Effect of expansion technique and plate thickness on near-hole residual stresses and fatigue life of cold expanded holes

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Cold expansion of fastener holes is a common way of improving fatigue performance of airframes. Among the several techniques applicable, the split-sleeve method is the most accepted in creating beneficial compressive residual stresses around expanded holes. In the present work, residual stresses at expanded holes in several types of aluminium plates produced by two different techniques, split-sleeve and roller burnishing, have been evaluated by the novel destructive Sachs method and then compared. It was found that stress distribution particularly at the vicinity of the hole was sensitive to the method of expansion and plate thickness, due to differing characteristics of the plastic material flow. Thus, secondary reverse yielding after cold expansion found to reduce residual hoop stresses at the edge of the hole, and excessive expansion above a limit, was thought to increase reverse yielding. S–N data revealed that no benefit was gained from expanding beyond this limit. It was suggested that the reduction in the number of cycles to crack initiation or more often to crack growth was due to increased reverse yielding at the vicinity of the expanded hole. © *1999 Kluwer Academic Publishers*

1. Introduction

Solid rivets and high-strength bolted fasteners are essential for thin and thick members of aircraft structures and components. Particularly, at high shear load transfer joints, where both thin and thick members may be clamped, fastener holes can become the main source of fatigue cracking if, primarily, the fasteners are installed with clearance-fits (i.e. the diameter of the fastener hole is greater than the diameter of the fastener) [1, 2]. One main solution to this problem is the process of cold expansion, and has gained special interest over the last decade to be widely used in both military and civil aircrafts [3]. Among the three principal residual stresses (hoop, transverse and radial) produced by cold expansion, particularly the hoop (tangential) stress distribution at the periphery of the hole results in considerable gain in fatigue life by a factor of two to ten [3–7], either by retarding crack initiation or more often by reducing crack growth rates [5, 8].

For prediction of fatigue life and crack growth results, it is important that residual strains and particularly residual stresses produced from the cold expansion process are accurately known. To achieve this, mostly two-dimensional analytical studies are employed, where two approaches can be taken.

1. The use of closed form solutions, such as adopting already existing solutions of thin-walled [9–12] and thick-walled [13–17] cylinders subjected to an internal pressure; where some workers, in addition, considered strain-hardening behaviour [10, 11, 13, 15, 16], elastic unloading [13], and non-linear elastic–plastic behaviour on both loading and unloading [17] of the material after the cold expansion process.
2. The use of finite element analysis methods [18–20], by considering reverse yielding on unloading [18], reverse yield zone on elastic–plastic unloading [19], and the contribution of the stress state, i.e. plane-stress and plane-strain conditions [20].

There are also some experimental studies to determine the residual stresses, but they are few in number [4, 21, 22–26]. Despite the similarities, the results of analytical and experimental works are not in perfect agreement, but in common prove that residual stresses at the vicinity of an expanded hole are compressive, and

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reverse yielding at the edge of the hole occurs when high levels of cold expansion are employed.

In general, the effect of differing expansion methods (such as, split-sleeve and roller burnishing) on residual stress distribution has been verified [3, 22, 27], but there is no detailed work to determine the values of residual stresses especially at the peripheries of expanded holes. The effect of the degree of expansion on stress distribution at the vicinity of an expanded hole is one common problem, thus the optimum expansion is not always consistent with the maximum available expansion degree [24, 25]. It may vary depending on the particular application and the local geometry of the component, and has not yet been verified precisely by either analytical or experimental methods. Recently, some fractographic evidence [5, 6], and three-dimensional numerical [28] and experimental analyses [22–26] have also indicated the non-uniformity of residual stresses across the thickness of the workpiece, which makes the solution even more complicated.

In the present work, for split-sleeve expanded and roller burnished holes, the question of residual stress "relaxation" at the edge of the hole due to reversed yielding and change in plate thickness will be shown in a quantitative way by obtaining experimental data from several types of aluminium plates, which are based on the assumption that the plane-stress condition prevails after cold expansion. This provides a better representation compared with the plane-strain solution [14] because of removal of the assumption that radial and hoop strains have to be equal in magnitude but opposite in sign. Thus, this paper presents results of the distributions of residual hoop stresses at cold expanded holes by employing an abridged version of the solution originally developed by Sachs [29].

2. Experimental procedure

2.1. Cold expansion methods

The most effective and widely accepted method of fastener hole expansion in the aerospace industry is the split-sleeve process introduced by Fatigue Technology Incorporated (FTI) of Seattle, USA. This method was first used by the Boeing Commercial Aeroplane Company in the early 1970s and is now in practice in manufacture and maintenance stages [3]. This process involves pulling an oversize tapered mandrel through an internally lubricated expandable split-sleeve inserted into the hole. The sleeve prevents direct contact between the sliding mandrel and the hole, reducing damage to the inside of the hole, and minimizing the material flow through the thickness direction. Consequently, the maximized compressive hoop stress at the periphery of the hole may further increase with the degree of cold expansion, which is mainly limited by available tooling.

The cold expansion of fastener holes can also be achieved by sleeveless methods [3]. Split-sleeves are expensive since a new sleeve is required for every hole treated, hence a new tool has been developed in the author's laboratory to cold expand fastener holes by a sleeveless roller burnishing (RB) technique. This tool consists of a tapered mandrel and pin roller bearings held in a cage. When inserted into the hole, the tapered mandrel is pulled through the roller bearing cage and the hole in a fashion similar to the mandrel in the split-sleeve method causing plastic deformation and flow of material in the vicinity of the hole. A detailed description of the mechanics of this process is given elsewhere [25], and will not be repeated here.

