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GROWTH OF FATIGUE CRACKS FROM COLD EXPANDED HOLES

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ABSTRACT

The cold expansion of fastener holes in aircraft components is a standard technique to improve fatigue life. However, there is uncertainty of the method for quantifying the improvement. In addition, there is concern that the beneficial residual stresses arising from cold expansion may relax due to creep, particularly in aircraft subjected to higher temperatures.

This paper begins with experimental measurements and finite element predictions of cold expansion residual stresses and their redistribution after creep. The results of fatigue crack growth experiments are then presented, demonstrating the benefits of the cold expansion process, even when creep relaxation occurs. Finally, a comparison of the fatigue crack growth rate is given with a prediction using base line data combined with the finite element calculation of residual stress.

KEYWORDS

Fatigue, residual stress, cold expansion, finite element analysis

INTRODUCTION

Cold expansion of holes in aluminium aircraft structures is commonly used to improve fatigue life [1]. When airframes are subjected to higher temperatures there is concern that the beneficial residual stresses resulting from cold expansion may relax due to creep. Predictions and measurements of residual stresses caused by the cold expansion process have been made [2, 3] and more recently the effects of creep relaxation have been investigated [4].

In this paper, experimental measurements and finite element predictions are presented of residual stresses in cold expanded holes, before and after creep relaxation. During creep relaxation, additional tensile load was superimposed to simulate the conditions in the aircraft. Experimental measurements of residual stress used a new method based on Sachs' boring to measure the average tangential residual stress. Axisymmetric and three dimensional finite element analyses were used to predict the stress distribution through the thickness of the component. The results of fatigue crack growth experiments for cracks growing from cold expanded holes are also presented. Comparisons of experimental crack growth with predicted growth using base line data and finite element residual stress predictions are made.

RESIDUAL STRESS MEASUREMENTS AND PREDICTIONS

Test Specimens

The material used in this research was a new aluminium alloy 2650 designed to provide creep resistance. Rectangular specimens with a thickness of 6 mm, a central hole of radius 3 mm, a width of 32 mm and a length of 140 mm were machined from the plate. The hole was cold expanded to a nominal expansion of 4 % using the FTI split sleeve method [5]. Specimens subject to creep relaxation were heated to 150°C inside an electric furnace and a load equivalent to a far field stress of 162 MPa was applied. The temperature and applied load were maintained for 1000 hours. To enable measurement of residual stress, discs of diameter 32 mm were cut from the specimens, centred on the hole.

Garcia-Sachs Method

Sachs' boring is a method of measuring the residual stresses around a hole by machining material from the hole edge and measuring the resulting strain change. Sachs boring can only measure an axisymmetric state of residual stress, but in this work non-axisymmetric residual stresses occur. The Garcia-Sachs method [6] has been developed, based on Sachs' boring, to measure such non-axisymmetric residual stress distributions. In this method the residual stresses are represented by a Fourier expansion. The strain change is measured at a number of angular positions and from these changes the magnitude of each component in the Fourier series or residual stress is inferred.

Material Properties

To predict the residual stresses arising from cold expansion it is important to measure accurately the reversed yielding behaviour of the material [2]. A series of cyclic tension and compression tests were therefore carried, both at room temperature and at 150°C. To evaluate the creep properties of the aluminium alloy 2650, several tests were carried out for different applied constant loads using static load creep test machines. For the range of temperatures and stresses considered in this work, the principal creep mechanism is power law creep.

Finite Element Predictions

The ABAQUS 5.7 finite element system was used to provide predictions of residual stress. An axisymmetric model was first used to simulate the cold expansion procedure [7] using a combined hardening model to approximate the cyclic stress-strain behaviour. Following the finite element prediction of the residual stress, a further step was used to model the creep relaxation [4]. A three dimensional model had to be used for this step, obtaining the initial residual stresses from the axisymmetric model. Additional load was applied and creep relaxation allowed to occur using a power law model with time hardening integration.

Results

Garcia-Sachs measurements of residual stress have been made for specimens after cold expansion and after creep relaxation under applied load. These experimental measurements have been compared with finite element predictions of residual stress using the combination of axisymmetric and three dimensional models described above. For conciseness, only results for the tangential residual stress are provided, in the direction normal to the loading direction.

