THE USE OF BARKHAUSEN NOISE FOR THE MEASUREMENT OF RESIDUAL STRESSES IN AIRCRAFT PARTS

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INTRODUCTION

Residual stresses in cold formed parts can be present at high levels and have detrimental effects on the performance of highly loaded parts. In particular, tensile residual stresses can have serious effects on static mechanical properties, fatigue behavior, fracture performance and stress corrosion resistance. In such parts, residual stresses may be higher than those from service loading and require characterization to ensure adequate product performance.

Specimens manufactured from a precipitation hardening stainless steel were found to be susceptible to stress corrosion cracking (SCC). Within the specimens were residual stresses resulting from cold forming after heat treatment which were not completely removable by subsequent stress relief heat treatments. It was desired to quantitatively determine the residual stress levels which contributed to the SCC.

RESIDUAL STRESS MEASUREMENT METHODS

There are many methods of measuring residual stress and none is universally applicable. Each method has its advantages and disadvantages that must be considered in the selection process. A brief discussion of the major methods will be given concentrating on those aspects pertinent to this problem.

X-ray Diffraction

X-ray diffraction is one of the most direct methods and involves measuring the lattice parameter of a particular set of crystallographic planes, {211} in this case, to calculate the strain in the irradiated volume and from that the stress is calculated [1]. X-ray diffraction measures the residual stress in a very thin (0.0004 inches or 10 μm) surface layer. To measure residual stresses at greater depths, material is removed in a way that does not alter residual stresses. X-ray measurements may be calibrated directly from elastic constants.

Barkhausen Noise

When a material is magnetized, magnetic domains either rotate or shrink and grow. If a small coil is placed in the vicinity of the surface as the material is magnetized by an alternating field a signal, called Barkhausen Noise (BNA), is detected. The strength of this signal is a very strong function of the microstructure and a strong function of the residual stress as they both affect the ability of magnetic domains to rotate and grow [2, 3]. The depth of the BNA effect is a function of frequency and is typically around 0.004 inches (100 μm). BNA measurements require calibration against residual stress measurements made by other methods on material having the same microstructure (on a micro and a macro level).

Mechanical Methods

Mechanical methods of measuring residual stress all involve mechanically (or chemically) removing material and measuring the response of the structure with strain gauges. It is clearly a totally destructive method and is also not very selective in terms of the depth of measurement. The strain gauges are attached to the surface but the residual stresses throughout the entire depth of the specimen are relaxed as the specimen is cut and the measured strain is a function of the total relaxation behavior of the specimen, including any bending stresses generated. Most of the mechanical methods also assume that the remaining material (with the strain gauges attached) is of zero width.

SENSITIVITY DETERMINATION AND CALIBRATION

Sensitivity Determination

A demonstration of the sensitivity and linearity of both the X-ray and Barkhausen Noise methods was performed. In particular, the linearity of the Barkhausen Noise method at high tensile stresses was important and is known to be problematical at higher stresses. A four point bend specimen was machined from the center of a specimen (where the residual stresses would be expected to be the lowest) and was incrementally loaded. X-ray and Barkhausen Noise stress measurements at each load level are shown in Figure 1.

It can be seen that the X-ray stress data are linear with strain up to approximately 3,500 με (corresponding to about half the bulk yield strength of the material) and there is a gentle departure from linearity (attributed to surface yielding). The Barkhausen Noise data are linear up to approximately 3,000 με, the lower onset of non-linearity being due to magnetic non-linearities.

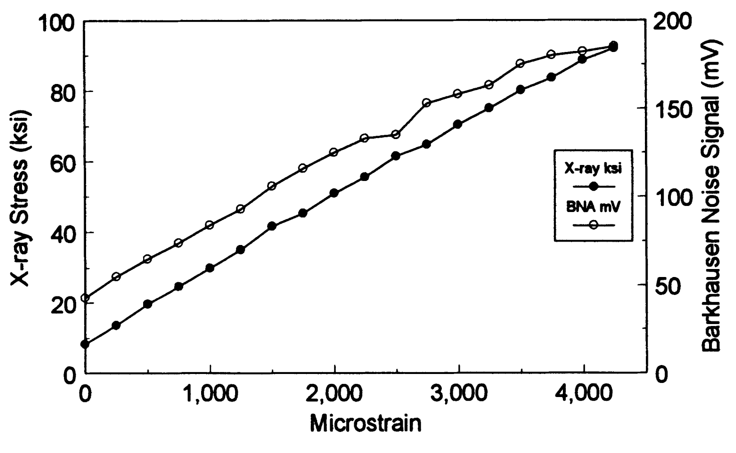


Figure 1. X-ray and Barkhausen noise measurements on four point bend sample.

