# Residual stresses induced by hole cold expansion

R. Cook, P. Holdway

*Materials and Structures Department, Defence Research Agency, Farnborough, Hampshire, UK*

ABSTRACT

This paper describes an X-ray diffraction technique for measuring residual stresses. The results of measurements at locations in the vicinity of plain and cold expanded holes in an aluminium alloy are presented. Residual stresses are shown to vary significantly in all three dimensions and two dimensional analyses commonly used for residual stress determination are shown to be inadequate. The results of a fatigue test programme are also presented in which simple aluminium alloy specimens containing plain and cold expanded holes were subjected to constant amplitude fatigue loading. The results show that cracks from plain holes continuously increase in growth rate to failure whilst cracks from cold expanded holes decrease in growth rate and frequently arrest. The arrested crack lengths are different on either face of the cold expanded specimens and this is equated to the different residual stress fields present. Fatigue crack growth rates predicted using a Green's function technique are compared with those measured experimentally.

## INTRODUCTION

Cold expansion of holes is a technique widely used to extend the endurance of airframe structures. In general, the improvements in endurance due to cold expansion are not determined for design life purposes and can only therefore be considered as an insurance that the design life will be achieved in service. This situation arises primarily from an inability to reliably predict the fatigue endurance of structures containing cold expanded holes. More extensive use of cold expansion as a manufacturing process will only be possible when improvements in the fatigue endurance of structures due to cold expansion of holes can be accurately predicted.

Damage tolerant design requires the prediction of the rate of growth of cracks from assumed initial flaw sizes to lengths which can be reliably detected during periodic inspections. For cold expanded holes, stress intensity factors must be calculated to account for both applied and residual stresses. It is the aim of this investigation to assess a method of determining residual stresses and a method of calculating the resultant stress intensity factor distribution. Residual stresses have been measured around both plain and cold expanded holes using an X-ray diffraction technique. This technique has previously been used to measure residual stresses around fastener holes in steel [1] and more

Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533



recently in 7050 Aluminium alloy [2]. The X-ray diffraction technique has the advantage of being non-destructive but due to the relatively low penetration depth of X-rays (30μm with Cu radiation), only measures surface stresses. The results of these measurements are used to explain the crack growth behaviour observed in an experimental study. Crack growth rates are predicted using the measured residual stress data in a Green's function technique, and compared with experimental measurements.

## FATIGUE TEST PROGRAMME

A fatigue test programme was carried out to determine the effect of cold expansion on the fatigue crack initiation period and on crack propagation rates in 7050-T76 aluminium alloy. Fatigue tests were performed at a stress ratio R of 0.1 with a peak nett section stress of 184 MPa. Tests were stopped at regular intervals and acetate replicas made of the specimen surfaces. Cracks from plain hole specimens continuously increased in growth rate to failure whilst in cold expanded specimens cracks grew rapidly through the thickness of the specimen and soon arrested. Cracks remained at the arrested length for a considerable period before rapid failure or remote failure occurred.

Fatigue endurances and lives to first observed crack are given in Table 1. A comparison of the log mean endurances shows that cold expansion extends the fatigue endurance of these specimens by a factor of about 10. The increase in initiation time, however, is only by a factor of about 3. The main effect of cold expansion at this stress level is to reduce the crack propagation life. The remainder of this Report will therefore concern crack propagation behaviour.

Crack growth rates were calculated using a seven point incremental polynomial method. Results from plain hole specimens are presented as symbols in Fig.1; the solid curves are data predicted using techniques described in the following section. Crack growth rates for cold expanded hole specimens are presented as symbols in Fig. 2. Cracks on the outlet face grew to lengths of between 0.1 and 0.3mm and then arrested while cracks on the inlet face grew to lengths of between 0.8 and 1.3mm and then arrested. Specimens which failed from sites remote from the test section were subsequently statically pulled to failure to examine the arrested crack profiles. A typical example is shown in Fig. 3.

