COMPARISON OF MODELS FOR SUSTAINED LOAD CRACK GROWTH IN ALUMINIUM GAS CYLINDERS

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ABSTRACT

Some common portable aluminium gas cylinders have developed cracking after a period of time. Previous modelling of the growth of these cracks under sustained load have been developed from specimen testing but produce results which produce values of crack growth which are too low when compared to some actual service experience.

This paper develops a model of the growth of these defects. The growth of the defects is assumed to be controlled by the local stresses in vicinity of the crack edge. The parameters in the model are determined by comparing to cracks actually found in cylinders which have leaked or failed in service. From this procedure a simple equation for the crack growth rate is developed.

KEY WORDS

Sustained load cracking, aluminium, gas cylinders, neck cracking, model of crack growth.

INTRODUCTION.

Portable aluminium cylinders are in common use in the world for purposes such as self contained underwater breathing apparatus (SCUBA), respirators for fire and medical use and other uses. There has been a history of cracking developing in some of these cylinders in the position shown in Figure 1. In Australia about 1,700,000 of these cylinders are in circulation and similar large numbers exist in most countries.

The cracking involves a phenomenon called solid metal induced embrittlement (SMIE) where crack growth is aided by surface diffusion of certain elements the most important of which is lead. The cracks grow under constant load so it is also described as "sustained load cracking". Since diffusion of elements is involved there are some similarities to creep crack growth and this terminology has also been used. The fundamentals of this process are described elsewhere Lewandowski et al. (1992) and Lynch (1989).

The position of most of the important cracking is illustrated on Figure 1. The cracking tends to grow from notches created during the forming process for the top end of the cylinders and is driven by stress not only from the pressure contained in the cylinder but also residual stresses from the manufacturing Ibrahim (1989).

Calculation of the rate of defect growth is an objective which has interested a number of researchers in order to achieve a basis for assessing acceptable defect sizes (Lewandowski et al., 1992, Ibrahim, 1989).

In 1983 the first two ruptures of hoop wrapped aluminium cylinders occurred in the United States (Failure Analysis Associates, 1984). This led to the identification of risk factors associated with the aluminium cylinders. These were:

- cracking originating at the neck shoulder region as shown on Figure 1 (said to be a region of high stress),
- folds in the neck region,
- lead levels of 100 ppm or higher in the aluminium alloy.

There have been more recent incidents in the US (Price et al. (1996b)..

There has been some failure experience in Australia. Poole(1995) describes a cylinder made to Australian standards which failed catastrophically in 1994 in New Guinea. A significant number of locally made cylinders experience cracking from the neck though the cracks may not be very large when detected.

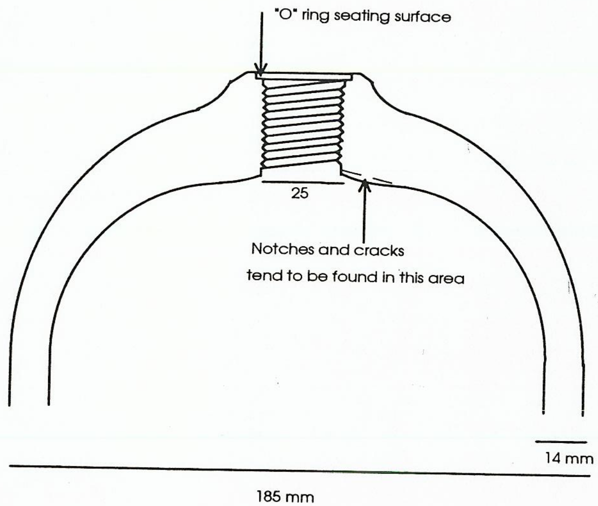

Figure 1 The top of an aluminium gas cylinder with the area of crack initiation and growth indicated.

MODELS OF CRACK GROWTH.

Crack propagation due to SMIE in small specimens under different imposed K_I values has been studied previously by Stark and Ibrahim (1992). One set of specimens was cut from aluminium ingots with an assay of 100 ppm Pb. The lowest value of K_I used for this series of tests was 13 MPa√m. The following equation was determined for crack growth rate,

$$\log_{10}(da/dt) = .234K_I - 7.719 \text{ mm/hr} \qquad (1)$$

Ibrahim and Stark (1988) present additional studies on some specimens cut from Australian pressure vessels and tested at room temperature. The alloys used in these gas cylinders had very low levels of lead present probably less than 10 ppm. The growth was much slower and the equation derived was:

$$\log_{10}(da/dt) = .20164K_I - 8.889 \text{ mm/hr} \qquad (2)$$

The prediction is of limited validity for K_I less than 18 MPa√m since no failures had occurred to specimens loaded to this level after 4 years.

