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The effect of cold expansion on fatigue resistance of fastener holes

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Abstract

It has long been known that cold expansion of fastener holes (as used on bolted or riveted metal joints) can be used as a means of improving the resistance of the hole to failure by fatigue. However, the fatigue resisting behaviour can be unpredictable as tensile fatigue tests carried out on batches of specimen made of aircraft grade aluminium alloy and containing a central hole has shown. Those subjected to the ballising method of cold expansion did not result in any noticeable improvement in fatigue life. This finding is partly supported by recently published research findings where finite element models have been used to predict residual stress distributions. Results have shown that sometimes positive, rather than negative, residual stresses can result at the edge of a hole after cold forming under certain conditions and this helps explain why the anticipated improvement in fatigue strength sometimes does not materialise.

This paper describes the results of a study that has sought to clarify the situation with regard to amount of interference and fastener material thickness. Results are presented of a two dimensional axisymmetric finite element study, which has accurately modelled the cold expansion process and the elastic/plastic isotropic material behaviour. It has confirmed that under certain circumstances positive tangential residual stresses are indeed possible at the critical edge of hole location and these will increase, rather than reduce, the possibility for fatigue damage.

1 INTRODUCTION

The cold expansion process involves expanding the hole beyond local yield with the aim of producing compressive tangential residual stresses around the inner circumference once the load causing the expansion is removed. If this is achieved it is generally very desirable under tensile loading as it helps counter the localised stress concentration effect and thus reduce the likelihood of fatigue damage. When hole diameters are large then sufficiently high pressure can be applied to cause tangential yielding but when diameters are small, as with bolt and rivet holes, the required pressure would be excessive and so an expansion device is necessary.

There are many practical examples where a cold expansion technique has been used to help improve the resistance of a fastener hole to fatigue damage. For example, the practise was once used in railway applications with the bolt holes of the lap-joint brackets used for fastening lengths of railway track together [1]. It is also widely used in aircraft construction at vulnerable bolt and rivet holes and special cold expansion devices are produced for this purpose [2]. Some devices rely on an oversize ball bearing (ballising) or use a pin that is directly forced through the hole whereas other devices use the expanding wedge principle. Although seeking to achieve the same function, the resulting residual stress distribution and consequent fatigue resisting strength may be very different as this paper reports.