## RESIDUAL STRESS MEASUREMENTS

Residual stress measurements were carried out using a Siemens D500 diffractometer equipped with a Position Sensitive Detector (PSD) and an X-Y stage. Cu $k_\alpha$ radiation at 40kV, 40mA was used and the X-ray beam was collimated to give an irradiated area of approximately 1 x 1.5mm$^2$. The centre of this rectangle was taken as the position of the beam. Initial alignment of the beam relative to the hole edge was carried out by eye with the aid of a fluorescent disk. Subsequent movements were then carried out using micrometer screw gauges. The $\sin^2\psi$ method [3,4] was used for residual stress measurements employing up to 15 $\psi$ tilts with $\pm 2^\circ$ oscillations at each tilt. The (422) peak at 137.5° $2\theta$ was used and measured strains were converted to stresses using values of Young's modulus and Poisson's ratio of 72 GPa and 0.34 respectively.

Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533



Residual stress measurements were carried out on both lightly ground and mechanically polished surfaces. Grinding was carried out to remove the burring found at the edge of the hole. Residual stress measurements [5] suggested that the difference between the two surface finishes was less than the errors in the individual measurements.

The radial and hoop residual stresses at four 90° locations around a 4% cold-expanded hole have been measured on a number of samples and a typical set for the mandrel outlet side are shown in Table 2. Position C corresponds to the sleeve-gap location. The radial stresses were compressive at the hole edge, increased away from the hole before decreasing again. The maximum radial residual stresses occurred between 1.5 and 2.5mm from the hole with those at C being greater than at other positions. The hoop stresses were a maximum at or close to the hole edge and became tensile at about 3.0mm from the hole. The maximum stresses were again found at C with the smallest stresses diametrically opposite at A. Stresses at B and D were intermediate of those at A and C. During the fatigue test programme position C was on the centreline of the specimen, thus cracking occurred at locations B and D. Repeat measurements were generally ±2 MPa at a particular position but varied by between 20 and 50 MPa for equivalent positions in different samples with the same degree of cold expansion.

Fig. 4 shows some representative plots from the mandrel inlet and outlet faces for a radial and hoop direction. Residual stresses were found to be greater on the outlet face compared to the inlet face at the same position around the hole. Differences were larger in the hoop direction than the radial direction close to the hole edge (< 2.0mm). The hoop stress distributions shown (position D) are the ones used in the prediction routines described later.

Fig. 4 also shows some representative results from a plain hole, at two locations 90° apart. The radial stresses showed a slight increase at the hole edge whereas the hoop stresses were much smaller and both were close to zero after about 2.0mm distance. For prediction purposes it is therefore assumed that the hoop residual stresses in plain hole specimens are negligible.

## PREDICTION OF FATIGUE CRACK GROWTH RATES

### Prediction method

The prediction method used requires a knowledge of the stress intensity factor as a function of the crack length and the total stress (applied plus residual), and the relationship between stress intensity factor and crack growth rate for the material being tested. The general method consists of determining the residual and applied stress distributions and summing them to give a total stress distribution. Stress intensity factors can be derived for through the thickness cracks at the edge of a hole in an infinite sheet using a Green's function derived by Shivakumar and Forman [6]. Crack growth rates can be determined from the stress intensity factors using a materials database. Details of the method used are given in Ref 7.

### Predictions for plain holes

The prediction routine was programed on a computer and is described in Ref. 8. The program was tested by performing predictions of crack growth rates for plain hole specimens and comparing them with experimental data. Cracks grew in the plain hole specimens as single or double corner cracks and single or double through the thickness cracks. Corrections were therefore required to the stress intensity factors derived in the program as the Green's function used was appropriate to symmetric through the thickness cracks. Corrections were derived from the work of Newman and Raju [9] and added to the computer program. Predictions were made for the experimentally observed cracking conditions. The slowest rates were predicted for a single corner crack growing through the plate and becoming a single through the thickness crack. The fastest rates were predicted for a double through the thickness crack. These two predictions are shown in Fig. 1, and form an envelope which encloses most of the experimental data. This gives some confidence in the proposed approach.