Lewandowski et al. (1992) give experimental data for alloy 6351 at tested at three temperatures in specially prepared ingots doped with controlled Pb additions.

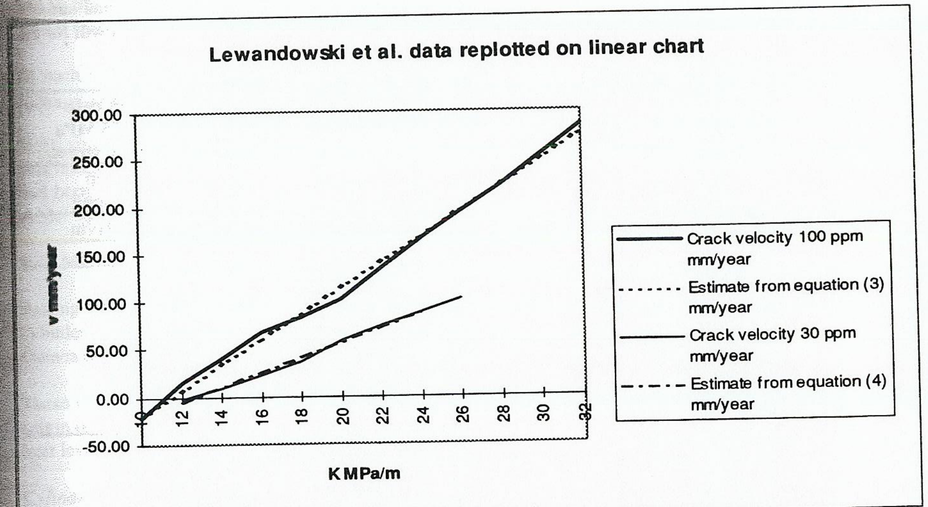

Figure 2 Some of the data from Lewandowski et al. When the present authors replotted the data it is revealed to closely obey a linear relationship. There is a threshold below which no growth occurs.

Some of the data from Lewandowski et al is represented in figure 2. When the present authors replotted the data the data was found to closely obey a linear relationship. This data is very closely described by the linear equations (3) and (4).

Upper bound growth rate 100 ppm at 30°C	$v = 13.4\times(K_I-11.5)$	(3)
Upper bound growth rate 30 ppm at 30°C	$v = 7.73\times(K_I-12.7)$	(4)

One feature of these equations when written in this form is that they clearly imply that there is threshold value of K_I below which no growth occurs. This is a key issue in determining a realistic equation for the growth in cylinders for many cylinders show no evidence of damage even after being in use for many years.

Price et al. (1996b) have reinterpreted the Lewandowski et al. data to determine that the growth rates would be reduced by a factor of about 4 for temperatures of 18°C to 20 °C. This means that at room temperature the first factors in the equations should be 7.73/4 = 1.93 and 13.4/4 = 3.4.

Examining a crack of 4 mm depth by 20 mm long in the position shown on figure 1 and using the stresses presented in Price et al. (1996a) an estimate of K_I can be made using British Standards PD 6493:1990 Level 2. If there is no residual stress K_I is 5.54 MPa√m. and K_I = 22.3 MPa√m if a residual stress of 155 MPa is included. The calculated growth rates predicted by the equations are as shown in Table 1.

Given the fact that in some cases grows through the walls of the gas cylinder, the growth rates predicted by these equations are unsatisfactory. With no residual stress there would be basically no growth. In fact no growth on any test specimen has ever been recorded at K_I below 10 MPa√m and the fact that some equations produce a growth is simply a feature of the log-log curves used.

If residual stress is included three of these predictions are reasonably high though the one which relates specifically to specimens removed from Australian cylinders is still too slow. So while residual stresses can produce a reasonable growth it must be remembered that residual stress can only affect growth for the first few millimetres. After that stage the residual stresses will quickly drop to zero.

