Residual stresses and crack propagation after coining of holes in aluminium plates: finite element calculations and verifying experiments
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ABSTRACT

Stress coining is a surface treatment method used to generate tangential compressive stresses on the bore of a hole. The plate containing the hole to be coined is placed between two steel mandrels which are pressed together. In this paper, it is shown that the complex and nonlinear process, stress coining, can be simulated successfully by use of the finite element method (FE-method). The build-up of stresses and strains in a 25 mm thick aluminium plate during coining is simulated and experiments are performed to verify the calculations. Resistance foil strain gauges were used to record the strains on the bore of a 27 mm diameter hole during the coining process. Good agreement was observed. The fatigue crack propagation of surface cracks at the hole depends on the residual stresses. By the use of stress coining it is possible to introduce residual tangential stresses that are capable of reducing or even inhibiting crack growth. Numerically calculated crack propagation, for two crack configurations in 16 mm thick plates with coined and non-coined holes is compared here. Use of stress coining may increase the fatigue life by as much as a factor of 10.

INTRODUCTION

A goal for all transport companies is to increase pay loads. To achieve this, it is often necessary to reduce the dead weight of the vehicles used. Sometimes, but not always, the consequence of reduced dead weight can be an increased risk of fatigue failure. For aeroplanes it is of extreme importance to have low dead-weight, but it is also true for other vehicles such as fast passenger ships, busses and trains.

In the present paper a mechanical method to reduce the risk of fatigue failure, stress coining, is studied. This method is used to introduce residual stresses...
around holes and slots mainly in aeroplane structures. Stress coining was first developed in the 1960's by the aircraft industry and it was then found that the fatigue life could be significantly extended by use of this method, see Philips1 and Speakman2-3.

To quantify the effect of coining a comparative investigation is performed in which the propagation of cracks in plates with coined and non-coined holes is numerically computed. The remote and residual stresses considered in the crack growth calculations are computed in a non linear finite element analysis (FE-analysis).

EXPERIMENTAL PROCEDURE

In the coining process studied here, 25 mm thick, circular AA6082-T6 aluminium plates with central holes are compressed between two steel mandrels, see Figure 1. The top mandrel is mounted to a rigid frame while the bottom mandrel is attached to a spherical bearing which is mounted on a 400 kN hydraulic cylinder. Between the mandrels, a position indicator is placed to measure the relative displacement during the coining process, see Figure 1. For more details see Ogemant4. The test specimens have a diameter of 200 mm and the holes are centrally located. The holes were first drilled to approximately 20 mm and then turned to the finished diameter of 26.55 mm. Within a diameter of 80 mm, the plates were turned on both sides to obtain uniform thickness in the coining area. Care was taken to keep the temperature below critical values in order to avoid thermally induced residual stresses caused by the mechanical processes used. A total of 9 test specimens were used. The mandrels were turned from high strength steel with a yield stress, \( \sigma_y \), of 850 MPa, to a diameter of 35.0 mm.
Figure 2. Strain gauge placement on the bore of the hole. The bore of the hole, for half of the thickness, is expanded to show the gauges properly.

The coining force is increased in steps until a noticeable nonlinear behaviour is obtained after which the step size is reduced. The process continues until the relative compression between the mandrels is 0.35 mm or 1.5% of the plate thickness. Thereafter, the force is released in three steps and the specimen is removed. During this process the relative displacement between the mandrels, and the strains at 8 positions at the bore of the hole together with the force applied are recorded. The strains are measured by the use of foil strain gauges, each covering an area of 1.4 x 4.0 mm. Figure 2 shows the gauge placement. After coining, the residual displacements of the plate contact surfaces and of the bore of the hole are measured.

NUMERICAL STUDY OF THE COINING PROCESS

In the present investigation a finite element code for nonlinear calculations, SOLVIA$^5$, is used. The code has the capability to simulate large strains, large displacement, contact conditions and non-linear material behaviour. In Ogeman$^4$ different combinations of these capabilities have been tested, and it was found that a nonlinear material model together with contact conditions was sufficient to simulate accurately the coining process.

Calculation Procedure

The axisymmetric geometry of the physical model suggests that a FE-model built up of axisymmetric semisolid elements could be used. It is also assumed that there is a plane of symmetry in the centre of the plate. Altogether this leads to a very simplified FE-model compared to a true 3-dimensional one. In total the FE-model consists of 292 axisymmetric, 8-node iso-parametric elements. Figure 3 shows the FE-model used. The coining process is modelled by using a
Surface Treatment Effects

Figure 3. Axial symmetric finite element model. Applied boundary conditions are shown.