Predictions for cold expanded holes

The residual stresses contributing to the Mode I stress intensity factor are the hoop stresses at the crack locations, i.e. positions B and D of residual stress measurement. It was observed earlier that stresses at these locations on the inlet face were markedly different from those on the outlet face, especially in the vicinity of the hole. Predictions of inlet and outlet face stress intensities are therefore considered separately. X-ray measurements were made as close to the hole as possible with the beam size chosen . This means that the hoop stress values in the vicinity of the hole are averaged over ~1mm which 'smears' out any steep stress gradients and leads to an underestimate of the residual stress. From the finite element results, this region was shown to have yielded in compression, as indicated by the reversal in slope of the residual stresses near to the hole (Fig. 5). It was decided to impose this behaviour on the measured residual stresses in order to allow predictions of crack growth rates in this region. The residual stress in the compression yielded zone were simply scaled by the peak compressive stress and added to the measured distributions as indicated by the dotted lines in Fig. 5. Predictions of crack growth rates were made using the distributions shown in Fig. 5 for the inlet and outlet faces of the specimen, and using the finite element solution.

The profiles of arrested cracks were measured from fatigue tests in which remote failure had occurred, a typical example is shown in Fig. 3. It can be seen that cracks on the inlet face were approximately quarter circular in shape whilst those on the outlet face were approximately through the thickness cracks. In the prediction routines, corrections were made to the stress intensity factor solution to allow for these observed crack shapes. The results of the predictions are shown as solid curves in Fig. 2 for the inlet and outlet faces; the finite element results predicted that cracks would not grow. The agreement with experimental data is poor, but crack retardation is predicted at about the correct crack length for the inlet face where a minimum in the crack rate is predicted at a crack length of about 1mm. It was expected that predicted rates would be faster than those measured as the magnitude of the measured compressive residual stress was thought to be underestimated, owing to the difficulty in making X-ray diffraction measurements in the steep stress gradient close to the hole, as already discussed.

Based on the assumption that the true hoop stresses were more compressive than those measured, further predictions were made using more compressive stresses adjacent to the hole. Stress distributions for inlet and outlet faces were used which maintained the overall shape of the measured distributions and also maintained the difference in compressive stresses between inlet and outlet faces

Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533



at a distance of 0.5mm from the hole. It was found that by increasing the maximum compressive residual stress of measured inlet and outlet face distributions by 75 MPa and adding the compressively yielded zone resulted in predictions close to the measured data. These predictions are shown as dotted lines in Fig. 2.

## DISCUSSION

The X-ray diffraction method described was found to be suitable for measuring surface residual stresses. However, because these stresses were averaged over the irradiated volume, it was not possible to resolve the steep stress gradients in the vicinity of the hole. Reducing the irradiated volume will result in poorer data quality unless the count times are significantly increased. It may also lead to problems if the irradiated volume becomes the same as the grain size. Texture in the plate will also give rise to errors in residual stresses due to anisotropic mechanical properties. Measurments showed that residual stresses in the hoop direction, which affect Mode I fatigue crack growth rates, were significantly less compressive on the mandrel inlet face than on the outlet face of cold expanded specimens. This was supported by experimental crack growth observations where the extent of crack growth was greater on the mandrel inlet face than on the outlet face. The X-ray measurements also showed a variation in hoop and radial stresses at locations around the circumference of the hole on both inlet and outlet faces. The least compressive hoop stress, i.e. the most fatigue critical location, was found diametrically opposite the sleeve-gap position. In structural components it would be preferrable to align the sleeve-gap with the main loading direction in order to avoid the fatigue critical hole location occurring at the point of maximum stress.

The two dimensional finite element analysis, by its nature, cannot indicate residual stress variations around the circumference of a hole nor through the thickness of a component. The residual stresses resulting from the FE analysis were much more compressive in the hoop direction close to the hole than those measured, typically by a factor of two. This resulted in no crack growth being predicted when the Green's function model was used. Whilst it cannot be concluded that the magnitude of the compressive hoop stress predicted by the FE analysis is too large, the measurements and predictions suggest that this may be the case. This is not a fault of the FE method, but of the assumptions made in this particular application. A full three dimensional FE analysis is clearly required to model the complete cold expansion process. The through the thickness variation in hoop residual stresses resulting from such an analysis could aid in explaining the crack shapes observed in tests.