	Type of specimen used in tests to develop equations	Growth rate with zero residual stress	Growth rate with zero residual stress	Growth rate with 155 MPa residual stress,
Defect size		4 mm deep 20 mm long	20 mm deep 45 mm long	4 mm deep 20 mm long
K_I		5.54 MPa√m	9.95 MPa√m	22.3 MPa√m
Equation		mm/year	mm/year	mm/year
(1)	100 ppm specimens	.0033	.036	28
(2)	from Australian cylinders	.00015	.0011	0.36
(3)	30 ppm specimens (adjusted to 20°C)	(below threshold)	(below threshold)	18.5
(4)	100 ppm specimens (adjusted to 20°C)	(below threshold)	(below threshold)	36

Table 1. Growth rates predicted by various equations for various cracks and stresses.

THE MODEL FOR CALCULATING CRACK GROWTH RATE

Ibrahim (1989) proposed a formulation of K_I was proposed and found to work for the specimens considered in that work. It was proposed to test a modification of this formula for the present case to give a localised value of K_I called $K_{I(local)}$ as follows:

$$K_{I(local)} = \sigma_\theta\sqrt{(2\pi r)}, \qquad (5)$$

where σ_θ is circumferential local stress in the crack tip region acting normal to the plane of the crack, and
r is a fixed distance from crack edge within crack tip region. In this trial the value of 0.3 mm was chosen following Ibrahim (1989).

From observations (including those discussed below) it was known that growth does not proceed consistently along the whole crack front. To carry out the crack growth the process was started with a calculation of stress distribution along the initial notch. Stress intensity factor, $K_{I(local)}$, was calculated for a set of points at the crack edge using equation (5).

The increment in crack size Δa after fixed period of time Δt was calculated using crack growth equation (1) replacing K_I with $K_{I(local)}$. Thus, for set of points approximately 5 mm apart at the crack edge the new

position of the crack was determined after the time increment Δt. The crack was presumed to move normal to its previous front.

This new position of the crack was then plotted on a drawing of the cylinder section and a new mesh made up with the crack front moved to a new position for the next step of analysis. The remeshing of the model is key feature of the process investigated in this paper

Residual stresses were not considered because they are probably not relevant after a little growth has occurred. Residual stresses have high positive values on the inside surface when the crack is small but once the crack grows a few millimetres these stresses will substantially decrease. In the long term the sustained load derived from pressure is the most important load. Notches often act as starters for cracks and so this initiating condition was considered. The growth was iterated through steps as the crack grew until it reached the outer surface or otherwise indicated instability.

At each step of crack growth, stress analysis for the cylinder was carried out using the finite element package MSC/NASTRAN. In order to converge the stresses given the singularity of $\frac{1}{\sqrt{r}}$ at the crack front, singularity pentahedron elements were employed. This type of element is obtained by moving the side nodes near the crack tip to the one quarter position. After stress distribution in the crack-tip region had been calculated, equation (1) was used to determine the location of the crack and the finite element model was rebuilt for the next step calculations.

EXAMINATION OF CYLINDERS

Among other defected cylinders and samples the authors have in their possession an Australian SCUBA cylinder made in 1983 which leaked during filling in 1994 and a part of the cylinder which failed in New Guinea discussed by Poole (1995).

These cylinders do not conform to the model of failure as described in the US work since although the origin of the cracking was in the same location on the neck neither cylinder has significant neck folds and lead levels are probably below 10 ppm.

Cylinder A This cylinder exhibited cracking so large as to cause a leak making it impossible to fill. The leaking defect penetrated through to the upper surface of the cylinder outside the O ring contact surface and thus causes the leak. The cylinder was manufactured in August 1983 and leaked in 1994.. The cylinder does not exhibit prominent folds or valleys. The cylinder is made of 6351 alloy and the trace elements in the alloy are low, lead content for example being in the range of 10 ppm.

The defects have been examined under scanning electron microscope as reported in Price et al. (1996a). Most of the defect surface exhibits the features observed before (for example by Lewandowski et al.) and thus is identified as having the SMIE growth mechanism. The appearance of the defect is interesting for it shows that there appears to have been sub-surface growth of the defect. This defect has been shown in Price et al. *ibid.*

Cylinder B was made in August 1987 but otherwise has similar specifications to Cylinder A. This cylinder failed catastrophically during hydrotest in New Guinea on 13th February 1994 and was inside a water filled concrete tank which also burst. The failure occurred in four places around the neck and the bottle broke into two. Figure 3 shows one of the cracks in the neck region. It appears that there is a region of quite different crack growth prior to the final failure which is indicated by regions of 45° shear. There are at least two visible beach marks on this specimen. The cylinder does not exhibit obvious notches in the neck region.

