provide a variety of advantages including increased wear, corrosion, and thermal resistance. Invariably, the application of a surface layer induces residual stresses in the layer and in the substrate near the interface. Because the layer is often used under harsh conditions, knowledge of residual stresses is critical for preventing failure. Failure or debonding is also a concern in the interface region. Many techniques have been used to measure stresses in such layers with varying degrees of success [5]. Compliance promises to address some of their limitations.

2. Theory

Residual stress variation with depth is determined from the measured strains using a technique similar to the power series method [6], which was originally developed for the hole drilling method. The unknown residual stresses are written as a series expansion

$$\sigma_y(x) = \sum A_i P_i(x) \tag{1}$$

where x is the depth direction, the A_i are unknown coefficients, and the P_i are terms in a polynomial series. Then for each term in the polynomial series the strain that would be measured at the strain gauge location is calculated. These strains as a function of depth are called the compliance functions C_i. Using superposition, the strains for the stress given by Eq. (1) can be written as

$$\varepsilon_y(x) = \sum A_i C_i(x) \tag{2}$$

Finally, a least-squares fit is performed between the measured strains and those given by Eq. (2), resulting in the coefficients A_i and, hence, the stresses from Eq. (1). This inversion procedure is very error tolerant compared to other methods for solving for stresses. For the hole drilling method, this technique is sparingly used because the solution is stable only to about two terms in the series expansion. However, for the compliance method the inversion is stable to about four terms for surface stress measurement and to seven or more terms for through-thickness measurements. This is because the slope of the curve plotting released strain vs. depth is steeper for a slot than for to a hole. Physically, this occurs because a hole is more constrained than a slot.

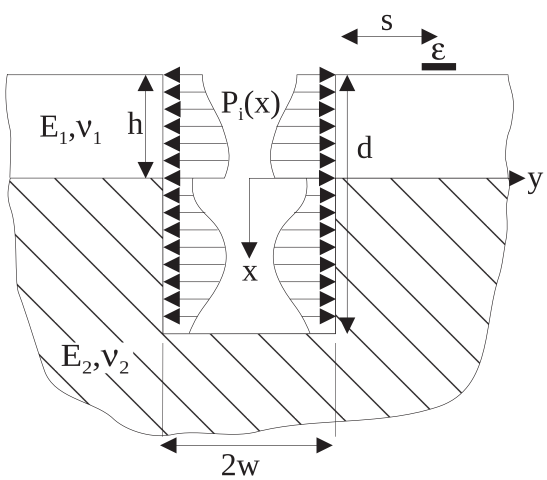

Figure 1. Geometry: finite width slot in a layered half-space.

For the application in this paper the compliances are calculated taking into account both the finite width of the machined slot and the surface layer of different elastic constants [7], see Figure 1. In previous compliance measurements of stresses in a clad layer [3] the elastic constants of the layer and substrate were close enough to each other to ignore the difference. For this work, the compliances were calculated using the body force method. Continuously embedded point forces were applied to the desired contours of the slot and free surface in joined half-spaces of different materials. Their magnitudes were adjusted numerically to satisfy the boundary conditions.

3. Experiments

The specimen tested consisted of a Cu alloy with additions of Ni, Fe, and Si laser-clad to a substrate of $AlSi_7Mg_{0.3}$. The cladding was done with a fast axial flow 1.5 kW CO_2 laser, which made rows 0.5 mm wide. The specimen was 53 mm long in the cladding direction and 26 mm wide. The approximately 1 mm thick layer had an elastic modulus of 134 GPa. The 20 mm thick substrate had an elastic modulus of 72.4 GPa. Both materials have a Poisson's ratio of about 0.33. After very light surface grinding to prepare the specimen for strain gauges, it was cut lengthwise, with the wider piece to be tested using compliance and the narrow piece by x-ray diffraction.