Cold expansion of open holes in simple specimens was shown to give a significant improvement in fatigue endurance over specimens with plain holes. The improvements comprised a threefold increase in the crack initiation period, but a seventeenfold increase in the crack propagation period. The crack propagation period in cold expanded specimens was very long because cracks grew and then arrested for a significant period prior to failure. The stress level used was close to the fatigue limit for cold expanded holes and at higher applied stress levels cracks would be expected to slow in growth rate but not arrest, leading to smaller fatigue life improvements due to cold expansion. In aircraft structures stress levels are relatively low and hence crack growth behaviour similar to that observed in this investigation is expected. This has an important bearing on service inspections where relatively shallow through the thickness cracks will need to be detected. The life of such structures will probably be governed by the ability of these arrested cracks to re-initiate, which should be the subject of further studies.

The prediction method adopted in this investigation appears promising. The main difficulty with predictions is in accurately defining the residual stress fields present. A number of practical and analytical programmes are being undertaken to produce this information. There are however, a number of limitations to the prediction method with regard to the redistribution of residual stresses during crack growth and the flank closure of cracks in compressive residual stress fields. Both of these aspects are being studied with a view to improving the prediction program by the incorporation of routines to account for these factors.

## CONCLUSIONS

1. The present study has shown that X-ray diffraction is a good method for determining near surface residual stresses around fastener holes in 7050-T76. However, in the vicinity of the hole where residual stress gradients are high, the averaging effect of the beam limits the resolution of the technique.

2. Two-dimensional finite element analyses are not suitable for the determination of residual stresses surrounding cold expanded holes.

3. At the applied stress levels used in this investigation, cold expansion mainly affects the crack propagation period.

4. The fatigue endurance of cold expanded components subjected to stress levels close to the endurance limit will be governed by the ablility of small cracks to re-initiate.

5. Crack growth prediction using a Green's function technique gave good agreement with experimental measurements in plain hole specimens and qualitatively predicted the growth behaviour in cold expanded specimens.

## REFERENCES

1. Dietrich, G. and Potter, J.M. 'Stress measurements on cold-worked fastener holes', Advances in X-ray analysis, Vol. 20, p. 321-328, 1977.
2. Holdway, P. and Bowen, A.W. 'Internal strains near cold-expanded fastener holes in high-strength 7050 Aluminium alloy plate', In Residual stresses III, Eds. H. Fujiwara, T. Abe and K. Tanaka, Publ. by Elsevier Applied Science London, p. 779, 1992.
3. Noyan, I.C. and Cohen, J.B. 'Residual stress - Measurement by diffraction and interpretation', Publ. Springer-Verlag, 1987.
4. Hawk, V. and Macherauch, E. A useful guide for X-ray stress evaluation', Advanced in X-ray analysis, Vol. 27, p. 81-99, 1983.from a circular hole in an infinite sheet' Int. J. Fracture, Vol. 16, pp 305-316,
5. Holdway, P. Unpublished work.
6. Shivakumar, V. and Forman, R.G. 'Green's function for a crack emanating 1980.

7. Cook, R., Rooke, D.P., Smith, A. and Bowles, R.I. 'Residual stress fields at notches: effect on fatigue crack growth', RAE Technical Report TR 85049, 1985.
8. Cook, R., Rooke, D.P. and Dorey, S. 'A computer program to calculate growth rates for cracks at notches in regions of residual stress', DRA Technical Memorandum TM 1207, 1992.
9. Newman, Jr., J.C. and Raju, I.S. 'Stress intensity factor equations for cracks in 3-D finite bodies'. Fracture Mechanics 14th Symposium, Vol. 1, Theory and Analysis, ASTM STP 791, 1983.

## ACKNOWLEDGEMENTS

The authors would like to thank Mrs S. M. Goodwin for assistance with X-ray stress measurements.