Residual Stress Distributions

It was anticipated that the residual stress distributions would be non-uniform along the length of the specimen, across its width and through its depth. The variation along the length were associated with the position of the cold formed bend. Variations across the width were caused by the distribution of stresses caused by yielding during bending and their subsequent relaxation when the loads were removed. A simplified calculation of these stresses was carried out (not allowing for reduction of the residual stresses due to stress relief heat treatments) and this is illustrated in Figure 2 (a). Variations in the residual stresses through the depth of the specimen were expected as the surfaces were dust blasted and this is known to introduce surface compressive residual stresses. X-ray measurements were carried out by successive electropolishing and measurement and are shown in Figure 2 (b) for three positions within the cold formed region and one position outside it.

The depth profiles demonstrated that the compressive residual stresses caused by grit blasting were confined to a region approximately 0.003 inches (75 μm) deep. Barkhausen Noise measurements made had an effective depth of approximately 0.004 inches (100 μm) and so the residual stresses at these depths were used in subsequent calibration of X-ray measurements against those using Barkhausen Noise.

Calibration of the Barkhausen Noise Method

Calibration of Barkhausen Noise against the X-ray method was carried out by measuring within the cold formed areas of two specimens and locating areas with differing Barkhausen Noise levels. X-ray measurements were taken at the same positions at depths of 0.003 to 0.005 inches and these are shown in Figure 3 as solid symbols. Measurements were also taken at an area that had not been cold formed and these measurements are shown as open symbols. It can be seen that the Barkhausen Noise measurements from the cold formed areas are, with the exception of one point at -39 ksi, linearly related to the X-ray measurements. The breakdown of linearity at relatively high compressive stresses was expected but accurate measurements of compressive residual stresses were not required.

A linear regression was performed for the remaining measurements and a regression coefficient (r^2) of 0.957 was obtained (solid line in Figure 3), indicating a strong linear relationship. The Barkhausen Noise measurements collected from the area that had not been cold formed were not well correlated with the X-ray data and a regression coefficient of 0.188 was obtained (dashed line in Figure 3). The slope of the unstrained data is an order of magnitude lower than that from the cold formed area.

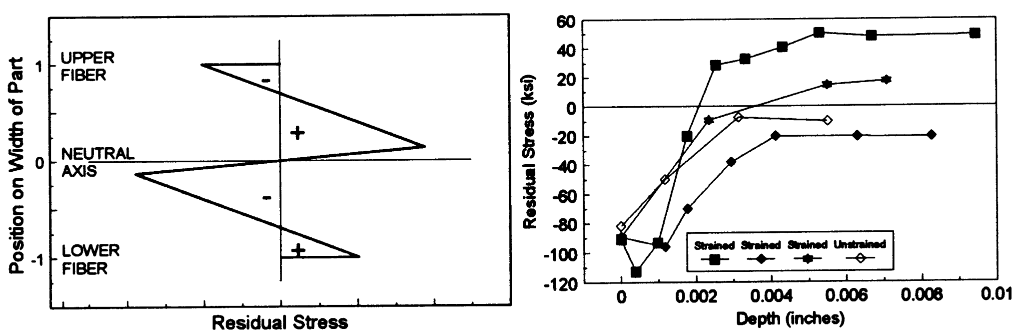


Figure 2 Width and depth variation of residual stress.