20-step load history where the displacement of the top of the mandrel is prescribed. Contact conditions with non-zero friction are considered for the parts of the plate and mandrels that are likely to come into contact, see Figure 3. Global convergence criteria for the finite element calculations are of two types, residual energy and residual contact force. The contact force criterion stipulates that the difference in the absolute values of the out-of-balance contact-force vector, between two consecutive iterations, should be less than 5% to obtain convergence.

Material Model

Typical tensile properties for the alloy used are a 2% offset stress, \( \sigma_{0.02} \), of 307 MPa, an ultimate strength, \( \sigma_{u.t.} \), of 322 MPa and Young's modules of 72 GPa. According to Mazzolani\(^6\), the behaviour of the plate material used is well approximated by the Ramberg-Osgood constitutive law.

\[
\varepsilon = \frac{\sigma}{E} + 0.002 \cdot \left[ \frac{\sigma}{\sigma_{u.t.}} \right]^n
\]  

For heat treated alloys, \( n \) varies between 20 and 50. The AA6082-T6 alloy is approximated successfully with \( n = 50 \), \( \sigma_{0.02} = 307 \) MPa and \( E = 72 \) GPa. The nonlinear material input for the FE-calculations is given as a uniaxial stress-strain relation. Most aluminium alloys show a semi-ideal or ideal kinematic Bauchinger effect during hardening, see Mazzolani\(^6\). Accordingly, a kinematic hardening rule together with von Mises' yield criterion and associated flow rule are applied during the FE-calculations.
RESULTS OF FINITE ELEMENT ANALYSIS AND EXPERIMENTS

In Figure 4, FE-calculated and measured displacements of the bore of the hole after coining are shown. Also the profile of the bore prior to the coining process is indicated. The values shown are estimated mean values from measurements performed on both sides, at three, equally spaced, locations. The maximum difference between measured and computed displacements is 20% and occurs close to the surface of the plate.

The calculated and measured total strains (for four of the test plates) at the location, corresponding to strain gauge 10, are shown in Figure 5. The calculated strains are estimated mean values from several Gaussian points corresponding to the area covered by the strain gauge. The largest difference found between measured and computed strains is 45% and occurs for plate 6.

CRACK GROWTH ANALYSIS

The propagation of cracks at coined and non-coined holes is compared for two crack configurations using numerical methods. In Figure 6 the crack configurations considered are shown. The plate that was subjected to a varying remote uniform load of constant amplitude is 16 mm thick, 900 mm long and 90 mm wide. The coining process that is simulated uses a mandrel diameter of 35.0 mm. Two $R$-ratios, measured on the remote load, $R = 0.1$ and $R = -1$ are applied. The weight function technique is used to estimate the stress intensity factors for the cracks in the residual stress field as well as in the stress field caused by the uniaxial remote load.
Figure 5. Tangential strain in gauge 10. FE-calculated results and experiments.

**K Estimations**

The weight function method, used here to determine \( K \), is based on the principle of reciprocity which states that the stress intensity factor, \( K \), can be determined, for a crack under general loading, if a reference stress intensity factor, \( K_{\text{ref}} \), and the corresponding displacement field, \( u_{\text{ref}} \), are known. The method was originally proposed by Petroski et al.\(^7\). Cruse et al.\(^8\), propose a locally averaged stress intensity factor which in Josefson et al.\(^9\) has the slightly modified form for growth in the a-direction:

\[
K_a = \frac{E \bar{\beta}}{\Delta S_a K_{\text{ref},a}} \int_S \sigma \frac{\partial u_{\text{ref}}}{\partial a} \delta a dS
\]  

(2)

where \( \bar{\beta} \) is an expression which describes the transition from plane stress to plane strain conditions for the crack, \( \delta a \) is the incremental crack extension and \( \Delta S_a \) is the corresponding area increment. For more details see Josefson et al.\(^9\).