On the surface of the compliance piece, constantan strain gauges with gauge lengths of 0.81 mm were mounted so that one gauge would be as close as possible to the cut and another would be about 1 mm farther away. The slot was made using wire electric discharge machining (wire EDM). The specimen was submerged in de-ionized water maintained at about 20° C. This was necessary for cutting and also gave more stable and precise strain readings. With a 0.1 mm diameter wire, a slot was cut to a depth of 1 mm in increments of 0.127 mm before cutting difficulties were encountered. With a 0.25 mm diameter wire, a second cut at another location with another set of strain gauges was made to a depth of 3.8 mm. The slots were 0.25 mm and 0.41 mm wide ($2w$ in Figure 1), respectively. The distance s from the edge of the cut to the center of the gauge length for the two gauges near each slot (four gauges total) was 1.9 mm and 3.0 mm, for both cuts.

The residual stresses were also determined using x-ray diffraction and the conventional d vs $\sin^2\psi$ technique. The measurements were performed in the longitudinal and transverse directions using Cr- Kα radiation and a vanadium filter. The illuminated area was restricted by a 0.5 mm pinhole collimator to about 0.8 mm in diameter. For each measurement, data was acquired at 15 ψ angles. The θ angle was oscillated ±1° to increase the number of grains sampled. For the Cu layer, the (220) reflection at $2\theta = 127.3°$, and for the Al substrate, the (311) reflection at $2\theta = 139.5^o$, were monitored. The plane specific elastic constants used were $\frac{1}{2}s_2 = 9.74\times10^{-6}MPa^{-1}$ for Cu and $\frac{1}{2}s_2 = 19.54\times10^{-6}MPa^{-1}$ for Al, from [8]. The subsurface stresses were corrected for the layers removed by electropolishing [9]. The correction never exceeded 10 MPa because of the large specimen thickness.

4. Results

The cladding thickness measured near the two compliance cuts after testing was 1.04 mm and 1.09 mm. It was 0.96 mm where the x-ray measurements were done. This indicates some variation in the process and possibly in the subsequent residual stresses. For the plots in this paper, the x-axes are scaled so that the interfaces overlay at 1.04 mm.

Stresses in only the clad layer

The residual stresses in the layer were expressed (Eq. 1) in terms of a third order (cubic) power series. Figures 2 and 3 compare the best fit strains from Eq. 2 to the measured strains.

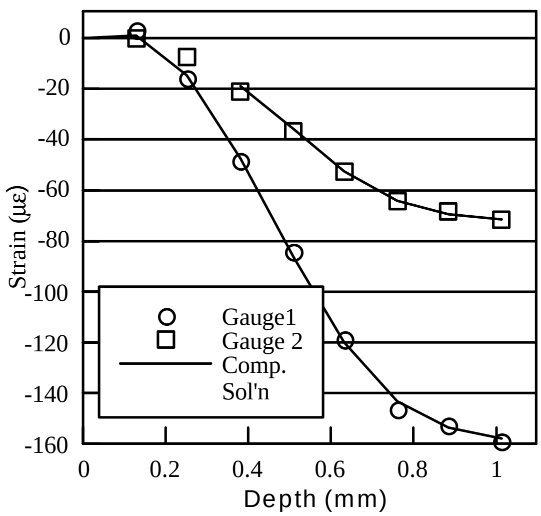

Figure 2. Measured strains and fit given by stress expansion: cut location 1.

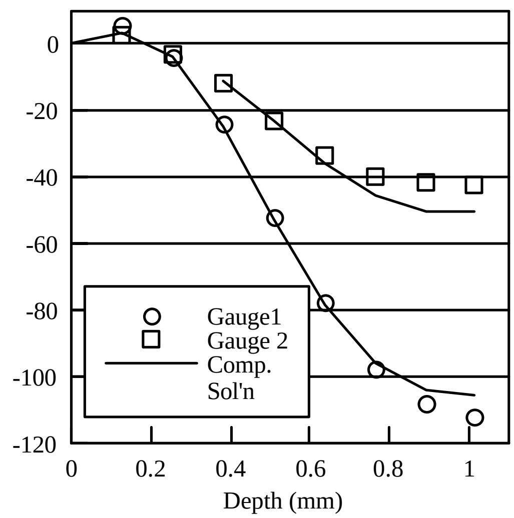

Figure 3. Measured strains and fit given by stress expansion: cut location 2.