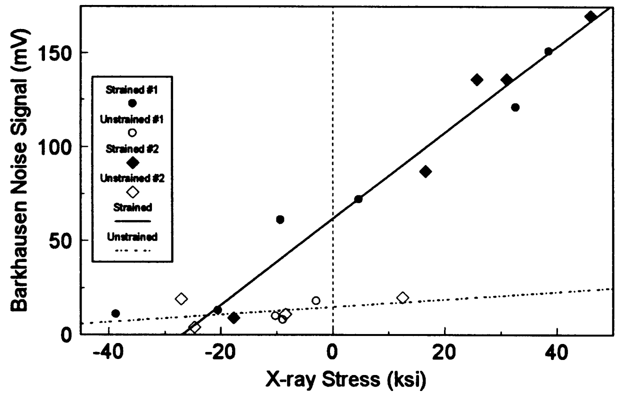


Figure 3 Calibration of BNA measurement against X-ray measurement.

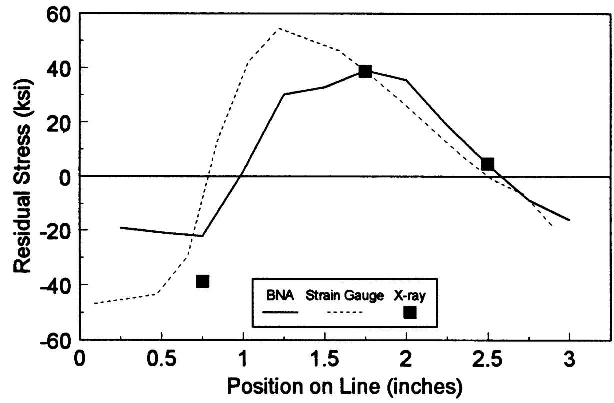


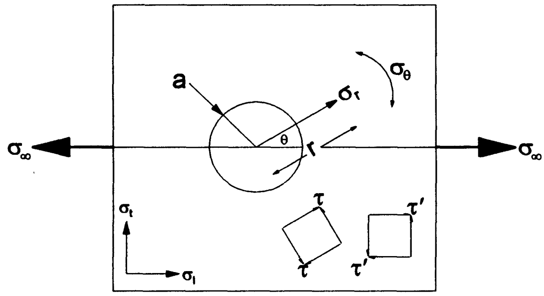
Figure 4 Check of measurement by X-ray, Barkhausen noise and strain gauge.

To perform a final accuracy check on the system, several measurements were made across the width of the cold formed region of a specimen using Barkhausen Noise and X-ray methods. The specimen was then strain gauged, cut and the residual stress distribution estimated from the change in strain gauge readings. These data are shown in Figure 4 and indicate a good relationship between the Barkhausen Noise and X-ray data and a reasonable correlation between the strain gauge data and that from the non-destructive methods. Differences between the width distribution in Figure 4 and that predicted by Figure 2 (a) were caused by stress relief treatments and machining of the specimen after cold forming.

STRESS CONCENTRATIONS AROUND HOLES

Holes were drilled in the specimens after cold forming and stress relieving. This gave rise to the possibility of stress concentrations around the holes causing changes to any residual stress fields resulting from the cold forming and drilling operations.

When a structure containing a hole is loaded, stress concentrations are formed around the hole. The stress concentrations can be thought of as bypass stresses and are well known [4]. It is not obvious that the same, or any, stress concentrations will exist for residual stresses as they are local stresses as opposed to long range applied stresses. The stress concentrations for applied load may be described by a simple set of equations defining the radial, tangential and shear stresses at any point around the hole as illustrated in Figure 5. Longitudinal, transverse and shear stresses may then be calculated as shown in the figure.



$$\sigma_r = \frac{\sigma_\infty}{2}\left[\left(1-\left(\frac{a}{r}\right)^2\right)+\left(1+3\left(\frac{a}{r}\right)^4-4\left(\frac{a}{r}\right)^2\right)\cos 2\theta\right]$$

$$\sigma_\theta = \frac{\sigma_\infty}{2}\left[\left(1+\left(\frac{a}{r}\right)^2\right)-\left(1+3\left(\frac{a}{r}\right)^4\right)\cos 2\theta\right]$$

$$\tau = -\frac{\sigma_\infty}{2}\left[\left(1-3\left(\frac{a}{r}\right)^4+2\left(\frac{a}{r}\right)^2\right)\sin 2\theta\right]$$

$$\sigma_l = \sigma_\theta \cos^2\theta + \sigma_r \sin^2\theta - \tau \sin 2\theta$$

$$\sigma_t = \sigma_\theta \sin^2\theta + \sigma_r \cos^2\theta + \tau \sin 2\theta$$

$$\tau' = -\frac{\sigma_\theta \sin 2\theta}{2} + \frac{\sigma_r \sin 2\theta}{2} + (1-2\cos^2\theta)\tau$$

Figure 5 Terms and stress concentrations around a hole under applied load.