Table 1 Fatigue test results

| Spec. No. | Hole condition | Life to first crack | Endurance | Failure position |
|---|---|---|---|---|
| CP 1 | PLAIN | - | 55,290 | HOLE |
| CP 2 | PLAIN | - | 72,150 | HOLE |
| CP 3 | PLAIN | - | 66,590 | HOLE |
| CP 4 | PLAIN | - | 45,358 | HOLE |
| CP 21 | PLAIN | 22,500 | 33,275 | HOLE |
| CP 23 | PLAIN | 37,500 | 53,025 | HOLE |
| CP 48 | PLAIN | 21,000 | 44,600 | HOLE |
| | | 26,070 | 51,402 | |
| CP 5 | CX | 75,000 | 509,278 | REMOTE |
| CP 6 | CX | - | 744,294 | HOLE |
| CP 7 | CX | 150,000 | 962,200 | HOLE |
| CP 25 | CX | - | 111,480 | REMOTE |
| CP 32 | CX | - | 95,770 | REMOTE |
| CP 55 | CX | 90,000 | 2,640,697 | HOLE |
| CP 56 | CX | 25,000 | - | - |
| CP 57 | CX | - | 180,825 | REMOTE |
| CP 60 | CX | 100,000 | 789,426 | HOLE/REM |
| CP 61 | CX | 80,000 | 1,530,000 | REMOTE |
| | | 76,631 | 507,818 | |

Note: Log-mean endurances are shown in boxes

Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533



TABLE 2 Residual stresses on outlet face of a cold expanded hole

| RADIAL STRESSES (MPa) | | | | |
|---|---|---|---|---|
| DISTANCE (mm) | POS A | POS B | POS C | POS D |
| 0.5 | -185±40 | -154±40 | -190±46 | -189±63 |
| 1.0 | -226±40 | -129±56 | -298±43 | -197±58 |
| 1.5 | -234±42 | -195±45 | -322±41 | -197±53 |
| 2.0 | -246±38 | -207±47 | -317±39 | -231±54 |
| 2.5 | -210±35 | -216±46 | -331±39 | -233±47 |
| 3.5 | -134±37 | -154±46 | -248±37 | -199±44 |
| 4.5 | -107±40 | -112±41 | -201±39 | -135±42 |
| 5.5 | -84±42 | -73±43 | -126±40 | -80±43 |
| 6.5 | -45±39 | -56±42 | -98±35 | -57±41 |
| 8.5 | -49±36 | -35±43 | -45±39 | -42±42 |
| 10.5 | -26±38 | -18±44 | -65±41 | -30±38 |
| HOOP STRESSES (MPa) | | | | |
| 0.5 | -246±59 | -352±47 | -464±56 | -425±44 |
| 1.0 | -208±55 | -348±43 | -463±52 | -326±40 |
| 1.5 | -146±51 | -269±47 | -432±51 | -272±41 |
| 2.0 | -86±47 | -216±42 | -346±45 | -161±40 |
| 2.5 | -28±46 | -153±40 | -277±49 | -100±39 |
| 3.5 | 36±44 | 8±37 | -80±50 | 17±38 |
| 4.5 | 56±46 | 53±36 | 17±47 | 48±41 |
| 5.5 | 56±53 | 40±40 | 54±43 | 57±35 |
| 6.5 | 36±47 | 37±38 | 59±43 | 36±36 |
| 8.5 | 37±42 | 38±38 | 50±48 | 20±35 |
| 10.5 | 26±45 | 32±37 | 45±47 | 33±41 |

