Measurement of mechanical strain at interior locations

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Mechanical failure caused by overloading or by cyclic loading typically occurs at locations where deformation and mechanical strain are concentrated. Consequently, a great deal of effort has been invested in both calculating and measuring mechanical strain distributions for engineering structures and components. A wide variety of powerful techniques have been developed for measuring strain at free surfaces [1]. These methods range from real-time single point measurements using electrical resistance strain gauges to bulk field measurements using Moiré interferometry. None of these techniques can measure strain at non-surface locations in optically opaque materials. A technique for measuring the distribution of strain on a selected interior plane using synchrotron radiation is being developed using the facilities at CHESS and at NSLS.

The interior strain distributions are often different from the surface distribution especially when heterogeneous properties are present. In general, the strain fields around inclusions are affected by the presence or absence of nearby inclusions. Surface and interior locations clearly have different nearest neighbor geometries. Three specific interior strain distributions are of interest in this investigation: strain fields in adhesively bonded joints, strain fields between layers in laminated composites and strain fields around individual fibers in composites. These problems generally involve relatively small structural features so maximum spatial resolution is desirable. The special properties of synchrotron radiation are critical to achieving high spatial resolution in the new method.

The goal of the method is to obtain high spatial resolution strain field measurements on a selected plane within a solid body. It is worth noting that strain information averaged through the thickness is not particularly valuable because spatial averaging in the through thickness directions would obscure the interesting and important regions of concentrated strain. The basic idea of the method is to implant opaque markers on a specific plane in a solid that is x-ray transparent and record radiographs of the precise location of the markers before and after mechanical loading. The two radiographs will then be carefully measured to quantify the deformation field. This process is carried out in three steps as illustrated in figure 1. The three steps are: 1) Use synchrotron radiation to photograph the markers before and after mechanical loading; 2) Enlarge the x-ray pictures to facilitate marker position measurement; and 3) Use an electro-optical setup to measure the marker positions to a resolution better than 0.03 inches, when referenced to the original photos. Strain can subsequently be calculated from the change in marker positions.

The exact experimental procedure used in the method is still being refined so that some of the specifics of the procedure have been and will be changed as improvements are made. Two general points should be kept in mind in understanding why certain techniques were chosen. First, higher spatial resolution requires placing markers closer and closer together. Unfortunately, the markers must be five diameters apart in...
order that the local strain field is not affected by the relativity shift markers [2]. Consequently, higher spatial resolution can only be achieved by making the markers smaller as their separation distance is decreased. Second, it is important to realize that the quantity of interest is the change in marker spacing due to mechanical loading. Thus, some image distortion can be tolerated provided that it is the same in the before and after radiographs. A more complete description of the technique and the results from verification experiments can be found in references 2 and 3. Some of the details of the current technique will be described.

The greatest contrast in the absorption properties of the markers compared to the sample is achieved by using polymer samples, containing metal markers (gold or nickel). Graphite epoxy composite samples have been made by depositing markers on the surface of the prepreg prior to heat consolidation. The marked layer is placed in the center of a composite panel when it is stacked up in the die prior to heat consolidation. The analogous procedure has been used to make marked boron aluminum composites. Marked adhesively bonded joints have been made by placing the markers on the surface of the plastic adhered prior to gluing the joint together. The resulting joint has markers at the adhesive adhered interface.

Currently, the nickel marker arrays are made in a uniform rectangular pattern with a 100 micron spacing. These markers are 20.90 microns in diameter and 30.95 microns thick. These marker arrays are made by an electroforming process. Diffraction limits for our geometry imply that the smallest marker that we will be able to see is of the order of a few microns. However, we are currently unable to microfabricate markers that are both a few microns in diameter and 10 to 30 microns thick. By decreasing the marker size, the technique has the potential for an order of magnitude improvement in spatial resolution. We are currently working on methods to approach that limit.

The majority of the synchrotron work has been carried out at station C2 at CHESS using a portable mechanical loading device which is installed in the hutch (Fig. 2). Most imaging is done by tuning the monochromator to the absorption edge of the marker, which typically is the L edge of gold or the K edge of nickel. In some cases, very thick nickel markers have been imaged well above the absorption edge, in order to penetrate ceramic loaded polymers that were hard to penetrate at lower energies. For highly absorbing samples, harmonic suppression is very important due to the tremendously greater penetration of the 3rd order harmonics that may be present.

We often use between 80% to 90% detuning to achieve harmonic suppression and to make the images long enough to be easily hand-traced using hutch shutters. A typical radiograph is shown in Fig. 3 and consists of white dots on a dark background. Intensometer ratios of the radiographs are made (3000 in a photo microscope, with care taken that corresponding markers in the before and after enlargement fall in the same part of the field of view of the microscope. This is necessary because the strain that is typically measured are on the order of 0.1%, while the microscope magnification non-uniformity is typically 1%.

A number of methods are possible for measuring the change in particle spacing to the desired accuracy of 1 part in 10,000. We developed the electro-optical setup shown in Fig. 4. Here, we project the image of the microscope illuminated by a laser onto a lateral effect photodiode that detects the image centroid to about 0.25 microns. The markers are successively centered in front of the diode and their position read to 0.2 microns by an accurate servo to move the exposure. This process is now fully automated and computer controlled. The current gauge length is 100 microns and the step resolution is 0.016 microns, referenced back to the original unaltered image, yields a spacing resolution of roughly 25 ppm. The raw data consists of before and after coordinate sets. At present, simple averaging methods are used to smooth the data.
data as part of computing strain by differentiation. Regularization schemes are being considered for more optimal data processing.

To illustrate the type of results achieved, we show in Figures 5 and 6 strain measured in a 4-layer graphite-epoxy composite. In Figure 5, the strain at the center of a circular hole at moderate load is shown compared to a calculated result. It is apparent that the agreement between theory and experiment is good. In Figure 6, the strain distribution around the same hole is shown for a load that was large enough to cause local delamination. The strain distribution shows a large disturbance that could not have been predicted. Prediction of such a strain distribution would require detailed knowledge of the damage zone geometry which is not available. It is further worth noting that the damage was not visually apparent but was clearly seen in the strain data.

In summary, a new method for measuring strain distributions inside optically opaque objects has been developed, which relies on the unique properties of synchrotron radiation. The technique has been shown to produce results that are more reliable than those obtained using the usual techniques. At present, the spatial resolution is 100 microns and the strain resolution is 100 ppm. Further improvement in spatial resolution of up to an order of magnitude may be possible before the diffraction limit is reached. Strain resolution improvement is also possible.

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