As shown earlier [22], the general equation governing the degree of expansion, x, is

$$x = \frac{D_2 - D_1}{D_1} 100\% \qquad (1)$$

Where D_2 is the diameter of the hole after expansion and D_1 is the diameter of the hole prior to expansion. The above equation is applicable in the calculation of the degrees of FTI and RB expansion methods. When correlating the difference between the two processes, it was found that expansions of 2, 4 and 6% FTI were equivalent to expansions of 1.2, 2.4 and 3.6% RB, respectively [22]. In the present work, it was observed that a 1.2% RB degree of expansion was practically very difficult to achieve, so instead, 2% RB was selected as the lowest possible degree of expansion. It suffices to note that both processes are similar in producing plastic deformation, but the magnitude of the residual stress field has been shown to be different [22, 25].

2.2. Materials and specimen design

This paper reports the measurement of principal residual stress distributions produced by both FTI and RB methods. To analyse thin material behaviour, first, an aluminium alloy (8090-T651) with a thickness of 1.6 mm was employed. The material was supplied in the form of flat sheets from which dog-bone-like specimens were machined (shown in [25]). The dimensions of the specimens were, 130×35 mm with a gauge length of 55 mm. The second material used was a 5 mm thick aluminium alloy (7050-T76) supplied in the form of rectangular plates, with a size of 300×40 mm. Both specimens (8090 and 7050) were cut with their long axes parallel to the rolling direction (RD) of the sheet. At the centroid of each plate a hole was later drilled, and then the plates after appropriate expansions were directly used as specimens for fatigue tests. As illustrated in Fig. 1, around an expanded hole, 12 : 00, 3 : 00 and 6 : 00 positions were labelled as A, B and C, where A and C were parallel to the RD of the plate. The main concern, however, was position B, i.e. it was parallel to the transverse direction (TD), and primarily affected by fatigue loading.

For each alloy, and particularly for each degree of FTI and RB expansion, the initial and final hole sizes were not the same. Thus, for a 2% FTI expansion, the initial hole diameter was 8.68 mm and the final hole size was 9.02 mm; and for 4 and 6% FTI expansion, the initial hole and final hole sizes were 8.69 and 8.52, and 8.95 and 8.92 mm, respectively. Expansion of the holes was achieved by aligning the split in the expansion sleeve to position A of the holes (Fig. 1). Holes initially introduced centrally to the specimens were 9 mm in diameter for the RB process. However, the final hole sizes were

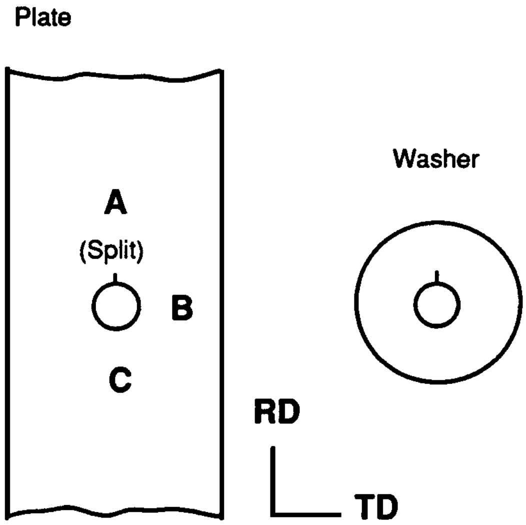

Figure 1 Schematic illustration of specimen and resultant washer, after removal from the plate.

continuously varied to produce the desired degrees of expansion. In the present work, for 2, 2.4, 3.6 and 5.5% RB expansions, the final hole sizes were 9.18, 9.31, 9.43 and 9.52 mm, respectively. The third material selected was a 19 mm thick 7010-T7651 aluminium plate with a dimension of 300.5×200.3 mm. Only 3% FTI expansion was applied to several 19 mm diameter holes (the final hole size was 19.59 mm), where for each, split orientation was arbitrarily chosen. Here, the results of the hole with split orientation parallel to RD (at position A) will only be given. The chemical compositions of the alloys are summarized in Table I, and their mechanical properties are given in Table II.

2.3. Determination of residual stresses

The specimen for the Sachs method was prepared from a rectangular plate by attaching a strain gauge to the inside of the hole, which was then spark eroded into a disc (washer) in which the expanded hole was central to the disc. This sequence was shown schematically and the details were given in [22, 24, 25], and the following is a summary of this process. Due to cutting the washer, a pressure is generated in the radial direction around the hole, $-P$. Thus, the wall of the hole experiences a tensile hoop strain and there must be a pressure of opposite sign at the periphery of the washer resulting in a compressive strain. The real residual hoop stress should be more positive than expressed by the Sachs method (or if this pressure becomes positive then the opposite occurs). Hence, the additional residual hoop stress $\Delta\sigma_\theta$, is proportional to $-P$, and should be added to the values obtained from the Sachs analysis; therefore $\Delta\sigma_\theta$ is

$$\Delta\sigma_\theta = \frac{\Delta\varepsilon_\theta E}{2}\left(1 + \frac{r_o}{r_i}\right)^2 \tag{2}$$

where $\Delta\varepsilon_\theta$ is the change in strain in the hoop direction at the wall of the hole; r_o and r_i are the inner and outer radii of the washer, respectively; and E is the modulus of elasticity. After removing the gauge (from the hole) and installing two further strain in gauges centrally on the outer rim of the washer in position B (one parallel to the thickness direction and the other perpendicular to it), the radius of the hole is increased by boring out small increments (typically 0.125 mm). This process entailed the use of a spark erosion electrode, which is essentially a copper rod containing accurately machined steps equivalent to the diameter of hole enlargement (see [22, 24, 25] for details). Two advantages are gained by this method: (i) the increments of the material cut from the hole are set precisely; and (ii) no residual stresses are introduced by this process, which is advantageous, since the removal of material changes the true stress over this increment without superimposing a residual stress from the cutting process.