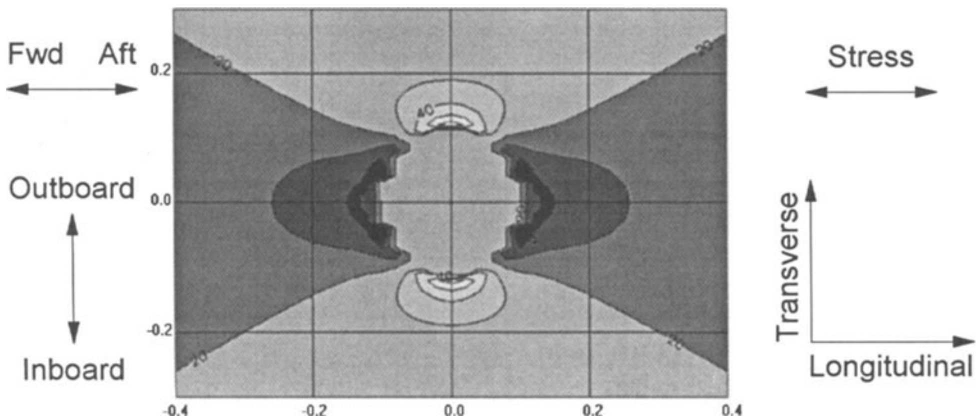
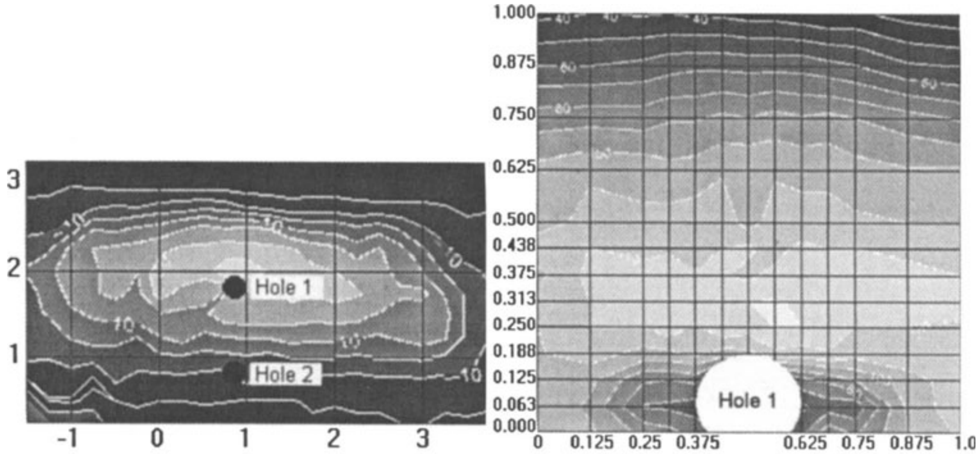


Figure 6 Calculated stress concentrations around a hole for an applied load of 20 ksi.

Figure 6 illustrates the calculated longitudinal stress distributions around a hole for an applied tensile stress of 20 ksi. This shows the classic increases in stresses at the top and bottom of the hole and reductions in the stresses at the sides of the hole. The effect of the stress concentrations is generally limited to a region around the hole of less than the radius of the hole. This calculation assumes a Stress Concentration Factor, K_t, of 3 which is the value appropriate for a hole in a uniaxially loaded infinitely wide plate. When the hole becomes large compared with the width of the plate, K_t drops to 2 [5]. The geometries of the samples used here were close to the infinite plate assumptions.