Figure 1 presents a comparison of the residual stresses measured by the Garcia-Sachs method and the averaged through-the-thickness stress from finite element analysis. Error bars on the Garcia-Sachs results are based on the calculation of the standard deviation of stress assuming a standard deviation of strain measurement of $\pm 1\ \mu\varepsilon$ [4]. Agreement with the finite element prediction is excellent except very close to the hole edge where likely errors in the Garcia-Sachs method increase and differences between the experimental and finite element material behaviours are more important.

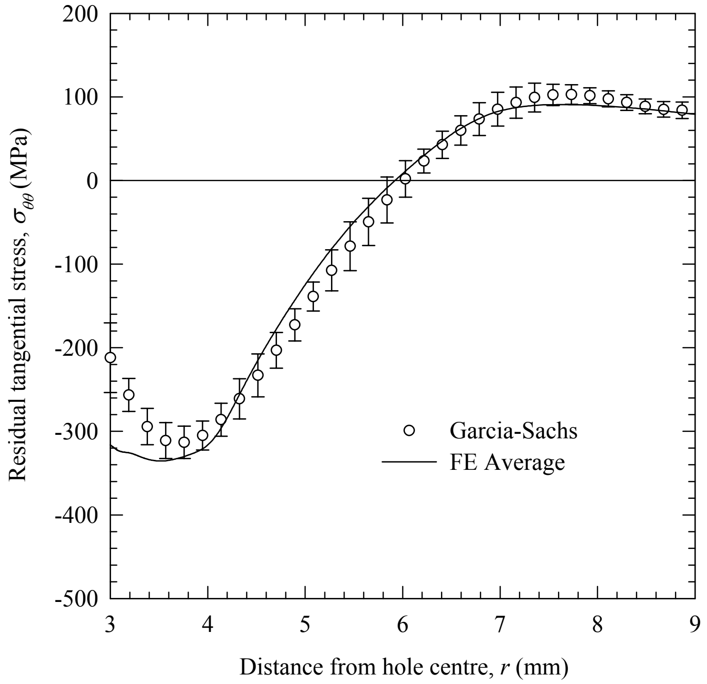

Figure 1: Measured residual tangential stresses after cold expansion compared with averaged finite element results.

Figure 2 shows Garcia-Sachs and finite element averaged stresses for the case where the residual stresses have been relaxed following creep relaxation with superimposed applied load. The agreement is reasonable although the measured residual stresses show more relaxation close to the hole edge than the finite element predictions.

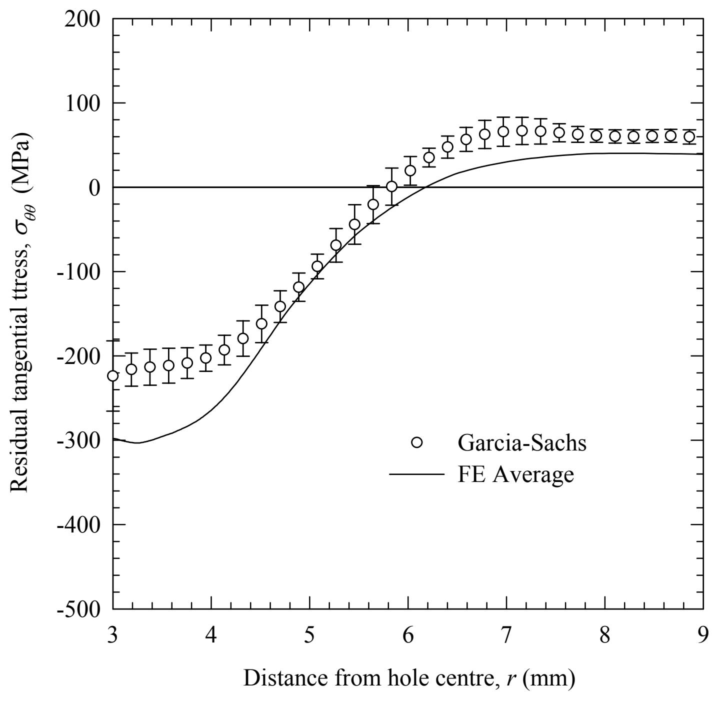

Figure 2: Measured residual tangential stresses after cold expansion followed by creep relaxation compared with averaged finite element results.