The hoop and transverse (longitudinal) strains, ε_θ and ε_z, were measured from the aforementioned surfaces of the washers and tests were terminated when the diameters of the holes reached 18 mm for both 8090 and 7050 specimens. For the thick 7010 plate, however, the hole size at the end of the boring-out process was about 50 mm. The method of determining the magnitudes of principal stresses requires the coefficients of the strain versus hole area curve to be found (typical plots were given elsewhere [22, 24]). This can simply be achieved by fitting third-order polynomials to the curves of both the hoop and the transverse strains. Once the coefficients are known, then it becomes a relatively easy task to compute the three principal residual stress distributions with respect to distance from the edge of the hole.

TABLE I Chemical compositions of 8090, 7050 and 7010 aluminium alloys

Alloy (wt %)	Li	Mg	Zn	Cu	Fe	Si	Ti	Cr	Zr	Mn	Al
8090	2.4	0.61	—	1.15	0.09	0.05	0.005	—	0.12	—	Balance
7050	—	2.25	6.2	2.3	0.15	0.12	0.06	0.04	0.115	0.1	Balance
7010	—	2.45	6.2	1.75	0.15	0.1	—	0.05	0.14	0.3	Balance

TABLE II Mechanical properties of 8090, 7050 and 7010 aluminium alloys

Alloy	Temper	0.2% proof stress (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Elongation (% in 50 mm)
8090	T651	480	510	80	6
7050	T76	545	590	71	16
7010	T7651	485	545	71	12

The mathematical expressions for the residual stresses obtainable by boring out small increments were derived by Sachs [29], and are given for the hoop stress, σ_θ, the transverse stress, σ_z, and the radial stress, σ_r, by the following equations

$$\sigma_\theta = E'\left\{(A_o - A)\frac{d\Theta}{dA} - \left[\frac{(A_o + A)}{2A}\right]\Theta\right\} \quad (3)$$

$$\sigma_z = E'\left[(A_o - A)\frac{d\lambda}{dA} - \lambda\right] \quad (4)$$

$$\sigma_r = E'\left(\frac{A_o - A}{2A}\right)\Theta \quad (5)$$

where, $E' = E/(1 - \nu^2)$, $\Theta = \varepsilon_\theta + \nu\varepsilon_z$, $\lambda = \varepsilon_z + \nu\varepsilon_\theta$, and E and ν are the modulus of elasticity and the Poisson's ratio, respectively. The symbol A denotes the instantaneous hole area, and A_o is the initial circular area of the washer. From these equations, two-dimensional residual stress distributions can easily be evaluated, and in this paper two-dimensional stress profiles at mid-thickness sections are only given. A new technique, however, was developed to visualize the three-dimensional residual stress pattern through the thickness direction of the plate. The method was partially introduced in a previous work [24], but the details of the technique are given elsewhere [26].

2.4. Fatigue tests

Fatigue tests were all conducted using constant amplitude loading (load ratio, $R = 0.1$) in laboratory air on a servo-hydraulic testing machine with a 100 kN load cell at a frequency of 10 Hz. Hydraulic grips were used to hold the specimens. Particularly for 7050 plates to avoid premature failure in the grips, $1 \times 50 \times 50$ mm steel plates were bonded to each end of the specimen with epoxy resin.

3. Results and discussion

The discussion of results is specific to three items of materials behaviour, and this knowledge allows selection of the optimum degree of expansion for an application where crack determent is important [8]. They are:

1. Characterization of the flow properties in general and the difference between FTI and RB expansion processes.
2. Dependence of reverse yielding on plate thickness.
3. Characterization of the extent of plastic flow as a function of materials properties.

The following describes each topic in detail.

3.1. Dependence of reverse yielding on method of expansion

Using a single curve fit routine of strain versus hole area curve as described in Section 2.3, rough distributions

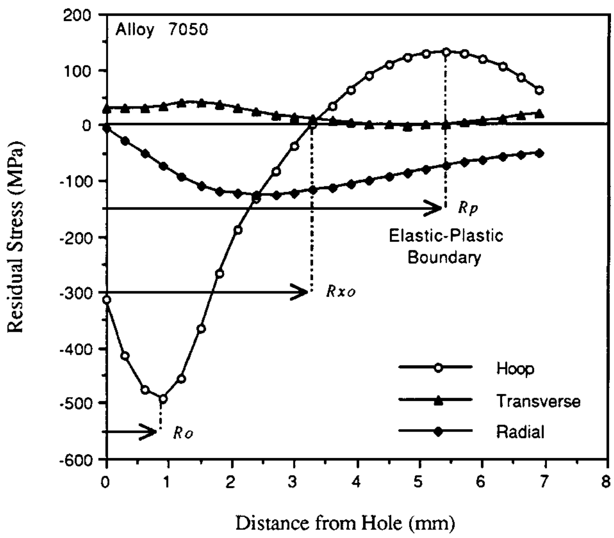

Figure 2 Complete residual stress distributions at a 4% FTI expanded hole in a 5 mm thick 7050 plate.

