



# Effect of residual stress on fatigue life of cold expanded fastener holes

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## ABSTRACT

Cold expansion of holes in aircraft structures to combat fatigue is now common practice. Expansion is usually achieved by a commercial split sleeve process using prescribed levels of mandrel interference. A sleeveless method of cold expansion which allows the degree of cold expansion to be infinitely varied in a simple manner has been developed at the Open University, applied to 5mm thick 7050 plate and compared to the commercial split sleeve process. It is shown that whilst both techniques produce significant increases in fatigue life, the commercial process is more effective. Measurement of the residual stress profile produced in each case using a modified Sachs boring technique shows that this is due to the greater compressive residual stress produced by the split sleeve process.

## INTRODUCTION

Rising demand for longer lives in both civil and military aerospace is likely to ensure that the economical lives of some aircraft structures will be dictated by their long-term fatigue performances. Generally, the primary source of fatigue damage, (cracking), is at mechanical joints and the problem becomes more vital as the demand for minimum structural weight to improved aircraft performance increases.

Mechanical joining methods are commonly used in aircraft structures. The transfer of loads from one structural member to another is accomplished either through the bolts in shear or by friction at the contacting surfaces by means of fastener clamping. When thin sections are tightly clamped together using high fastener torques the proportions of the load transferred by interfacial friction is large, so the fastener holes are not always deleterious to fatigue performance. However, at high shear load transfer joints, where thin or thick members are jointed, fastener holes can become the major source of fatigue cracking, (Mann and Jost [1], Schwarmann, 1982).



Cold expansion techniques have been used for over thirty years to produce fatigue life enhancement and have been recently reviewed by Champoux, [3]. Cold expansion of a hole can be achieved in a number of ways but all involve using a hard tool to plastically deform material in both radial and hoop directions so as to permanently increase its diameter. When the tool is removed from the hole, the elastic bulk surrounding the plastically deformed material forces it to spring back so that the vicinity of the hole experiences compressive residual stresses. Superposition of these residual stresses with service loads then leads to improvements in fatigue life either by delaying or suppressing crack initiation or more often by reducing fatigue crack growth rates.

### COLD EXPANSION METHODS

The most effective and widely used method in the aircraft industry is the split-sleeve process marketed by Fatigue Technology Inc. of Seattle, U.S.A. Expansion is achieved using prescribed levels of mandrel interference. The optimum degree of mandrel interference for a particular application will however depend on the local geometry of the component and fatigue life predictions of structures containing such expanded holes rely critically on estimates of the residual stress distribution surrounding the hole.

An alternative sleeve-less method for cold expanding circular holes has been developed at the Open University which allows the expansion to be infinitely varied in a simple manner. This system greatly facilitates the study of the effect of degree of cold expansion on both the residual stress distribution and its subsequent effect on fatigue life. It basically consists of a tapered mandrel around which are located a set of three caged rollers. When the mandrel is rotated and advanced into the cage, the rollers rotate in a planetary motion around the circumference of the hole, increasing its diameter.

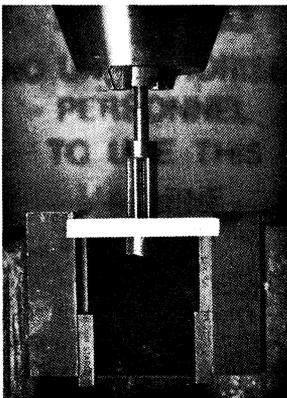


Figure 1

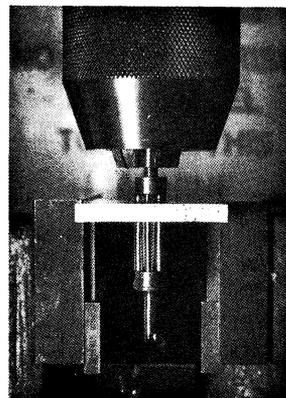


Figure 2

By arranging for the taper on the rollers to "cancel" out that on the mandrel the opposite sides of the hole remain parallel after treatment. The tooling can be used on a pillar drill or standard milling machine. The specimen is first clamped in the vice and the hole position is located under the milling head. The initial hole is then drilled using a suitable lubricant. The expander is manually positioned in the hole and the stationary centre mandrel is lowered until the rollers lightly grip the edge of the hole. The mill is then started, lubricant is applied and the centre roller is fed into the cage so expanding the hole. This sequence of events can be visualized by comparing figures 1 and 2 which show the tooling at the beginning and end of expansion respectively. Note that the mandrel travels through the cage as both slowly precess down through the hole. Finally the hole is deburred and reamed to the appropriate size.