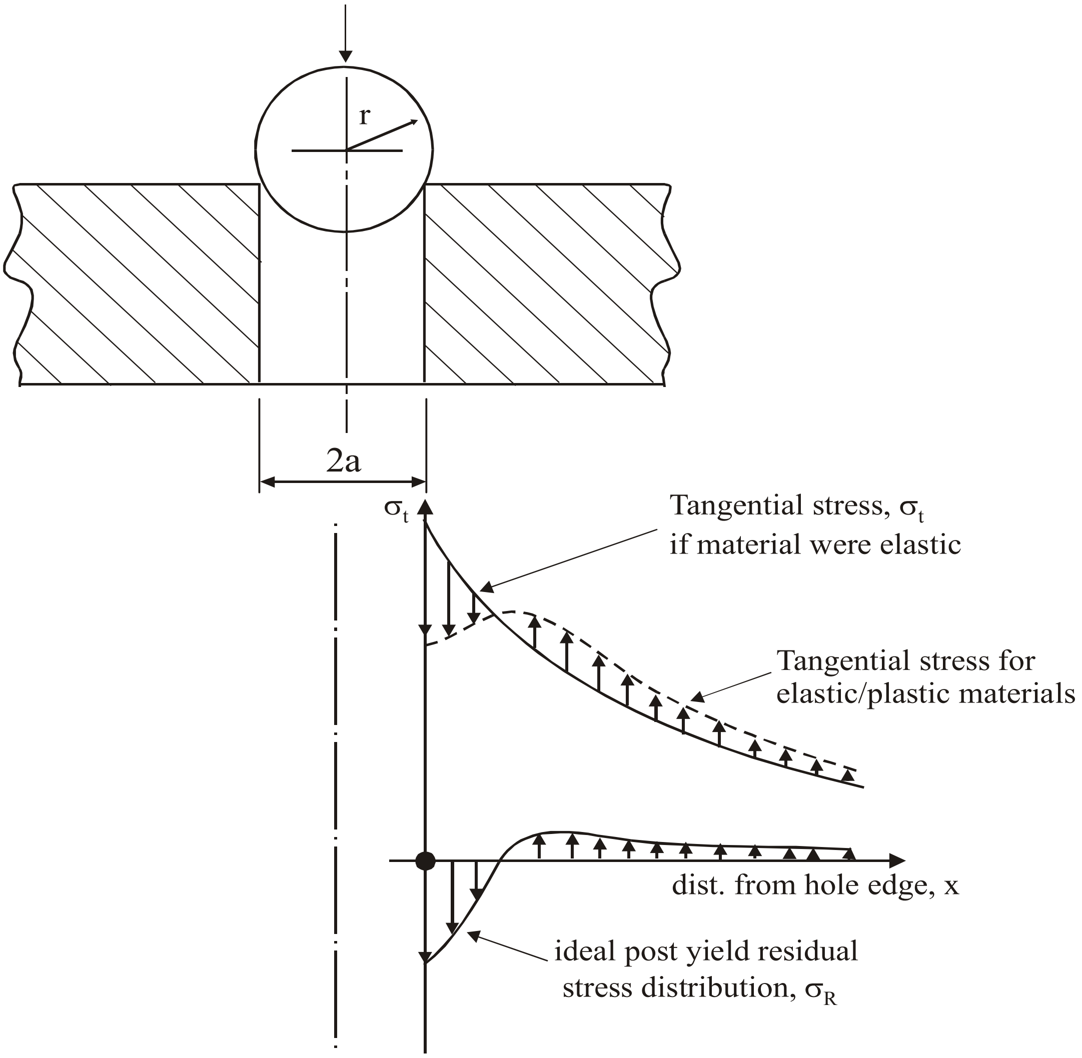

Figure 1 Hole Ballising and the Ideal Tangential Residual Stress Distribution

2 THE IDEAL STATE

The ballising method of cold expansion is illustrated in Figure 1. The oversized ball is forced through the hole causing the hole diameter to expand as the ball passes through. If the amount of interference (the difference between ball and hole diameters) is relatively small then the expansion occurs within the elastic range of the material and so the hole returns to its original size and unstressed state. However, if the amount of diametral interference is sufficiently large to cause localised yielding then the hole will not return completely to its original size. The tangential stress distribution also does not return to the unstressed state and ideally varies from compression at the edge of the hole changing to tension away from the hole (thus maintaining equilibrium) as shown in Figure 1. This ideal state is what is obtained from applying the Wohler hypothesis [1]. This predicts that the resulting residual stress magnitude, σ_R is the difference between the actual tangential stress that occurs during expansion (based on the actual stress/strain relationship as idealised in Figure 2) and the 'hypothetical' stress that would have resulted had the material continued to behave elastically. This difference is shown on revised axes on Figure 1. Generally, it is found, the greater the amount of interference, the greater the region of yielding that occurs and the larger the magnitude of the compressive residual stress at the hole edge.

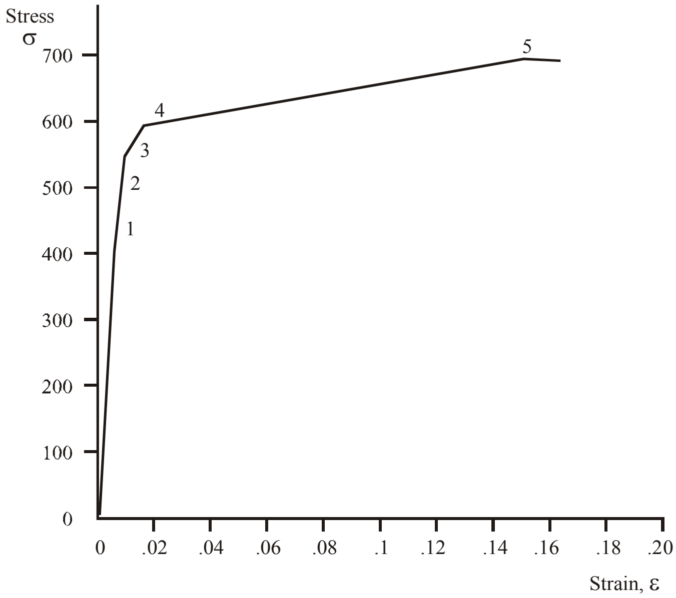

Figure 2 Idealisation of Aluminium Alloy 7075 True Stress – Strain Behaviour

3 EXPERIMENTAL TESTS

Static tensile and fatigue tests have been carried out to support the finite element study. The material used for the plate was aluminium alloy 7075 T6. This is an aircraft specification, light alloy material and has been assumed to be isotropic for simplicity. The ball was made from steel with an elastic modulus, $E = 210$ GPa and $\upsilon = 0.3$.