of the principal stresses can be obtained by evoking Equations 3–5 [22, 24, 25]. However, particularly at the vicinity of the hole, more precise knowledge of the stress distribution is essential. To achieve this, a multiple curve fitting programme, as will be described in detail in [26], was used. Simply, the data were divided into small discrete ranges and a low-order polynomial was fitted to each portion of the data. This had the advantage that, by successive use of a number of low-order polynomials, all the features of the original data were reproduced on the final distributions of the residual stresses (Fig. 2). While similar curves may be obtained with different degrees of expansion, the most significant part is the change in the hoop stress with distance from the hole, and in the following, among the three principal stress distributions, the residual transverse and radial stress profiles will be ignored. It is seen from Fig. 2 that there is a region of stress relaxation (due to reverse yielding) at the vicinity of the hole. From the edge of the hole, the maximum compressive stress (−490 MPa) is found at a distance of R_o (0.9 mm). The compressive stress value then decreases rapidly, reaching zero at a distance of R_{x_o} (3.4 mm), and after that rises gradually to a maximum tensile stress value (135 MPa) at the elastic–plastic (plastic zone) boundary, R_p (5.3 mm). Thus, the complete hoop stress distribution (for 4% FTI expanded hole in a 5 mm thick 7050 plate) extends to 7 mm from the hole. The present work, however, will only consider the direct vicinity of the hole, i.e. the region between 0 and 3 mm from the edge of the hole, in which reverse yielding takes place right after the expansion process. It is generally believed that, in this small area, the position of the maximum compressive stress is critical for arresting short cracks to ensure an increase in fatigue life [8].

Fig. 3 shows the change in hoop stress distribution with respect to the degree of FTI expansion for the 8090 plate. As this is the alloy with the lowest yield strength (see Table I), plastic flow at the vicinity of the hole is easy. For 2% FTI expansion, the hoop stress at the edge of the hole (−450 MPa) is almost at the yield point of

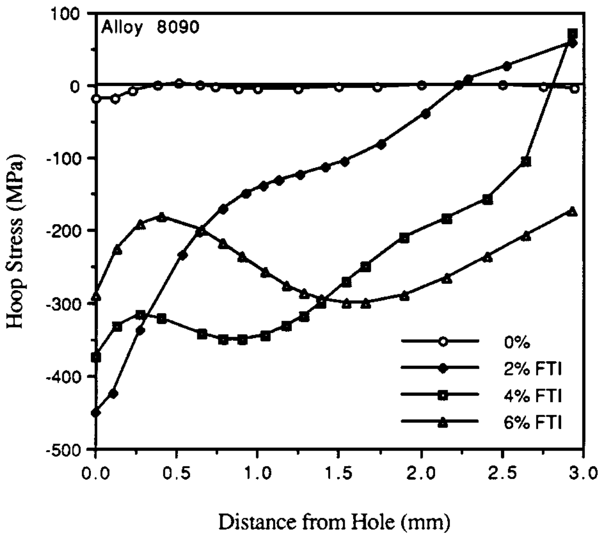

Figure 3 Effect of degree of cold expansion on residual hoop stress distribution at the vicinities of FTI expanded holes in 1.6 mm thick 8090 plates.

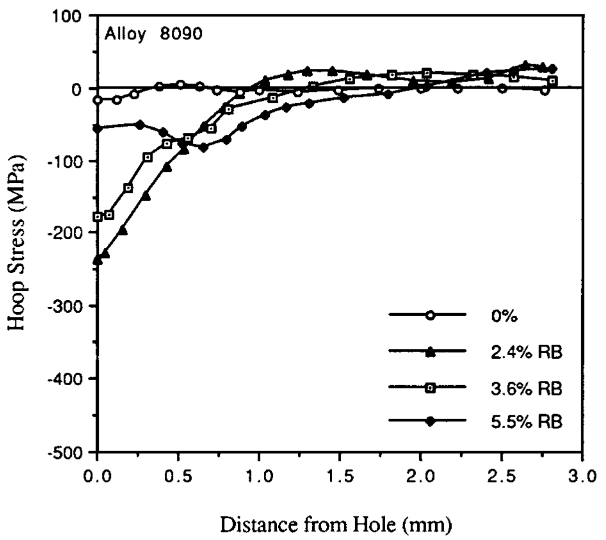

Figure 4 Effect of degree of cold expansion on residual hoop stress distribution at the vicinities of RB expanded holes in 1.6 mm thick 8090 plates.

the material. However, as the degree of expansion increases, the hoop stress at the hole edge becomes less compressive (−370 and −290 MPa for 4 and 6% FTI expansion degrees), but the area under the compressive part increases. In this respect, the zero stress position is found at 2.2, 2.7 and 3.7 mm for expansions of 2, 4 and 6% FTI, respectively (some values lie outside the frame of Fig. 3). For the same material, the hoop stress profiles generated by the RB process are given in Fig. 4. Compared with FTI expansion, stresses at the hole edge become less compressive (−240, −180 and −60 MPa), and the zero stress position gradually extends (1.1, 1.6 and 1.9 mm) with increasing degree of expansion from 2.4 to 5.5% RB. It is anticipated that when the degree of expansion increases, the stress at the vicinity of the hole will become more compressive due to increasing backwards elastic constraint of the material surrounding the plastic zone. However, it is clear from Fig. 4 that, at the highest degree of expansion (5.5% RB), the value of the maximum compressive hoop stress is reduced to a moderate value, −80 MPa, which is 0.65 mm from the hole.