RESIDUAL STRESS MEASUREMENTS

The first residual stress measurements made were around two $^1/_4$ inch diameter holes in the cold formed region of a specimen. This is illustrated in Figure 7 (a) where the data were collected on a $^1/_4$ inch grid with a calibrated probe. A higher resolution contour map is shown in Figure 7 (b) where the data were collected on a $^1/_{16}$ inch grid with an uncalibrated probe. All residual stress data are measured in the longitudinal direction (horizontal on all figures). The data in Figure 7 showed that the maximum residual stress was close to one of the holes and the question arose as to whether this was a coincidence, the result of stress concentration or a function of residual stresses created or modified by the act of hole drilling and any subsequent relaxation. To attempt to quantify any stress concentrations around holes, detailed X-ray measurements were made in the region of Hole 1. Data were collected along lines in the inboard and outboard directions and are shown in Figure 8 along with calculated stress concentrations for K_t values of 3, 2.5, 2 and 1.5.



(a) Low Resolution (ksi)   (b) High Resolution (mV)

Figure 7   Barkhausen noise residual stress contour maps.

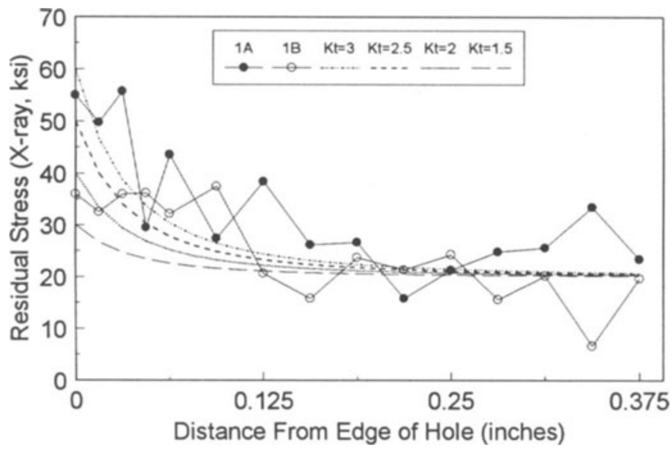


Figure 8   Measurements around a hole with tensile residual stress.

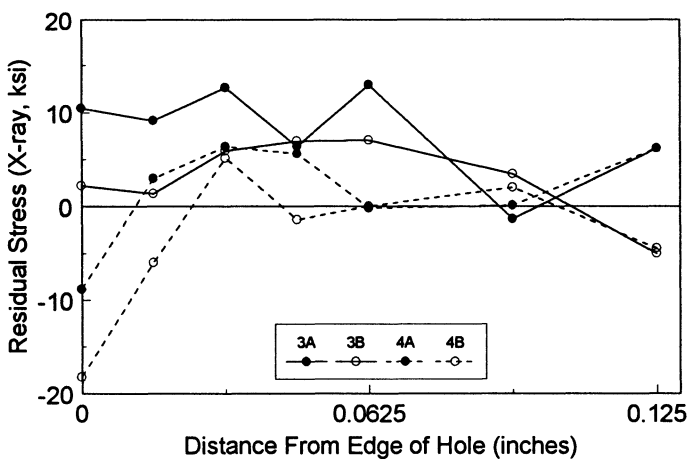


Figure 9   Measurements around two holes with approximately zero residual stress.

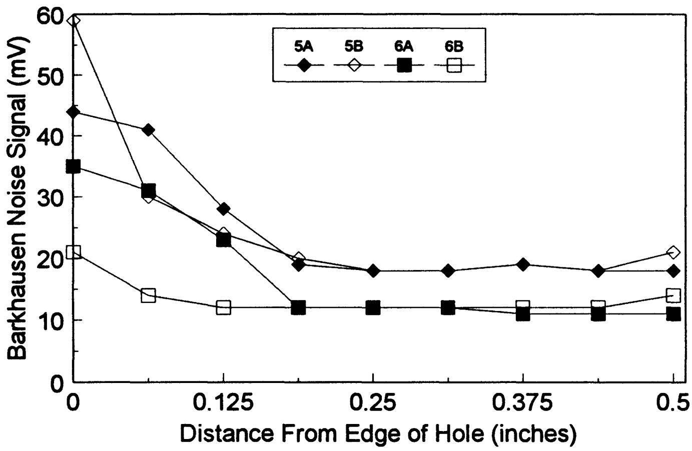


Figure 10 Transverse data around two holes with compressive residual stress.