Two batches of ten fatigue test specimen were produced from aluminium alloy 7075 T6 2 mm thick sheet material cut into 25 mm widths and 150 mm in length. A 2.9 mm diameter hole was drilled through the centre of all specimen and for one batch a 3 mm diameter, steel ball was forced through the holes; this equates to an interference of 3.3 %. The test specimen were then fatigue tested in an Amsler Vibrophore, resonant frequency machine at 90 Hz and the resulting semi-stress amplitude/fatigue life performance is displayed in Figure 3. As can be seen in this S – N diagram there is no discernible difference in behaviour between the best fit curves for the two sets of results beyond the normal scatter inherent with this type of test.

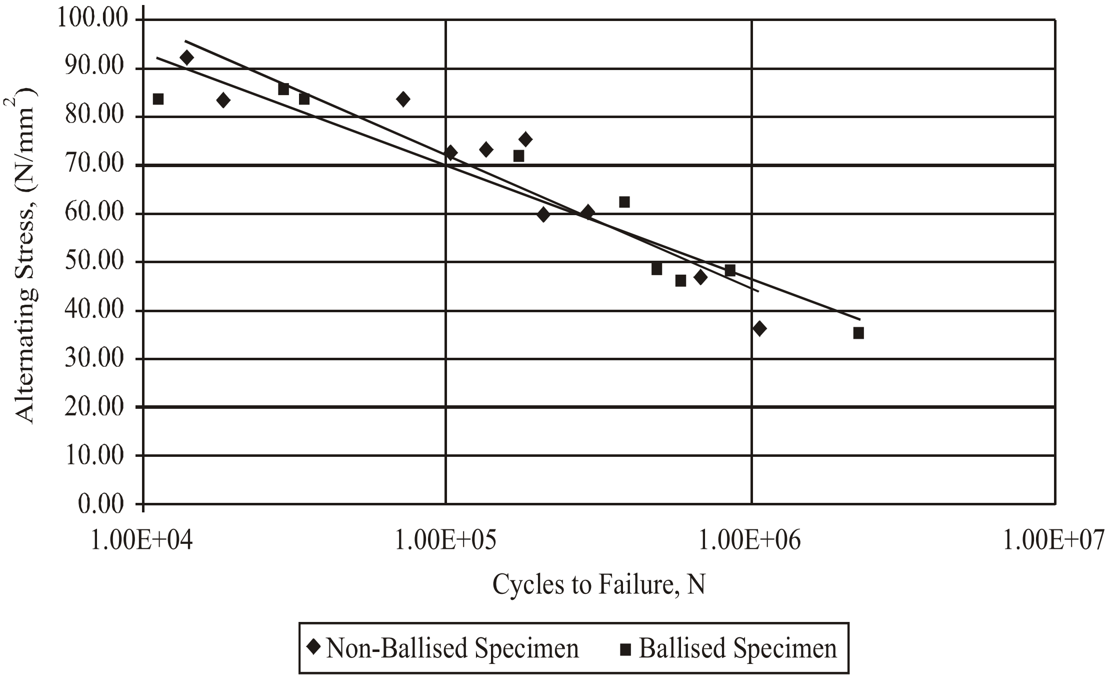

Figure 3 **Effect of Ballising on Fatigue S – N Diagram**

4 FINITE ELEMENT MODEL

An annular shaped plate was chosen for the finite element model - rather than a rectangular plate with a central hole (as used for the test specimen) because it enabled an axisymmetrical element mesh to be used, as shown in Figure 4. This was felt justified because the stress behaviour in the region of the hole is much the same in both plate shapes and the ease in modelling a circular plate offers considerable advantages. Four node quadrilateral elements have generally been used (with 2 x 2 Gaussian integration points) and also contact elements are used at the surfaces to correctly allow positive pressure to be transferred between contacting surfaces.