In common, for both methods of expansion, plastic zone size is a critical factor in creating compressive stresses. With high yield strength, large plastic zone size leads considerable contraction of the hole after expansion, and so positively affects the degree of secondary yielding at the edge of the hole. It would be anticipated that secondary yielding, and so relaxation of residual stresses at the edge of the hole, is large for the FTI method, because this technique comparatively introduces larger plastic zone sizes [3]. During FTI expansion, extensive forcing of the mandrel easily deforms the material beyond the yield point and extends the plastic zone to a large distance. And after removal of the mandrel, elastic constraint causes extensive reverse yielding of the material at the edge of the hole and so relaxes this highly over strained region. Although similar behaviour is observed in RB expanded holes, the size of the plastic zone is relatively small, but the amount of stress relaxation is substantial and so residual hoop stresses at the vicinity of the hole are far below the yield strength of the material (Fig. 4). The only reason for this contradiction could be severe frictional forces between the roller cage and the wall of the hole. Friction causes considerable plastic flow in the transverse direction (see Fig. 5, which shows symmetric sidewards flow of the material out of the hole during the RB process), and therefore reduces the amount of plastic deformation in both the radial and hoop directions, where in return, both the size of the plastic zone and the magnitude of the material constraint decrease, and so on the average less compressive residual stresses are created. Stress relaxation at the edge of the hole is, however, particularly the result of extensive transverse plastic deformation, which is a typical characteristics of the RB process. Consequently, compared with the FTI process, residual stresses around RB expanded holes are less compressive even for equivalent degrees of expansion. Thus, the sleeve has great importance in minimizing transverse material flow (see Fig. 6, which illustrates the

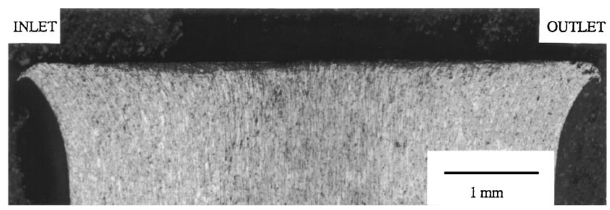

Figure 5 A metallographic section through a 2% RB expanded hole in a 5 mm thick 7050 plate.

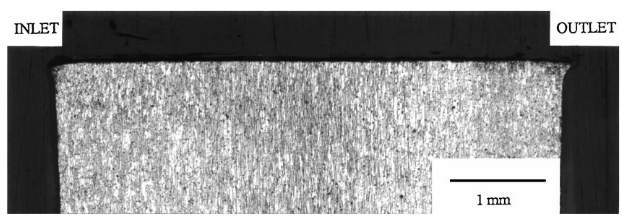

Figure 6 A metallographic section through a 4% FTI expanded hole in a 5 mm thick 7050 plate.

difference in material flow between mandrel-in (inlet) and mandrel-out (outlet) surfaces during the FTI process). Therefore in general, the value of the maximum compressive hoop stress, its position from the hole, zero stress position and the plastic zone size are comparatively large in the FTI process.

3.2. Dependence of reverse yielding on plate thickness

In a previous work, the effect of several expansion techniques on residual stress distributions in several 7075-T73 aluminium plates was studied [27]. It was indicated that particularly at split-sleeve expanded holes, compressive residual hoop stresses reached to highest possible levels and became increasingly compressive as the plate thickness increased for a given degree of expansion. To analyse and verify the dependence of the stress distribution on plate thickness, in the present work, residual stress profiles obtained from several types of aluminium plates were individually considered and then compared to clarify the relation.

Fig. 7 shows a detailed analysis of 2, 2.4 and 3.6% RB expanded holes for the 7050 alloy. This material has a higher yield strength, and is thicker than alloy 8090. As is clear from the figure, the three stress profiles are very similar, in particular the maximum compressive hoop stress values are concentrated around −250 MPa, and positioned 0.4 mm from the hole. It can be seen from Figs 4 and 7 that maximum compressive stresses at (5 mm) 7050 plates are on the average larger than those of 8090 (1.6 mm) plates. Furthermore, as the degree of RB expansion increases, reverse yielding becomes substantially large, i.e. as seen from Fig. 7, at 3.6% RB expansion, the hoop stress at the edge of the hole reaches a tensile value of 40 MPa. This in fact indicates how the size of the plastic zone, particularly in 7050 plates, is not effected by the degree of expansion. Thus, after cold expansion, rather than elastic contraction of the plastic zone, the aforementioned process

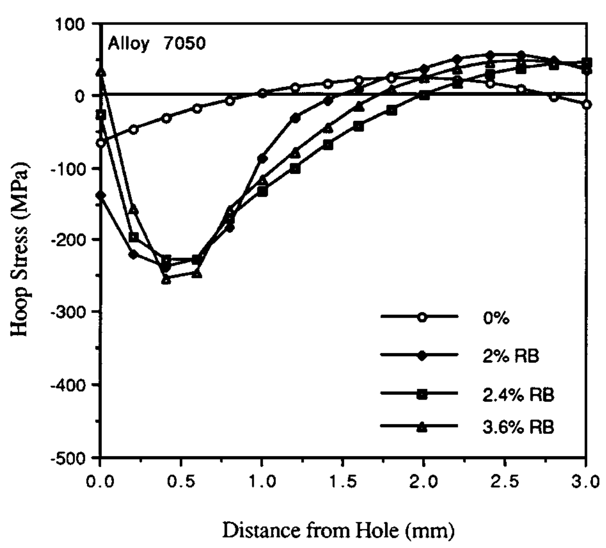

Figure 7 Effect of degree of cold expansion on residual hoop stress distribution at the vicinities of RB expanded holes in 5 mm thick 7050 plates.