This cold expansion technique is somewhat similar to roller burnishing, [4], which also typically uses tooling consisting of caged tapered rollers revolving around a tapered mandrel. However, conventional roller burnishing involves the use of fixed working diameter tooling where the rollers are set to a given size before being fed sequentially through the hole in the workpiece. If the rollers are inclined at a slight angle to the hole axis then the tooling is self feeding. Either mechanism of operation can only be used for relatively small expansions and conventional roller burnishing is mainly employed for either improving surface texture or finishing holes to tight tolerances.

Although higher expansions have been achieved using multiple passes, Cassatt and Tenclay, [5], and variable diameter tooling has been mentioned in the technical literature, [4], the authors are unaware of the use of either tooling system to produce high levels of cold expansion in one operation and thus we believe the technique developed at the Open University to be novel. It has been shown to produce increases in fatigue performance in both thin, (<2mm), sheet, Hermann and Reid [6], and thicker, (5mm), material, Edwards and Ozdemir, [7]. The present paper compares the residual stress profile and consequent fatigue performance of 9.52mm holes in 5mm thick 7050 aluminium alloy plate of dimensions 300mm x 40mm expanded by the two methods.

## RESIDUAL STRESS MEASUREMENT

A destructive method of measuring residual stresses on workpieces of cylindrical symmetry was first proposed by Sachs, [8] and the method has since been further developed, Lambert [9]. Weiss [10] tried to simplify the Sachs equations but his equations are essentially the differential forms of the conventional Sachs equations indicating that the measurement of residual stresses for this geometry is dependent not on the absolute values of the measured strains but their relative incremental change with hole area.

In order to create a workpiece suitable for Sachs analysis a circular washer of 40 mm outside diameter is removed symmetrically from around the hole in the plate specimen and strain gauges placed in both the hoop and transverse directions on its outside edge. The output of these gauges is then monitored as the central hole is sequentially bored out by a stepped copper tool using electrical discharge machining. The basic experimental setup is shown in figure 3. The geometry of the specimen is illustrated by the dummy specimen used for temperature compensation seen to the left of the picture. To compensate for

stresses relaxed during during initial machining of the washer from the plate specimen, hoop and transverse strain gauges are positioned inside the hole to monitor any strain changes that occur . A more detailed description of the complete stress measurement method is given elsewhere, Edwards et al. [11].

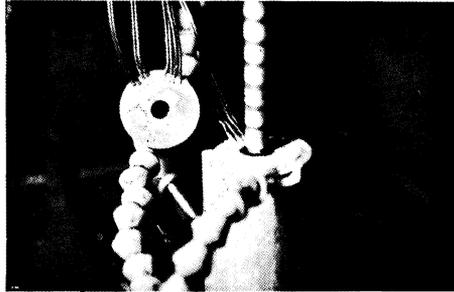


Figure 3 Experimental Sachs set up.

#### DEFINING THE DEGREE OF HOLE EXPANSION

Conventionally, cold expansion levels using mandrel methods such as the FTI method used here have been defined by comparing the size of the undeformed mandrel, (and lubricated sleeve), and the undeformed hole. Thus for FTI expansion we have:

$$\text{Degree of cold expansion (\%)} = \frac{D_2 - D_1}{D_1} \times 100\% = E_{(FTI)}\%$$

where  $D_2$  is the diameter of the mandrel plus sleeve and  $D_1$  is the diameter of the hole. Of course, whilst the expansion is taking place the mandrel is compressed elastically and some of the hole expansion is also elastic so some recovery occurs once the mandrel is removed from the hole. Thus, the final diameter  $D_4$  of the expanded hole will be given by:

$$D_4 = D_1 + (D_2 - D_1) R = D_1 (1 + E_{(FTI)}.R)$$

where  $R$  is the retained expansion, ( $\approx 60\%$  for 7000 series alloys).