The annular plate model has been constrained in the vertical direction around the 50 mm outer circumference. This avoided having any localised support reaction effects influencing the residual stress distributions in the region of the hole as would occur had the plate been supported close to the exit region of the hole as would happen in practice. The ball was constrained from moving horizontally and was forced through the hole in 150 incremental step displacements to its top node; this was a sufficient number to reach convergence. Zero friction between steel ball and light alloy plate was assumed.

Finite element analyses have been carried out for nine variants - three different plate thickness' (T = 2, 5 and 10 mm) and with three different cold expansion interference magnitudes (I = 2%, 4% and 6%) to show the changing trends. The ANSYS finite element package [3] was used.

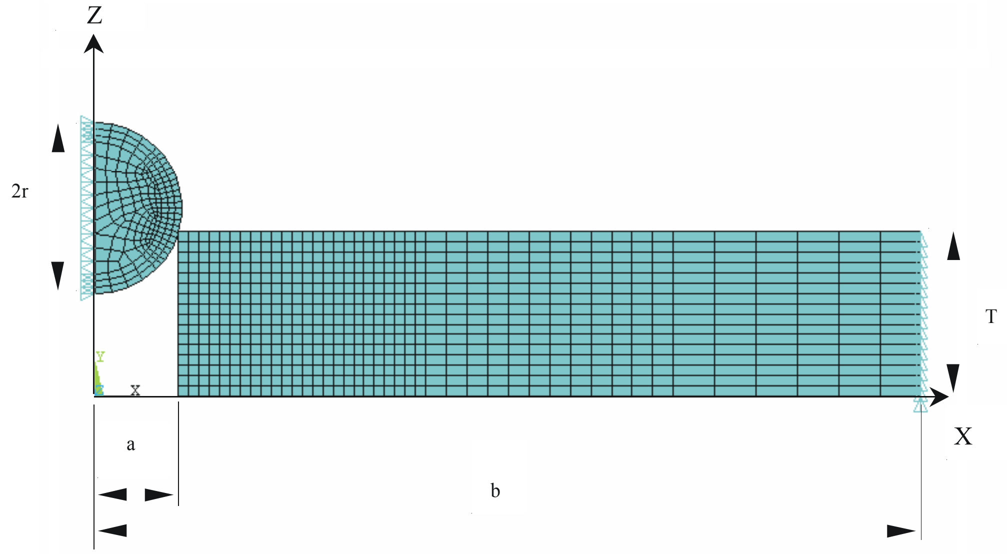

Figure 4 Axisymmetric Finite Element Mesh

5 DISCUSSION OF RESULTS

The tangential residual stress distributions obtained by finite element analysis are displayed in Figure 5. This figure shows that residual stress magnitudes are different at the entrance face, mid-thickness and exit faces for each of the three plate thickness' and three interference cases considered. With the exception of the smallest material thickness and least interference case, tensile residual stress occurs at the edge of the hole at the entrance surface. This is contrary to the ideal state as shown in Figure 1 and is of concern because residual stress magnitudes up to 500 MPa are reached. This can have a profound influence on the likelihood of a fastening hole initiating and propagating a fatigue crack under cyclic loading conditions and would help explain why there was no advantage gained in increased fatigue life from the ballised specimen. This result supports similar finding by Pavier [4] and Papanikos [5].

6 CONCLUSIONS

This study has shown that when cold forming is achieved by directly force fitting a ball through a hole it is possible that substantial tensile residual stresses can occur at a hole entrance location. Rather than nullifying the stress concentration effect of the hole, as intended, this can have the opposite effect and exaggerate the stress raiser. This can thus reduce the fatigue strength of a fastener hole rather than increase it.

Fatigue experiments completed on aluminium alloy 7075 T6 specimen have shown that a hole which has been ballised does not lead to a noticeable improvement or reduction in fatigue life beyond the normal scatter inherent with such experiments.