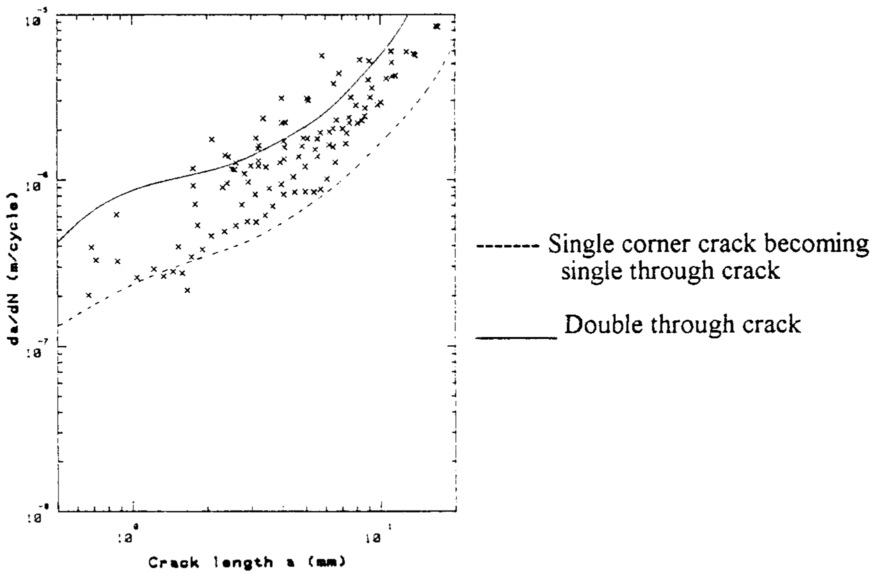
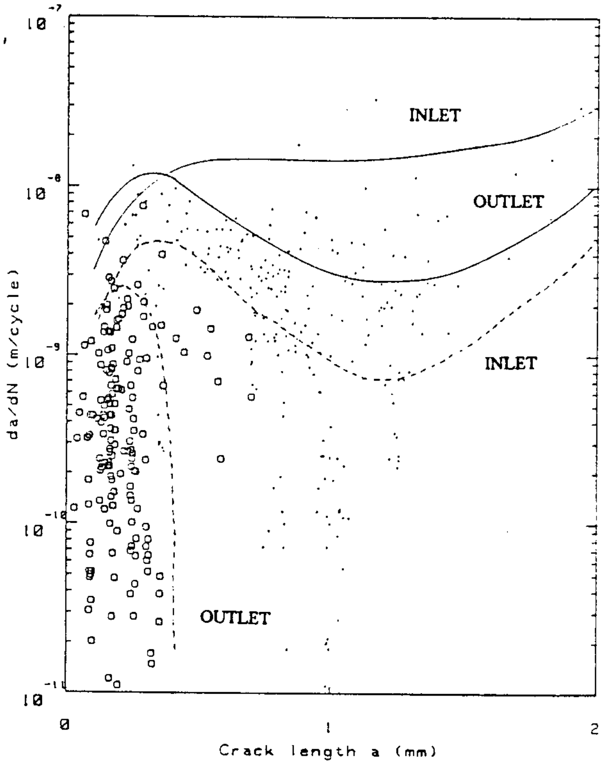



Figure 1 Crack growth rates from plain holes




0 Mandrel outlet face

. Mandrel inlet face

**Figure 2 Crack growth rates from cold expanded holes**

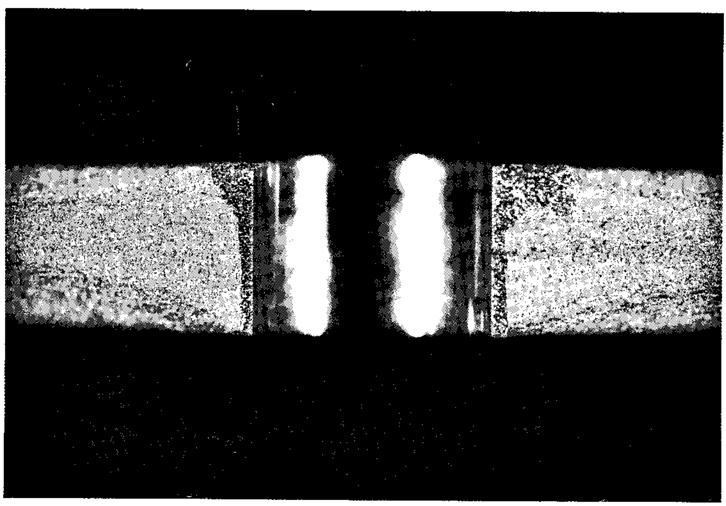


Figure 3 Arrested fatigue cracks

Transactions on Engineering Sciences vol 2, © 1993 WIT Press, www.witpress.com, ISSN 1743-3533

