MEASURING RESIDUAL STRESS USING X-RAY DIFFRACTION

Introduction

The concept of stress in a material is familiar to all of us. Residual stress, on the other hand, might sound a bit peculiar, but it is real and it can be utilized to strengthen materials or if can lead to premature failure. It can also be measured and in some industries residual stress measurements are routinely done.

Stress, the force per unit area experienced by a material, is a result of the restoring force exerted by the bonds between the atoms. When a material is under load the bonds stretch and distort to an extent that the restoring force equals the applied load. When the load is removed the bonds revert to their original state, causing the material to return to its original dimensions. But now consider what would happen if a portion of this material were to permanently change. This could happen in a number of ways. Heat treatments can produce phase transformations and since the density of any two phases is rarely the same there will be localized changes in volume. As a result stresses develop in the regions of the density changes. If these phase changes are not distributed uniformly throughout the material macroscopic distortion of the part may occur. An example would be rapid cooling following a high temperature treatment which results in rapid phase changes only near the surface. Another example is welding, where material along a line is rapidly melted and cooled again. Warping and distortion are not unusual when making long welds in thin materials. In all three cases there are stresses in the material in the absence of an externally applied load.

Another example of dimensional changes that produce residual stresses is simple bending. When a bar is bent the stress in the outer fiber of the outside radius experiences the maximum tensile stress, the outer fiber along the inner radius experiences the maximum compressive stress while the center, the neutral axis, experiences no stress at all. If the bar is bent so that the outer fibers are loaded beyond the yield strength then when the external load is removed the bar will spring back somewhat

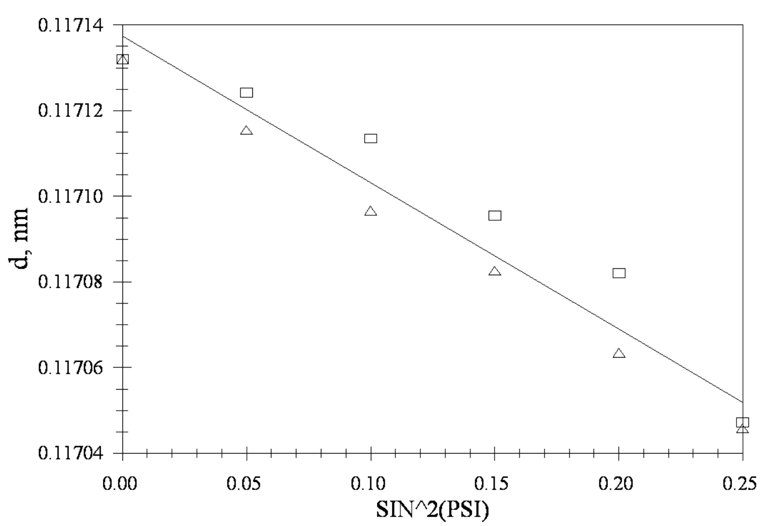

Figure 1 Typical results from a sin2R analysis of residual stress.

due to the elastic nature of the stress in the material. However, since the outer fibers are now longer along the outer radius and perhaps shorter along the inner radius than they are in and near the center, the undeformed center portion of the bar will continue exert a force on the outer fibers. The final condition of the material is one where the outer radius is now under compression and the inner radius is under tension.

A final example of residual stress is the secret to the strength of Corning's Corell Ware ceramic used to make dishes. This ceramic is actually a combination of a crystalline ceramic center coated on both sides with a glass ceramic. This layered composite is processed at very high temperatures and then allowed to cool slowly. It turns out that the coefficient of thermal expansion of the crystalline ceramic is greater than that for the glassy outer material, which means that as the composite cools the center shrinks more than the outer part, causing the inner part to be loaded in tension and the outer part to be loaded in compression. This pre-stressing of the outer material strengthens the material since in order to produce sufficient tensile loads in the outer surface to cause cracks to form and grow one has to first apply a sufficient load to get back to a stress of zero.

In this experiment the residual stresses in a flat spring steel is measured. A typical spring steel is basically a medium to high carbon steel which has been processed to a high strength condition (1000 to 2700 MPa, 100 to 400 ksi), giving them a high modulus of resilience. Plain carbon steels are frequently used but alloy steels tend to be used to make larger springs due to hardenability requirements.

Objective

The single objective of this experiment is to measure the residual biaxial stress in a piece of spring steel. This will involve first verifying diffractometer alignment by measuring the residual stress in a stress-free iron powder and then measuring the residual stress in a piece of spring steel.

Materials

1. Iron powder to be used as a stress-free standard.

2. The residual stress will be measured in a flat steel spring provided by the diffractometer's manufacturer.

Equipment

The equipment used during this experiment is:

1. Scintag XDS 2000 x-ray diffractometer configured as a 32 goniometer

Procedure

The following is a fairly detailed procedure for this experiment. Please note that you will have to reconfigure the goniometer in order to do this experiment and then return it to its original state when you are finished.

1. Obtain the PDF file for pure iron.

2. Use *Hardware/Configuration* program (password required) to configure the goniometer as a 2/32 goniometer with a 22 range of -2 to 163 degrees and an T range of -2 to 110 degrees.

This will redefine how 2 and T are used and will activate the motor which drives the angle N (specimen rotation). Don't forget to execute this program so that the new numbers are loaded into the configuration file.

3. Calibrate the goniometer, making sure that all three angles, 2, T and N are correct.

4. Peak intensities tend to be low so you will have to install the tube and detector slits that will give you higher intensities. 22-resolution is not an issue in this experiment.

5. Using the stress-free iron powder, run the residual stress data collection program. Select a peak, setting the 22 range for approximately 2 degrees on each side of the peak, the step size to 0.2 degrees per step and the preset time to 2 to 5 seconds. Set Q for ±20 or 30 degrees in 7 or more steps of $\sin^2$Q. Make sure this specimen is properly installed in the sample holder before starting the scan.

6. Run the residual stress analysis program on the data. The stress in the iron powder should be close to 0 MPa.

7. Run the residual stress data collection and analysis programs on the spring. Use the same parameters as were used for the iron powder.

8. Optional: Measure the residual stress utilizing other peaks. Also, try rotating the specimen 90° and rerunning the residual stress programs for the same peaks.

9. Return the angle N to zero and then return the goniometer to its original state: 2/2 configuration, -2 to 70 degrees for 22 and -2 to 90 degrees for T. Recalibrate the goniometer.

Results

1. Comment on the alignment of the diffractometer as indicated by analyzing the iron powder.

2. In both cases note the residual stress and the standard deviation.

3. How close was the stress to what is was previously reported to be?

Additional

1. There is an example of the results of this same experiment in the binder in the laboratory. While the data collection in this example took over 17 hours the counting statistics were much better than what you will probably see in this experiments. Also, 11 positions for the angle Q were used, providing more points along the line whose slope yielded the value of the residual stress.

2. Using wider slits will give one higher intensities and will reduce data collection time. This sacrifices resolution but then that isn't really an issue in this experiment.