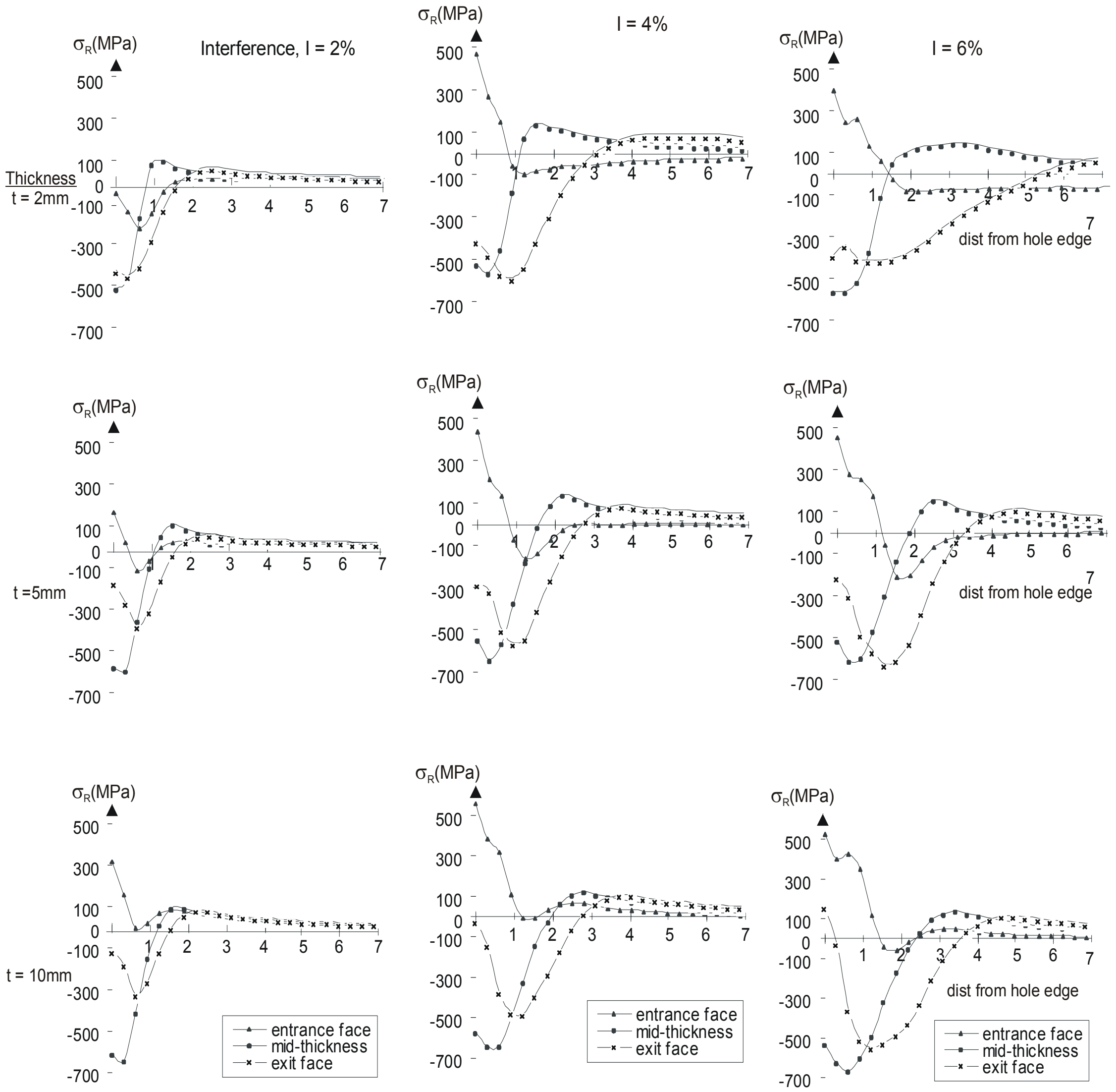

Figure 5 Tangential Residual Stress Distributions due to Ballising for Different Plate Thickness and Hole Interference

7 REFERENCES

[1] Cannon DF, Sinclair J, Sharp KA Improving the fatigue performance of bolt holes in railway rails by cold expansion Proceedings A.S. Metals Conference editor VS Goel pp 353 – 363 1965

[2] Poussard C Pavier MJ, Smith DJ Analytical and finite element predictions of residual stresses in cold worked fastener holes Journal of Strain Analysis Vol. 30 No. 4 pp 291-304 1995

[3] Swanson Analysis Systems Inc. ANSYS version 5.4

[4] Pavier MJ, Poussard DJ, Smith DJ A finite element simulation of the cold working process for fastener holes Journal of Strain Analysis Vol. 32 No. 4 pp 287-300 1997

[5] Papanikos P, Meguid SA Three dimensional finite element analysis of cold expansion of adjacent holes Int. Journal of Mech. Science Vol. 40 No. 10 pp 1019-1028, 1998