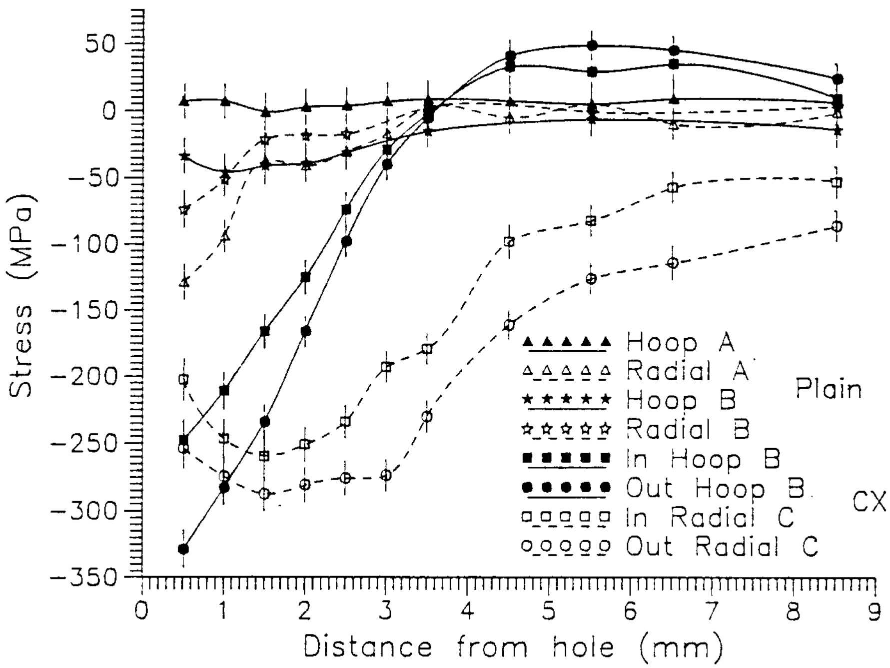




Figure 4 Measured residual stress distributions

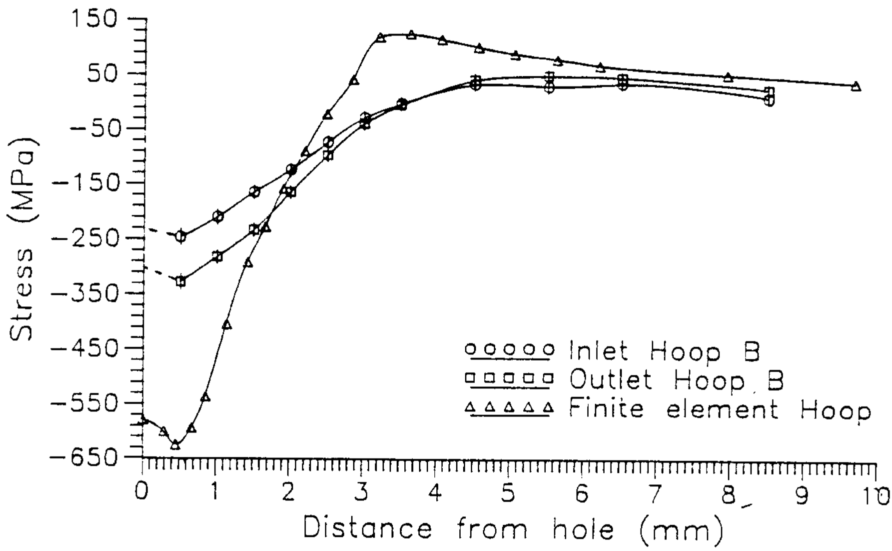



Figure 5 Residual hoop stress distributions used for crack growth predictions