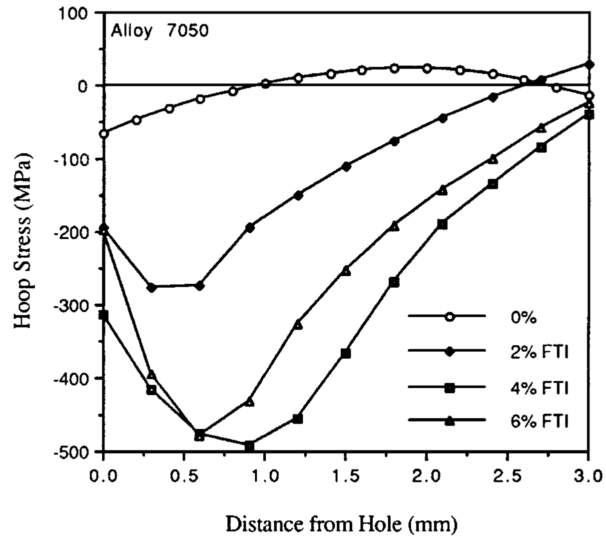

Figure 8 Effect of degree of cold expansion on residual hoop stress distribution at the vicinities of FTI expanded holes in 5 mm thick 7050 plates.

deficiency seems to be primarily responsible for the apparent residual stress relaxation at the vicinity of the hole. The degree of relaxation is a function of sidewards plastic flow, which increases considerably during further efforts to push the mandrel into the roller cage to maximize the degree of RB expansion (Fig. 5). As the thickness of the plate increases, the resulting material constraint (blocking action behind the plastic zone) also increases. Thus, the material at the vicinity of the hole is further forced to flow in the transverse direction due to intensified hole edge frictional forces. This means that the efficiency of the RB process degrades remarkably.

Fig. 8 on the other hand shows hoop stress distributions at 7050 plates for 2, 4 and 6% FTI degrees of expansion. As seen from the figure, each curve has a maximum compression in stress (between −270 and −490 MPa) and is at some distance from the hole (between 0.5 and 1 mm). Similar arguments with regard to sidewards material flow and resulting secondary yielding could also be valid for FTI expanded holes. However, as mentioned before, the sleeve minimizes frictional forces between the mandrel and the hole edge, and so increases the efficiency of the FTI expansion process (Fig. 6). It can be seen that, as the degree of expansion increases, residual stresses generated near the hole become more compressive. However, no further rise is evident on increasing expansion beyond a certain degree (Figs 3 and 8). The effectiveness of the FTI expansion process is therefore not unlimited, and maximum compressive stress saturates. In the present work, at 1.6 mm (8090 plate) the maximum available compressive stress (−450 MPa) was easily reached at 2% FTI expansion, where stress saturation (−490 MPa) could only be achieved at 4% FTI expansion for the 7050 (5 mm) plate. This variation in stress saturation can simply be related to the thickness of the material. The explanation behind this is the easy onset of plastic flow during the lowest degree of expansion. For a thin specimen, material constraint and so resistance against mandrel work is low. Thus, reaching easily to the tensile yield strength, the hole edge material deforms, and therefore the elastic–plastic boundary created gradually spreads from the edge of the hole. During unloading, however, the hole contracts and the already created compressive stresses near to yield strength are further forced beyond this limit. Hence on reverse yielding, residual compressive stresses at the edge of the hole relax. As the degree of expansion increases, reverse yielding intensifies resulting in less compressive residual stresses. When, however, a hole in a thick specimen is FTI expanded, due to an increase in material constraint, the equipment to push the mandrel through the hole has to provide additional process forces. After expansion is successfully achieved, applied forces create a large plastic zone around the hole and, consequently, extensive compressive residual stresses are generated. It is also apparent from Figs 3 and 8 that the value of the maximum compressive stress is affected by the degree of reverse yielding. Thus, expanding the hole beyond the saturation limit only intensifies the stress relaxation at the edge of the hole; where in return, maximum compressive stress, from its saturated value, is reduced.

To portray the effect of plate thickness in detail, normalized residual hoop stress (hoop stress/yield strength) distributions of 4% FTI expanded 8090 (1.6 mm) and 7050 (5 mm) plates together with a 3% FTI expanded 7010 (19 mm) plate were plotted in Fig. 9. It is clear that plate thickness is very effective in increasing the maximum compressive stress, its position, the zero stress position and the plastic zone size in the FTI process. However, because of practical reasons, the degree of expansion could only be increased to 3% FTI (further attempts to increase expansion caused cracking of the hole edge during the process). It is apparent that 3% FTI expansion for the thick plate (19 mm) still gives a deeper compressive stress field than the other two thin (1.6 and 5 mm) plates expanded by 4% FTI. Thus, when the values of zero stress position and plastic zone size are compared (values lie out of the range of Fig. 9) they are at 6.3 and 11.5 mm for the thick 7010 plate, and at 2.9 and 3.5 and 4 and 5.4 mm for

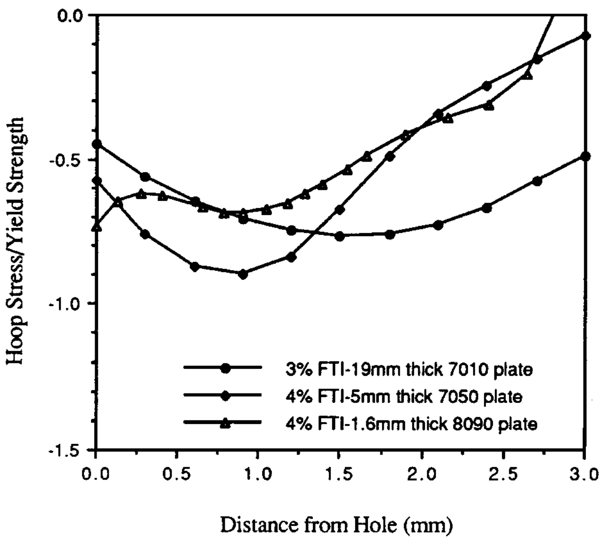

Figure 9 Effect of plate thickness on normalized residual hoop stress distribution.

the thinner 8090 and 7050 plates, respectively. These results suggest that, in the case of a successful increase in the degree of expansion of the 7010 plate from 3 to 4% FTI, the residual stress field would be more broad and compressive. A larger hole size may be an alternative factor in producing this deeper stress field, i.e. according to [23] for the same plate thickness, an increase in hole diameter may produce a more compressive residual stress distribution. However, in the present work, this possibility seems to be less effective. The diameters of the untreated holes in the 8090 (1.6 mm) and 7050 (5 mm) plates were identical, and therefore the difference between the stress distributions of these specimens reflects the effect of plate thickness.