These distributions resulted from fitting the strains from both gauges using a single least-squares fit. The first two data points from the second gauge were omitted from the fit since that gauge was too far from the cut to record meaningful results for shallow cuts. For both cuts, when considering each gauge separately, the third order expansion was able to fit the measured strains to about ±1 με root mean square (rms) error. Because strain is measured to an approximate accuracy of ± 1 or 2 με, a higher-order expansion would likely “overfit” the data. For the first cut, including both gauges in a simultaneous fit resulted in an rms error of only about ±1.5 με. For the second cut, using both gauges in the fit gave an error of ±4.0 με because of different results near the substrate. This may be due to inaccurate knowledge of the cut depth and the location of the substrate. Also the stress may vary in the out of plane direction because of the clad’s nonhomogeneity, which would affect the two gauges differently.

Figure 4 shows the longitudinal stress distributions in the layer measured by both compliance and x-rays. The stresses were tensile through most of the clad layer, with small compressive regions near the free surface and the interface. The results agree qualitatively but are off by up to 50% in magnitude. The transverse stresses measured with x-rays are not plotted. They show a tensile stress peak that is less broad but about 50 MPa higher than that in the longitudinal direction.

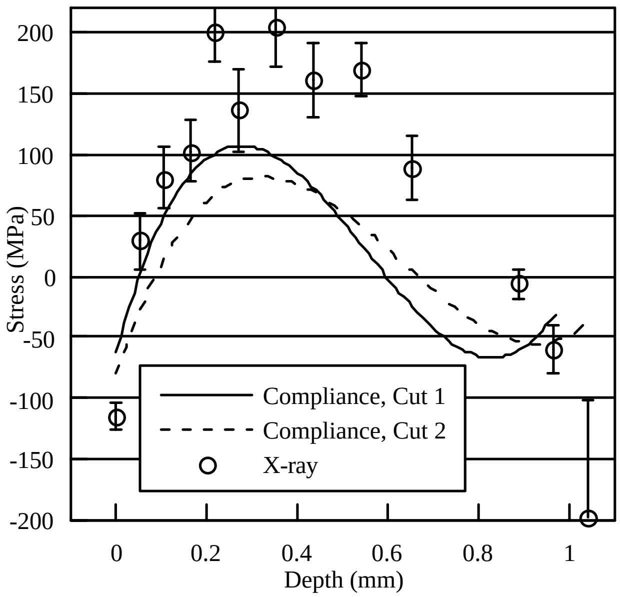

Figure 4. Stresses measured in the layer compared with x-ray results.

Stresses into substrate

Because only the cut at the second location extended into the substrate, a single set of results for stresses in the substrate is presented. The first step in calculating the substrate stresses was to calculate the strains resulting from the stresses in the layer for a slot extending into the substrate. These strains were then subtracted from the measured strains, leaving the strains caused by substrate stresses only.

Figure 5 shows the total measured strains and the fit given by the compliance solution. Only the strains from the gauge farther from the cut were used in solving for stresses in the substrate. The readings from a gauge close to the cut eventually become "saturated" and unsuitable for use in inverting back to residual stress. This depth can be estimated using a uniform stress variation and plotting the strain measured at the gauge as a function of depth. When the slope of the curve goes to zero, the attempted inversion results in a singular, or nearly singular, matrix. The practical limit occurs before the slope actually reaches zero and is manifested through increasing instability of the inversion [10]. For the gauge closer to the slot in this test, the practical limit occurred fairly early in the substrate, so these readings were discarded.