However, as the size of the tooling used in the Open University, (OU), method is variable we define the degree expansion as :

$$\text{Degree of cold expansion (\%)} = \frac{D_4 - D_1}{D_1} \times 100\% = E_{(OU)}\%$$

So comparing the two methods we have

$$E_{(OU)}\% = \frac{D_1 (1 + E_{(FTI)}\%.R) - D_1}{D_1} = E_{(FTI)}\%R$$



Thus the commercially used FTI expansions 2%, 4% and 6% are equivalent to OU expansions of 1.2%, 2.4% and 3.6% as shown below:

|            |               |      |      |      |              |
|------------|---------------|------|------|------|--------------|
|            | $E_{(FTI)}\%$ | 2%   | 4%   | 6%   |              |
| Equivalent | $E_{(OU)}\%$  | 1.2% | 2.4% | 3.6% | (if R = 60%) |

This paper compares holes expanded 4% by the FTI method with holes expanded 2.4% by the OU method.

## RESIDUAL STRESS DISTRIBUTIONS

Residual stress distributions have been measured for varying degrees of expansion both before and after reaming of the expanded holes. However, OU expansion produces shallow fretting cracks at the bore of the expanded hole so whilst the results presented here consider both reamed and unreamed holes for the FTI case they will be confined to reamed holes expanded 2.4% for the OU case. In both methods we expand before reaming to size; for the FTI expansion the initial hole size was 8.69 mm and size after expansion was 8.92mm and for the OU expansion the initial hole size was 9.1mm and the final hole size was 9.31 mm. The FTI initial hole sizes were similar to those performed in commercial practice whilst the OU sizes were determined by the contingencies of OU expander manufacture. After expansion, all specimens were deburred with emery paper. The OU expanded specimens were also surface levelled with a slot drill as the process formed a small lip at the edge of the hole which if retained would produce difficulties for the use of many fasteners, Edwards and Ozdemir, [7].

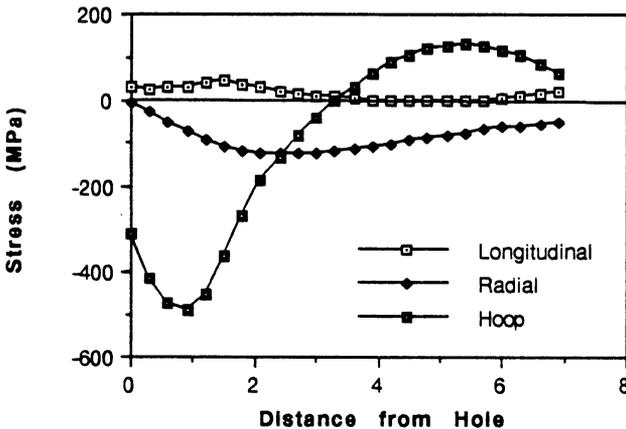


Figure 4. Residual stresses at a 4% FTI unreamed hole

Figure 4 shows the measured residual stress profile at an unreamed 4% FTI expanded hole. It can be seen that a substantial compressive hoop stress is created near to the hole. There is also evidence of reverse yielding at the hole edge leading to a relaxation of the hoop stress in that region so that the maximum

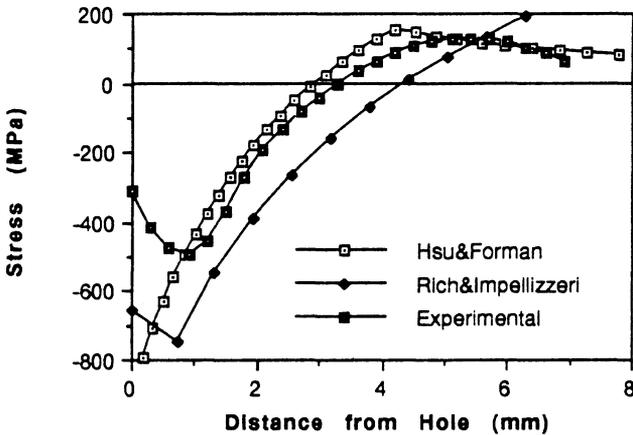


Figure 5. Comparison of measurement with theoretical predictions.

residual compressive hoop stress occurs at  $\approx 1$  mm from the hole. The residual radial stress is zero at the hole edge but becomes compressive away from the hole achieving a maximum value, ( $\approx 100$  MPa), at about 2.5 mm from the hole which approximates to the edge of the plastic zone caused by the expansion. The transverse stress is low at all positions.