The data from the outboard side of the hole (1A) show a significant increase near the hole but it is difficult to state that the stress concentration follows any particular K_t value. The data from the inboard side (1B) show a much smaller increase near the hole. If stress concentration factors were to be estimated from these data, they would be in the range from 1.5 to 2.5. Figure 9 shows similar measurements collected from two holes in an area having a residual stress close to zero and no stress concentration can be seen. These data should illustrate any residual stresses caused by the drilling operation. The data indicate that any residual stresses caused by drilling are either very small or even compressive near the edge of the hole. The residual stresses that are formed seem to be distributed in a zone around the hole somewhat larger than that caused by stress concentration.

One of the problems experienced in making either X-ray or Barkhausen Noise measurements around holes is that any stress concentrations are very short range and typically extend for approximately one hole radius before they become negligible. Two holes in specimens with compressive residual stress were available for (uncalibrated) Barkhausen Noise measurement. The holes in these specimens were approximately 35% of the width and so a maximum K_t close to 2 should apply along the transverse line. Figure 10 shows the data collected from two transverse lines and there appears to be an increase in the Barkhausen Noise signal near the edge of the hole. The far field stresses are, however, clearly compressive (a value of approximately 60 mV represents zero stress; values below that are compressive). The theory discussed earlier suggests that a stress concentration applied to such compressive stresses should give higher compressive stresses along a transverse line approaching the hole. This should decrease the Barkhausen Noise signal as the edge of the hole is approached and is clearly not the case for the data in Figure 10.

Figure 11 shows data taken from longitudinal lines and a small increase in the Barkhausen Noise signal can be seen as the edge of the hole is approached. The theory discussed earlier suggests that the stress concentration along such a line approaching the hole should result in the residual stresses becoming less compressive and finally becoming tensile at the edge of the hole. In terms of the Barkhausen Noise signal, this should increase significantly as the edge of the hole is approached and only a very small increase can be seen. Considering the data from the transverse and longitudinal lines, the data in the compressive residual stress field do not match the theory describing stress concentrations at holes for applied compressive stresses.

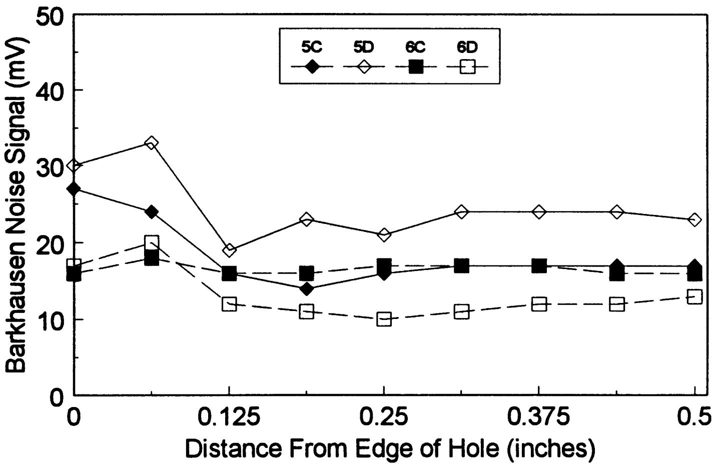


Figure 11 Longitudinal data around two holes with compressive residual stress.

When holes are drilled in these specimens, a number of processes can occur. Any residual stress present in the specimen may be concentrated by the presence of the hole (in the same way as applied stresses are concentrated by holes) but the magnitudes of any stress concentrations may be different from the applied stress case. The act of drilling the hole may introduce residual stresses as a result of mechanical deformation and local heating. The material removed in the drilling operation may not have had a net zero stress and, if so, would result in a change and redistribution of the remaining residual stresses. Unfortunately it is not possible to separate these different effects and performing controlled experiments is extremely difficult (as creation of uniform residual stress fields is almost impossible).

CONCLUSIONS

Barkhausen Noise is a useful method of rapidly and quantitatively measuring residual stress when calibrated for a particular material and condition. Differences in strain history invalidate any calibration (as do differences in microstructure or composition).

X-ray measurements around holes appear to show stress concentrations for tensile residual stresses of similar magnitude to those for applied stresses. Barkhausen Noise data around holes with compressive residual stresses indicate changes to tensile residual stresses at the edges of the holes, the opposite of the classic applied stress case.

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