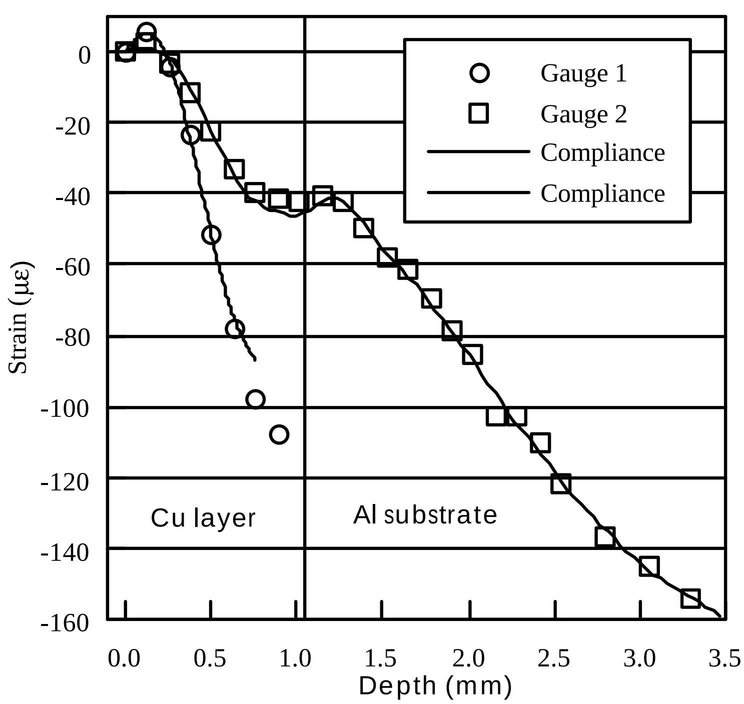

Figure 5. Strains measured into substrate and fit given by compliance solution.

A single continuous fourth- or lower-order polynomial for the stresses in the substrate was unable to accurately fit the data. So "overlapping piecewise functions" [11] were used. This method involved fitting overlapping subsets of the data with lower-order polynomials. In [11] first- (linear) or second-order (quadratic) polynomials were used. In this work, the first six strains measured in the substrate were fit by averaging the second- and third-order expansion results. Averaging successive orders in a polynomial expansion reduces the oft-observed endpoint instability. The remaining 10 strain readings, including an overlap of one point with the previous interval, was also fit by averaging the results from second- and third-order expansions. This stress expansion fit the strains as shown in Figure 5, the stresses are shown in Figure 6.