There have been many theoretical predictions of the residual stress field around cold expanded holes. The exact predictions depend on the approach used and the boundary conditions considered. However, it is worth comparing the results obtained here with two typical theoretical analyses. Hsu and Forman [12], considered the case of a finite plate under plane stress conditions and allowed for work hardening. Rich and Impellizzeri [13] used plane strain conditions but also considered the elastic deformation of the mandrel and the effect of secondary yielding near the hole. Figure 5 compares the hoop stress distribution measured in the present work with that predicted by these authors. The predictions of Hsu and Forman seem more accurate far from the hole but no account is taken of secondary yielding. Although this is predicted by Rich and Impellizzeri, there is little correlation away from the hole. It is worth noting that both theoretical predictions produce residual stresses above the yield stress of the material, (543 MPa), whilst the measured stress profile is always below this value which may be more physically realistic.

In commercial practice the majority of cold expanded holes are reamed to enable the fitting of precision or interference fit fasteners and so to investigate the effect of reaming the residual stress profile at an expanded and reamed hole was also determined. Figure 6 shows the measured residual stress profile at a reamed 4% FTI expanded hole. By comparison with Figure 5 it can be seen that the only substantive change is an increase in the compressive hoop stress created at the hole edge removing any evidence of reverse yielding. Part of the reason for this is that the material containing the relaxed stress has been machined away

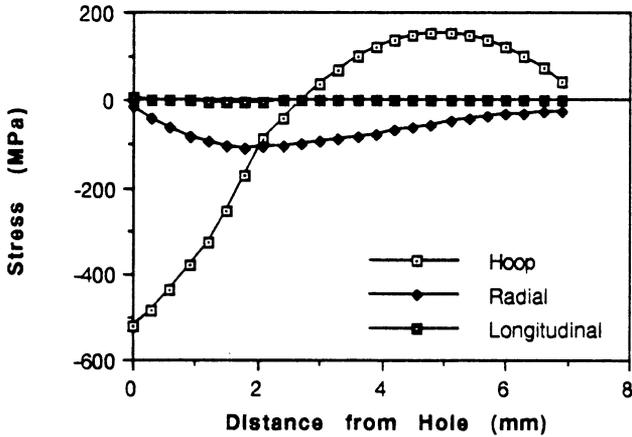


Figure 6. Residual stresses at a 4% FTI reamed hole

but it is possible that the actual reaming process also introduced further plastic deformation into the hole so slightly increasing the residual hoop stress at the hole edge. It may be noticed that the residual radial stress is still zero at the hole edge and the transverse stress remains low at all positions.

Figure 7 shows the measured residual stress profile at an reamed 2.4% OU expanded hole. It can be seen that although the residual stress profile has essentially the same shape as seen in the FTI expanded hole there is a significantly lower compressive hoop stress created near to the hole. There is evidence of reverse yielding at the hole edge leading to a relaxation of the hoop

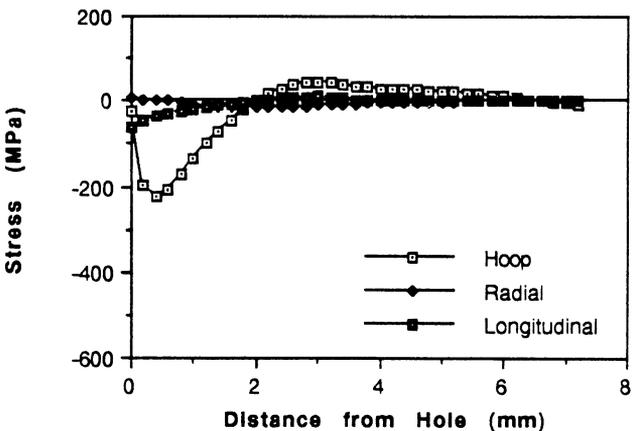


Figure 7. Residual stresses at a 2.4% OU reamed hole



stress in that region and the maximum residual compressive hoop stress occurs at  $\approx 0.5\text{mm}$  from the hole which is nearer than observed at the FTI expanded hole. Both the residual radial and transverse stresses are again low at all positions.

The reason for differences in the residual stress distributions produced by the two expansion methods is that the stresses produced are controlled not only by the degree of plastic expansion of the hole but how the expansion is produced, Edwards and Ozdemir [7]. The FTI expansion method results in substantial hoop and radial plastic strain which leads to a deep plastic zone causing substantial residual compressive hoop stresses. In contrast the OU expansion method causes significant longitudinal plastic strain as well as hoop and radial strain which results in significant plastic flow of material sideways out of the hole and a relatively shallow plastic zone. This results in lower compressive residual hoop stresses for the same nominal expansion.