The effect of plate thickness can be explained by referring to previous work [20–24, 26]. Thus, as the residual stress distribution was measured at three different positions across the depth of the plate, a rough estimate of three-dimensional through-thickness residual hoop stress distribution was obtained [20–24, 26]. Even though these approximated three-dimensional profiles far from visualized the complete three-dimensional distribution, they could give enough information about how the residual stress values at mid-thickness section were more compressive than those close to plate surfaces. Consequently, it was found that at a split-sleeve expanded hole going from inlet to outlet sides, the most compressive residual stresses were located at the mid-thickness section of the hole. This was infact the region where the plane-strain condition was valid. On the contrary, of course, the condition of plane-stress was at each plate surface. Considering two plates, a thin one with plane-stress and a thick one with plane-strain conditions, variation in through-thickness stress distribution in the thin plate is small and can be ignored. Hence, residual stresses in the thin plate are two-dimensional, i.e. change only with distance in from the edge of the hole. In plates of intermediate thickness, however, the state of stress changes from plane-stress to plane-strain conditions, i.e. the transitional case. During cold expansion, material at the mid-thickness section flows in radial and hoop directions, and therefore high compressive stresses are generated. However, the method of cold expansion apparently affects the part of the hole wall in which the plane-strain condition is valid. Thus, the success of the FTI process directly relies on the sleeve, which satisfies the condition of plane-strain, where in return the resulting plastic zone size and so residual compressive hoop stresses become comparatively large. On the other hand, extensive sidewards material flow in the RB process causes the hole wall readily to behave in the plane-stress condition, and thereby results in substantial reverse yielding and so stress relaxation.

3.3. Effect of material properties on plastic flow

It is apparent from Sections 3.1 and 3.2 that, even if the basic principles of producing beneficial compressive stresses are identical, due to differing mechanics, the same material with the same initial hole size gives a different response to these separate methods of expansion.

However, the success of each expansion method may also be dependent on the material properties of the workpiece used, such as per cent elongation and yield strength. Per cent elongation, in particular, is a measure of plasticity and when it increases, the size of the plastic zone becomes larger [10–12]. However, strain-hardening is a parameter that has an adverse effect on plasticity. In the case of strain-hardening, with the same work of expansion, less plastic flow occurs around the hole, and hence the size of the plastic zone is confined to the edge of the hole [10, 11, 13–17, 19]. Yield strength (or flow stress) on the other hand, positively affects the elastic constraint around the plastic zone. Thus, given the same plastic zone size, as yield strength or flow stress (in case of strain-hardening) increases, elastic constraint after expansion becomes large enough to intensify the compressive stresses at the edge of the hole. However, as strain-hardening elevates the yield stress, it may in return reduce the extent of reverse yielding in the hole region [14–17, 19].

In this work there are no complementary data relating the effect of material properties on the resulting residual stresses. It is clear from Table II that aluminium alloys have differing mechanical properties, but there are similarities in some of the values. Thus, alloys 7050 and 7010 have a close per cent elongation, whereas alloys 8090 and 7010 possess almost the same yield strength. Infact to minimize the factor of varying yield stress, normalized values of residual stresses were evaluated and used in Fig. 9 to show the effect of plate thickness. However, differing plasticity and flow stress values may cause confusion, and so the residual stress profiles in the figure can only give approximate information.

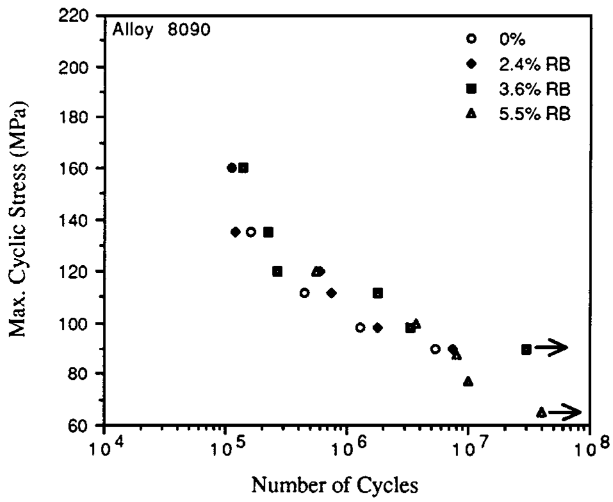

Figure 10 Improvement in fatigue life at RB expanded holes in 8090 plates.

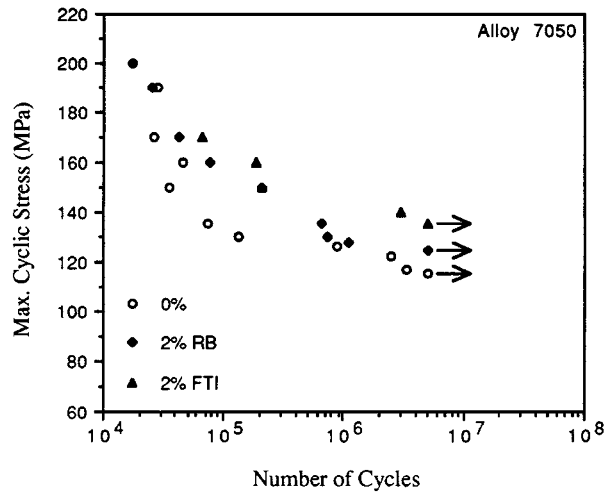

Figure 11 Comparison of improvements in fatigue life at 2% RB and 2% FTI expanded holes in 7050 plates.