FATIGUE CRACK GROWTH MEASUREMENTS AND PREDICTIONS

Test Specimens

The test specimens for measurements of fatigue crack growth were of 6 mm thickness with a central hole of radius 3 mm, a width of 100 mm and a length of 245 mm. Two initial starter cracks were machined using an EDM technique on one face of the specimen and on both sides of the hole [8]. For specimens that had been subjected to cold expansion the starter cracks were located on the entrance face, defined by the FTI method.

Fatigue Loading

The specimens were fatigue loaded in a 250 kN servo hydraulic test machine at a rate of 10 cycles per second. The maximum load applied to the specimens was equivalent to a far field stress of 162 MPa. Various R ratios were used, but in the results described here an R ratio of 0.1 was used. Surface crack growth was measured on both surfaces of the specimen and on both sides of the hole using vernier microscopes as a function of the number of cycles of load. From these measurements, the rate of crack growth versus crack length was calculated.

Fatigue Properties

The crack growth rate was assumed to be a function of the effective range of stress intensity factor. This function was measured using a specimen of dimensions defined above with a non cold expanded hole. To ensure the measurements were not effected by closure, a high R ration of 0.7 was used.

Finite Element Predictions

Finite element predictions of fatigue crack growth rate were made using a two dimensional model of the test specimen. The model was run repeatedly using different crack lengths and the stress intensity factor calculated for each length. Predictions were also made of the load required to cause the crack to open enabling the effective range of stress intensity factor to be calculated for each crack length. The function of crack growth rate versus stress intensity range derived form high R ratio tests was then used to make predictions of crack growth rate.

Results

Measurements of crack length versus number of cycles are shown in Figure 3. The crack length in the figure is the average of the two lengths measured on the entrance face of the specimen. The measurements for three cases are presented: for a non cold expanded hole, a cold expanded hole and a cold expanded hole with creep relaxation while under applied load. Cold expansion can be seen to lower substantially the rate of fatigue crack growth. Creep relaxation removes some but not all of the benefit of cold expansion.

Figure 4 presents the experimental measurements of crack growth rate versus the crack length for the case of a specimen with a cold expanded hole. Measurements for both cracks on the entrance face of the specimen are provided: the crack to the left and to the right of the hole. Also shown are the finite element predictions of crack growth rate. The comparison shows the finite element model under-predicts the growth rate for small crack lengths and over-predicts the rate for large crack lengths. Because of the two dimensional nature of the finite element model, the crack is assumed to have a parallel through-the-thickness geometry whereas the actual crack has a complex three dimensional shape for small crack lengths. At large crack lengths the finite element predictions suggest the crack is always open during the entire load cycle whereas substantial closure is observed in the experiment. This closure is believed to be due to plasticity around the crack tip and would tend to reduce the effective stress intensity range and therefore the crack growth rate.

Finally, Figure 5 shows the experimental measurements and finite element predictions of crack growth rate for the case of a specimen with a cold expanded hole subject to creep relaxation. The crack growth rates for small holes are essentially the same as for cold expanded holes without creep. For cracks of intermediate length, from about 1 to 2 mm, the growth rates are higher. Again, the finite element model under-predicts the growth rate for small crack lengths and over-predicts the rate for large crack lengths.

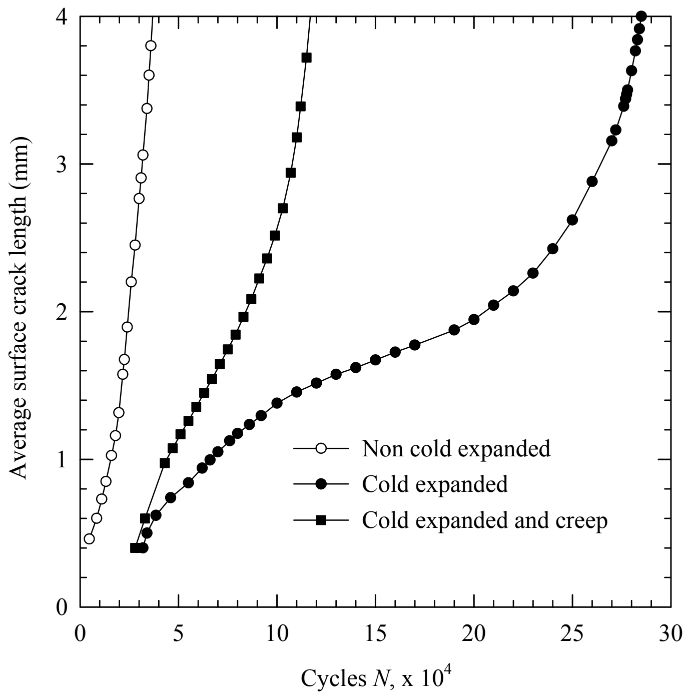

Figure 3: Average fatigue crack lengths versus number of cycles.