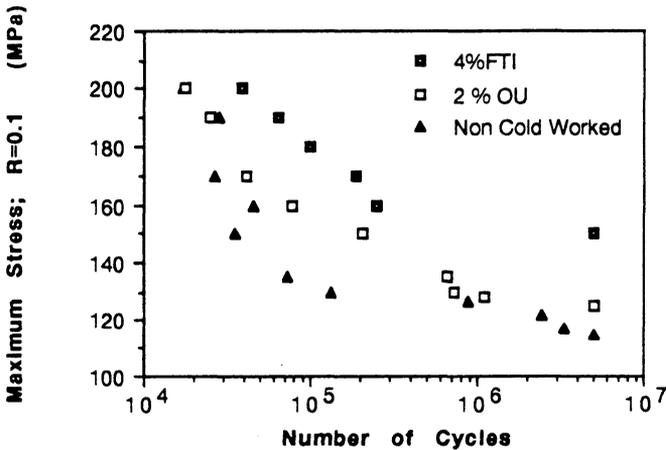


Figure 8 Effect of expansion on fatigue life.

## FATIGUE LIFE

To investigate the effect the differing residual stress distributions produced by the two expansion methods have on fatigue life S/N curves were produced for specimens containing virgin holes, holes expanded 2% by the OU method and holes expanded 4% by the FTI method. In each case the final hole was reamed to 9.52mm, (3/8"). All experiments were performed at constant amplitude loading with a R-ratio of 0.1 at a frequency of  $\approx 10\text{Hz}$ .

The fatigue results are presented in Figure 8. It can be seen that both expansion methods produce a substantial improvement in fatigue life particularly at low and intermediate stress levels. In addition, FTI expansion consistently produces a greater enhancement in fatigue life than OU expansion. Furthermore this effect becomes larger as the fatigue limit is approached. The improvement in fatigue life in both cases over non cold worked holes is due to the residual compressive



hoop stress produced by the cold expansion process. Thus the increased efficacy of the FTI process is due to the higher residual hoop stresses produced near to the hole in this case.

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## REFERENCES

1. Mann, J.Y. and Jost, G.S., Stress Fields Associated with Fitted and Cold Expanded Holes, *Metals Forum*, 6:43-53, 1983.
2. Schwarmann, L., On Improving Fatigue Performance of a Double Shear Lap Joint, *International Journal Of Fatigue*, 2:105-111, 1982.
3. Champoux, R.L., An Overview of Cold Expansion Methods, in *Fatigue Prevention and Design*, ed. J.T. Barnby, Chamelon Press, London, 35-45, 1986
4. Tool and Manufacturing Engineers Handbook, Vol III, Chapter 16: Mechanical and Abrasive Deburring and Finishing, Society of Manufacturing Engineers, Michigan.
5. Cassatt, G.G. and Tenclay, T.C., A Comparison of Residual Stresses Around Fastener Holes Produced by Three Different Methods of Mechanical Overstraining, in *Proc of 1982 Joint Conf. on Experimental Mechanics*, Amer. Soc. for Strain Measurement.
6. Hermann, R. and Reid, C.N., Experimental Analysis of the Stress Distribution around Cold-Expanded Holes in Thin Sheets, in *Residual Stresses - III* eds. Fujiwara, H., Abe, T. and Tanaka, K., 1:785-789, 1992.
7. Edwards, L. and Ozdemir, A.T., Measurement of the Three-dimensional Residual Stress Distribution Around Cold Expanded Aircraft Fastener Holes, in *Residual Stresses - III* eds. Fujiwara, H., Abe, T. and Tanaka, K., 1:1039-1044, 1992.
8. Sachs, G., Der Nachweis Innerer Spannungen in Stangen und Rohren', *Zeitschrift fur Metalkunde*, 19: 352-262, 1927, .
9. J. W. Lambert, 'A Method of Deriving Residual Stress Equations', *Proc-SESA*, 12:91-98 1954.
10. V. Weiss, 'Residual Stresses in Cylinders', *Proc-SESA*, 15:53-61, 1960.
11. Edwards, L., Ozdemir, A.T., Hermann, R. and Reid, C.N. to be published.
12. Hsu, Y.C. and Forman, R.G., Elastic-Plastic Analysis of an Infinite Sheet Having a Circular Hole Under Pressure, *J. of Applied Mechanics*, 42:347-352, 1975.
13. Rich, D.L and Impellizzeri, L.F., Fatigue Analysis of Cold Worked and Interference Fit Fastener Holes, in *Cyclic Stress-Strain and Plastic Deformation Aspects of Fatigue Crack Growth*, ASTM STP 637, 153-175, 1977