3.4. Fatigue life improvement on cold expansion

Generally, it is assumed that the long-term benefits in fatigue life of cold expanded holes are associated with the presence of favourable compressive stress fields that can be maintained only if no relaxation in the magnitude of these stresses occurs. Relaxation can mostly result from either cyclic loading [8] or from exposure to high temperatures [30, 31]. Stress relief, however, can also be due to reverse yielding near the hole. Thus, the initial rapid crack growth from a cold expanded hole followed by a decreasing growth rate, or crack arrest, is generally attributed to a crack growing through an increasingly compressive stress field, i.e. the reverse yielding zone [5, 6, 8]. On the other hand, it has been noted that life improvement does not rise invariably as the degree of expansion increases [1–4, 22–25]. Because, as also verified through this work, there is a practical upper limit for cold expansion.

In the present work, the effect of reverse yielding on fatigue life was also studied. Fig. 10 shows the fatigue behaviour of the 8090 (1.6 mm) alloy expanded by the RB process. Only a marginal improvement in fatigue life is observed for both 2.4 and 3.6% RB degrees of expansion. On the contrary, no further enhancement could be detected for 5.5% RB expansion. The relatively short fatigue life of this alloy at intermediate and high stresses is in agreement with the relevant residual stress profiles. Thus, a 2.4% RB expanded hole has the largest maximum compressive stress value (−240 MPa) compared with that of 3.6% RB (−180 MPa) and 5.5% RB (−80 MPa) expanded holes (Fig. 4).

The effect of fatigue loading on 7050 (5 mm) specimens expanded by 2% RB and FTI is given in Fig. 11. At high cyclic load levels, specimens having expanded and non-expanded holes behave almost identically. At intermediate and low load levels, however, FTI expanded specimens give better results. For the same alloy, a summary of S–N curves for several degrees of FTI expansions are given in Fig. 12. It is clear that fatigue performance increases as the degree of expansion is raised from 2 to 4% FTI. However, additional enhancement of fatigue life could not be observed when the expansion degree was further increased to 6% FTI. As mentioned in Section 3.2, the maximum compressive hoop stress rises from −270 to −490 MPa for expansions of 2 to 4% FTI, but further increase of expansion to 6% FTI results in a drop to −470 MPa due to reverse yielding (Fig. 8). This is simply the reason why no further improvement in fatigue life could be detected.

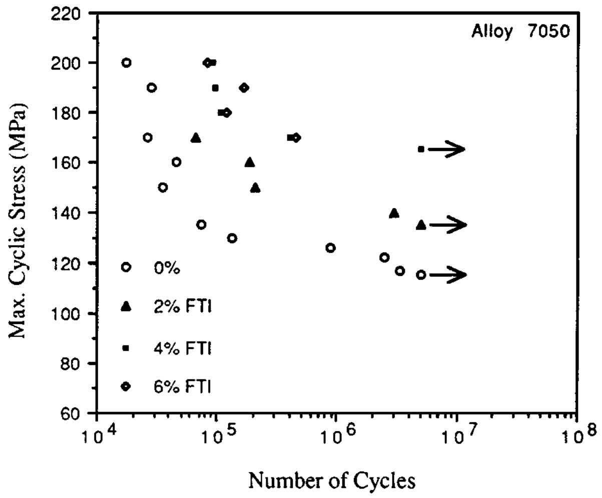

Figure 12 Improvement in fatigue life at FTI expanded holes in 7050 plates.

As a summary: for RB expansion, good results are obtained at low degrees of expansion regardless of plate thickness, such as for 8090 (1.6 mm) and 7050 (5 mm) plates; the optimum expansion is about 2% RB, which gives the highest possible level of maximum compressive stress (Figs 4 and 7) and so improvement in fatigue life (Fig. 10). On the other hand, FTI expansion is very sensitive to plate thickness. Thus, as plate thickness increases, the degree of optimum expansion also elevates. As seen from Figs 3, 8 and 9, to reach the maximum possible compressive stress, only 2% FTI expansion is required for the 1.6 mm plate, where for the 5 mm plate 4% FTI expansion is sufficient to achieve the optimum distribution of the residual stress, and so the optimum fatigue performance. Even though there are no sufficient data to justify the relation between the optimum degree of expansion and optimum increase in fatigue life, it would not be wrong to state that there is a direct relationship between these two parameters. Thus, the primary requirement for an improvement in fatigue life is the beneficial compressive part of the residual stress distribution; or, simply, the value and the position of the maximum compressive hoop stress, which is the critical barrier to initiation and growth of short cracks [8].

4. Conclusions

1. When residual stresses at the edge of the hole reach yield strength, stress relaxation results from reverse yielding of this over-strained region.

2. With increasing thickness, the state of stress changes from the plane-stress to a plane-strain condition. Consequently, the residual stresses produced after cold expansion become more compressive.

3. When a hole is cold expanded by the RB process, extensive plastic flow in the through-thickness direction provokes the material at the vicinity of the hole to behave in the plane-stress condition and, therefore, the resulting residual stress distribution becomes less compressive and close to the hole. On the contrary, the sleeve minimizes transverse plastic flow and, therefore, the FTI process generates a large and deep compressive stress field.

4. The near-hole stress distribution at the optimum level of cold expansion is controlled by the degree of reverse yielding, and is both a function of the method of cold expansion and of plate thickness. Compared with RB, the FTI process gives better fatigue performance; however, in common, no benefit is gained above the optimum level of cold expansion.

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