Figure 3 The fracture surface on one of the four fractures on cylinder B. The photograph has been marked to high-light beachmarks caused either by damage during hydro tests of the cylinder or indicating changes to the crack growth mechanism. Some growth stages might leave no clear beach mark.

a	**Area of different morphology indicating initial defect.**
a-b	**Area of growth which has appearance of being mainly intergranular which is consistent with SMIE. Note that in this region some grains are very large because of the nature of recrystallisation during the heat treatment cycle`**
b-c, c-c'	**Faster area of growth, plastic areas mixed with SMIE**
After c,c'	**Plastic rupture, surface approaches 45° to previous fracture plane.**

RESULTS AND DISCUSSION.

Figure 4 shows theoretically calculated crack fronts in a cross section of the neck region of the cylinder. This presentation shows the following.

- The shape of crack predicted is consistent with the observations on cracked cylinders which have been examined (for example see figure 3).
- The crack growth accelerates as the crack grows larger.

If the model is used to match the crack growth in a cylinder for which the loading conditions are reasonably well known, an estimate can be made of the parameters in equation (1) to suit that actual cylinder.

The most accurate procedure for doing this would be to examine cylinders which had been pressurised under laboratory conditions. However there are significant difficulties with this concept because there are long time intervals involved and the fact that the test cylinders would have to be given deliberately cut notches.

The alternative procedure is to estimate growth parameters from cylinders removed from traffic which have large defects in them such as cylinders A and B. The problem with cylinders removed from traffic is that there is only approximate knowledge about their service life.

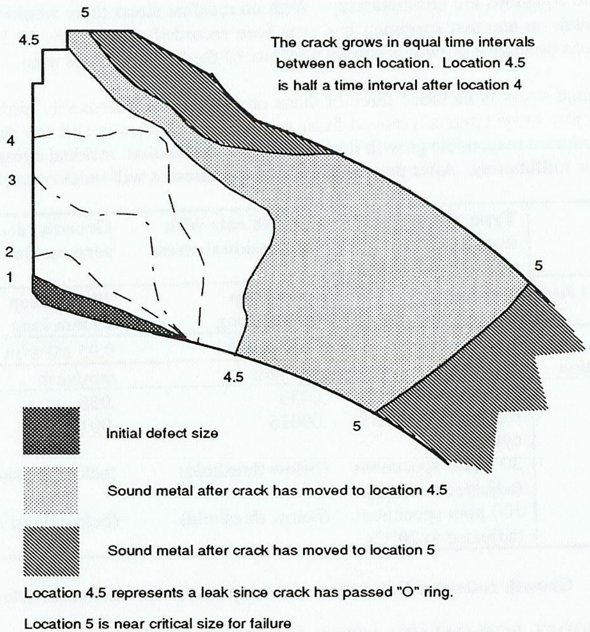

Figure 4 Theoretically calculated crack positions for the pressurised cylinder over a period of time. These positions are similar to beachmarks such as those seen on figure 3. The constants in the growth model were adjusted until the time of growth plausibly fitted the time available for growth in observed cylinders.

Assumptions must thus be made. In this work it is assumed that Cylinder A grew to the point of leakage in 4.5 time intervals and that Cylinder B took 5 time intervals to reach the critical size from whence it failed during test. The time interval was set to one year which presumes that neither cylinder was continuously filled during its service period. Crack growth phenomena was assumed to be essentially the same in both cylinders.

The authors have thus effectively tested the following equation:

$$\log_{10}(da/at) = \alpha(\sigma_L - \beta) \qquad (7)$$

where α and β are constants
σ_L is the local normal stress at 0.3 mm in front of the crack front.

Moreover, if it is assumed that the defects seen in practice are modelled by this equation and that the time intervals proposed for the two cylinders examined are correct it is possible to give values to the constants in the equation as follows:.

$$\log_{10}(da/at) = .015(\sigma_L - 183) \qquad (8)$$

These values are approximate for the reasons given earlier. However the accuracy of this equation at describing actual observed growth is, as noted, orders of magnitudes better than the equations (1) to (4) determined from small specimen testing.

CONCLUSIONS

A new approach was used for modelling the crack growth in sustained load cracking in aluminium alloys. The constants in the equation used are estimated by examining actual failed cylinders and matching the theoretical model to the observations.

The earlier models of crack growth are based on specimen testing which predicts extremely low or zero crack grow rates when applied to actual cylinders and thus cannot predict failure of the cylinders in less of than thousands of years if at all.

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