**Crack Growth**

In the study of crack growth, only the propagation of a macroscopic crack is considered here. The crack growth calculations are carried out with Paris's law, Equation 3, and with another version of it, modified according to Dahlberg\(^10\), Equation 4, in which the threshold value of the stress intensity factor, \( \Delta K_{\text{th}} \) is taken into account.
Surface Treatment Effects

A-A

Central crack

Corner crack

Figure 6. Crack configurations considered together with cyclic loaded plate

\[
\frac{da}{dN} = C \cdot (\Delta K_{\text{eff}})^m
\]  

(3)

\[
\frac{da}{dN} = C \cdot (\Delta K_{\text{eff}})^{m+\alpha} \cdot (\Delta K_{th})^{m+\alpha})^{m-\alpha}
\]  

(4)

In Equations 3 and 4, C, m and \( \alpha \) are material constants estimated from regression of experimental data, for the aluminium alloy AA6061-T6, see Fleck et al.\(^{11}\). This alloy has much of the same properties as AA6082-T6, which is used in this investigation. The effective variation of the stress intensity, \( \Delta K_{\text{eff}} \) is defined as:

\[
\Delta K_{\text{eff}} = K_{\text{eff,max}} - K_{\text{eff,min}} \quad \text{where}
\]

\[
K_{\text{eff,max}} = K_{\text{remote,max}} + K_{\text{res}} \quad \text{and} \quad K_{\text{eff,min}} = K_{\text{remote,min}} + K_{\text{res}}
\]

but \( K_{\text{eff,min}} \geq 0 \) and \( \Delta K_{\text{eff}} \geq 0 \)

COMPUTED CRACK GROWTH

Crack growth in the a-direction, here considered the most dangerous, for the two cracks shown in Figure 6 is calculated with Equations 3 and 4. Here \( m = 2.63, C = 2.94 \times 10^{-10} \) and \( \Delta K_{th} = 2.5 \text{ MPa}\sqrt{\text{m}} \). In Figure 7, the growth in the a-direction of an initially 0.5 mm long (\( a_0 = 0.5, c_0 = 0.5 \text{ mm} \)) central crack during cyclic remote load is shown. The maximum remote load is \( S_{\text{max}} = 25 \text{ MPa} \) and \( R = -1 \). In Figure 8, the number of cycles, computed with Equation 3, needed to propagate a corner crack (\( a_0 = 1.0, c_0 = 0.5 \text{ mm} \)) in the a-direction to 4.0 mm length, for two different \( R \)-values, is shown. In Figure 9, in a corresponding way the central crack is presented (\( a_0 = 0.5, c_0 = 0.5 \text{ mm} \)).
Figure 7. Calculated crack growth in the a-direction for coined and non-coined holes according to Equation 3 and Equation 4. $S_{\text{max}} = 25$ MPa and $R = -1$.

Due to limits of the crack sizes allowed in the estimations of $K$, the calculations of $a$ and $c$ are stopped at $a = 4.0$ mm or $c = 2.5$ mm in Figure 8. In Figure 9 the limits for $a$ and $c$ are 4.0 mm.

CONCLUSIONS

The following conclusions may be drawn from this investigation:

- By using a nonlinear finite element code, it is possible to predict the strains, displacements and stresses around a hole subjected to coining.
- Crack growth can be reduced by the use of coining. The reduction is by at least one order of a magnitude for a corner crack in the geometry used here.
- For the central crack, no significant reduction in crack growth can be observed with the geometry used here together with actual coining parameters.
- For low remote loads, the threshold value of the variation in the stress intensity, $\Delta K_{th}$, has a noticeable effect upon the growth. Therefore the use of Equation 4 can be relevant at low remote loads.

DISCUSSION

A remote load with constant amplitude is applied in this investigation. The effect of coining, and of residual stress methods in general, is believed to be more important when the applied load is of spectrum type. On the other hand, the permanence of the residual stresses obtained by coining has not been thoroughly investigated. Relaxation of the residual stresses can occur, depending of the magnitude of the remote loads, see Josefson et al.9.
The growth of a central crack can be significantly reduced when a mandrel with larger diameter is used in the coining process. In Ogeman it is shown that an increased mandrel diameter yields a more homogenous residual stress field through the thickness of the plate. This affects the magnitude of $K_{res}$ positively and, thereby, also reduces the crack growth.

Figure 8. Computed number of cycles to propagate a corner crack to $a = 4.0$ mm, while $c<2.5$ mm, in a plate with a coined and a non-coined hole.

Figure 9. Computed number of cycles to propagate a central crack to $a = 4.0$ mm, while $c<4.0$ mm, in a plate with a coined and a non-coined hole.
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REFERENCES