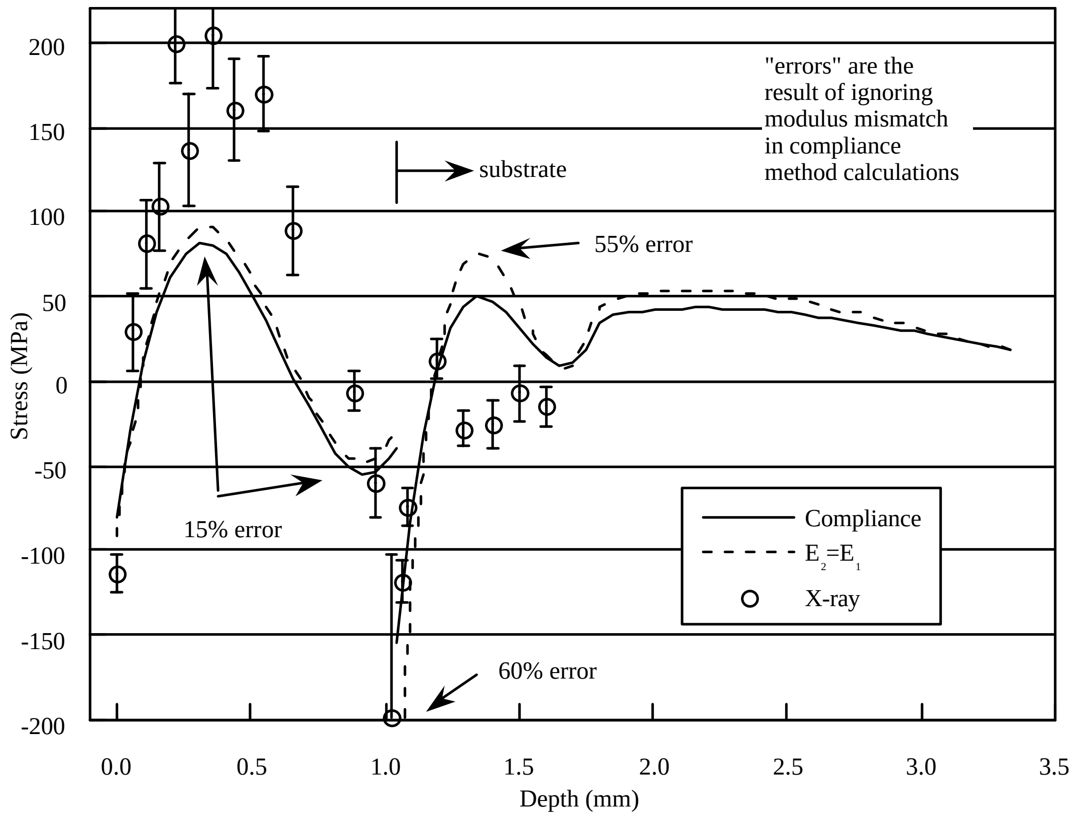

Figure 6. Stresses measured in the clad layer and substrate. Curve $E_2 = E_1$ shows erroneous results caused by ignoring modulus mismatch.

The stress distributions measured using compliance and x-rays are similar. Both methods measure a region of fairly high compressive stress in the substrate just below the interface and lower magnitude stresses deeper in the substrate. The results from ignoring the modulus mismatch, i.e., setting E_2 equal to E_1, are also plotted. These results indicate errors of 15% in measuring the peak values of the distribution in the layer and errors exceeding 50% in the substrate.

There are several factors that may explain the difference between the compliance and x-ray results. The main consideration is that there are indicators that the specimens were nonhomogeneous. The compliance measurements at two different locations indicate that the stresses varied along the specimen length. The x-ray measurements were performed at a third location on a small piece cut from the main specimen. Also, the clad layer at each of the locations had a different thicknesses.

Possible errors in the x-ray measurements include the following:

1. The grains were fairly large and showed some texture, especially in the cast-like structure of the layer. Both of these effects add uncertainty beyond the plotted error bars, which represent the reproducibility of a single measurement.
2. When the depth profile was measured, the specimen position was not fixed precisely. Furthermore, the size of the illuminated area was about the same as the width of a single cladding row. With the nonhomogeneous nature of the clad, this can explain the large variation in the x-ray measurements.

Possible errors in the compliance measurements include the following:

1. The stresses may vary in the 26 mm width out-of-plane dimension. The compliance results will be a weighted average of the stresses over some out-of-plane distance.

2. The compliance functions were calculated without regard to the free surfaces of the specimen's back face and edge. Although the back face effect is probably small, it increases for deeper cuts. The edge effect was greater for the second cut, which was closer to the edge.
3. EDM machining can produce a recast layer that can effect the measured strains. As a result of extensive testing [1], the parameters to minimize this effect have been determined, but the effect will be greater with the larger wire used for the second cut.

It may be observed that the distributions given by both compliance and x-rays show a net tensile force. In both cases, the average compressive stress necessary over the remaining depth to achieve equilibrium of the net section is less than 5 MPa.

Conclusions

It has been demonstrated that the compliance method is a powerful technique for measuring residual stress in layered materials, especially for resolving the depth profile. However, the lack of quantitative agreement with x-ray measurements, probably because of the nonhomogeneity of the specimen, was disappointing. Further tests are planned.

Acknowledgment

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