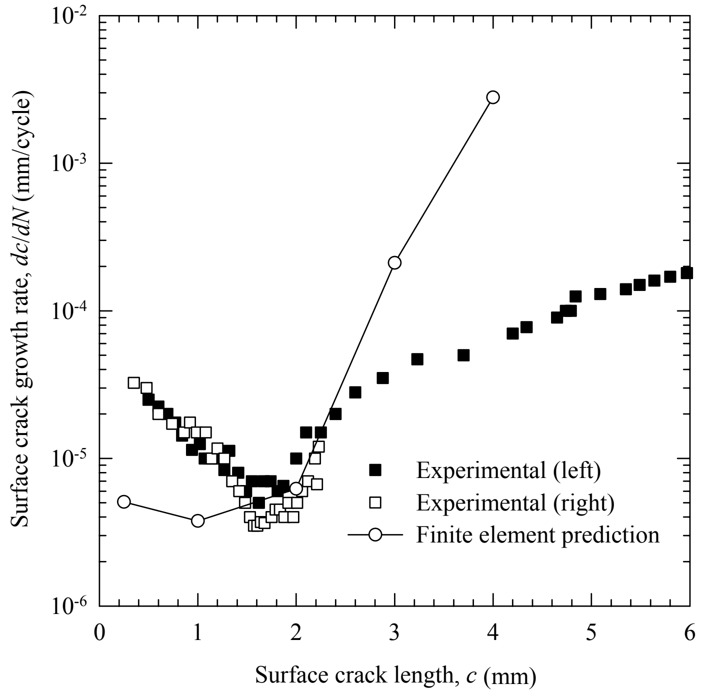

Figure 4: Measured fatigue crack growth rates for cold expanded specimens compared with averaged finite element results.

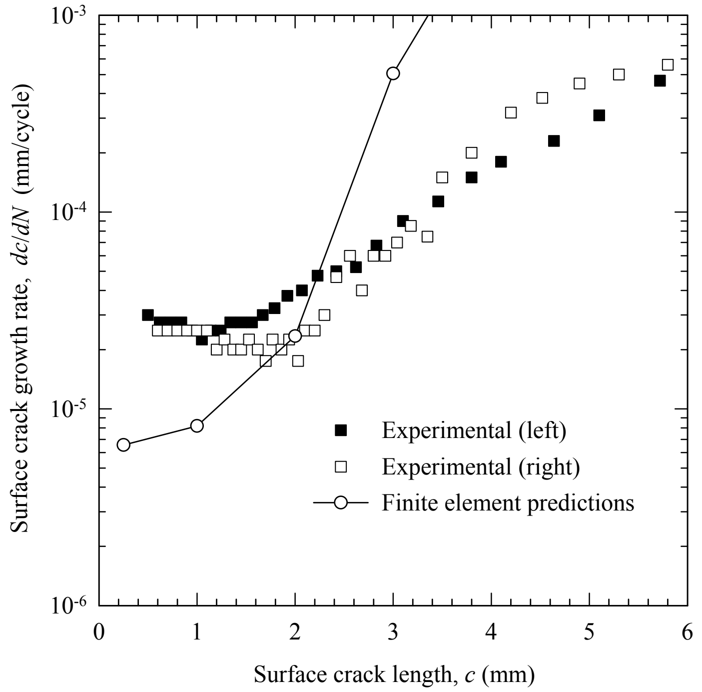

Figure 5: Measured fatigue crack growth rates for cold expanded specimens subjected to creep relaxation compared with averaged finite element results.

CONCLUSIONS

Residual stresses arising from cold expansion and after creep relaxation have been predicted using finite element simulations and measured using the Garcia-Sachs method. A generally good agreement was obtained between prediction and measurement except near the edge of the hole.

Fatigue crack growth rates have been measured for cracks growing from non cold expanded and cold expanded holes with and without creep relaxation. Creep relaxation reduces the resistance to fatigue, but there is still a benefit of cold expansion. Finite element predictions of growth rates have been made but only partial agreement with measurement has been obtained.

ACKNOWLEDGEMENTS

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