

## Understanding brittle failure of uPVC (unplasticised polyvinyl chloride) pipe

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**Abstract** - uPVC pipes are designed to have a 50 year lifetime. Although their performance in service is generally very satisfactory, there have been occasions where premature brittle failure has occurred. It is shown that the effect of processing variations on the yield stress is not great but that processing has dramatic effects on the brittle failure stress. Incomplete gelation of the PVC decreases the brittle failure stress and introduces flaws into the material from which brittle failure can occur. Means of predicting the lifetime to brittle failure for uPVC pipe under static and dynamic pressure are presented.

### INTRODUCTION

Unplasticised PVC is extensively used world wide in pressure pipe applications. These pipe systems are usually designed for a 50 year lifetime and service performance of uPVC since these pipes began to be installed in the 1950's has generally been very satisfactory. This is reflected in its growing penetration of especially the small to medium diameter (up to ~ 200 mm) pressure pipe market. However, there has been a number of cases where uPVC pipes have failed at unexpectedly short times and this has led to considerable work on assessing the performance of uPVC as a pipe material. This paper draws together much of this work to give a clearer understanding of the long term behaviour of uPVC pipe.

### MODES OF FAILURE

Three types of failure can be identified in a uPVC water pipe. The pipe can fail in a ductile fashion which involves extensive yielding and deformation of the material before failure of the pipe occurs. This type of failure is often seen in short term hydrostatic tests performed in the laboratory especially at elevated temperatures. It is rarely if ever encountered in service field failures.

Field failures are almost invariably brittle in nature where a small 'penny-shaped' crack penetrates the pipe wall or a fast moving crack splits the pipe sometimes up to a length of several metres. These brittle cracks are local phenomena and do not involve gross plastic deformation of the surrounding material. The brittle failures can be separated into two types: those that result from a constant or static pressure in the pipe and fatigue failures resulting from cyclic pressure variations. Examination of the fracture surfaces does not always clearly differentiate between these two brittle failure modes. The release of high pressure water when the pipe fails can destroy characteristic features of the fracture surface. There is also some doubt as to whether the tell tale striations characteristic of fatigue failures in other materials are present on the fracture surface of fatigued PVC of a molecular weight used for pipe extrusion (K value >K65) (Ref. 1). It is often then necessary to know or measure the pressure sustained by the pipeline to determine whether fatigue was a contributing factor to the failure of the line.

To date, many of the mechanical strength requirements in the Standards to which uPVC pressure pipe is made are based on the yield behaviour of PVC. For example, the Australian Standard AS1477 requires that a section of the pipe be subjected to a hydrostatic pressure which will produce a hoop stress of 39.6 MPa in the wall and that this pressure be withstood for >1 hour. A second test which gives failure at ~ 1000 hrs is also conducted so that the failure stress at 50 yrs can be extrapolated and this must be >23.6 MPa. Reference to the yield data for PVC in the literature (eg Ref 2, 3) indicates that this requirement parallels the yield or ductile failure behaviour of PVC with a necessary safety factor, Fig. 1. Such an approach takes no account of other possible failure modes becoming important beyond the rather short times of 1 to 1000 hrs. Knowledge of the factors which affect the stress at which different failure modes occur and in particular the time dependence of the failure stresses would be instructive in understanding the long term failure of uPVC pipe.

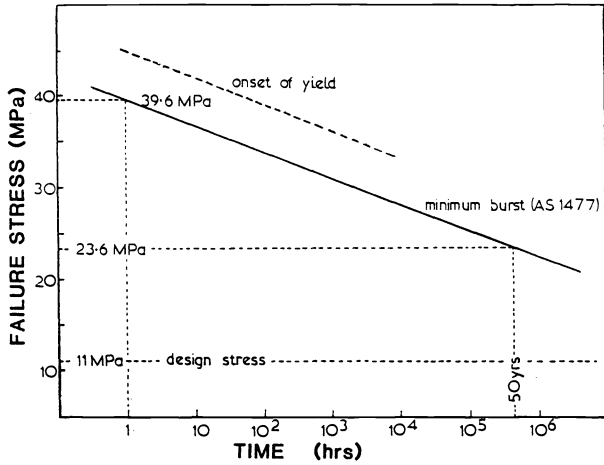


Fig. 1. Hydrostatic burst requirements for AS1477 pipe and its relationship to the onset of yielding.

Two obvious factors that could affect the ductile and brittle failure stresses are service temperature and polymer molecular weight. Since most pipes are made from similar K-value PVC, molecular weight effects will not be discussed here. The majority of uPVC pressure pipelines operate at ambient conditions. Elevated temperatures are well known to accelerate brittle failure in polyethylene pipes and a similar phenomenon may also occur in uPVC (Ref. 3). However, little information is available on the brittle failure of uPVC at elevated temperatures although data on ductile failure is available (page 18, Ref. 2). Temperature derating procedures are available in the Standards for reducing the design stress at elevated temperatures.

PROCESSING MECHANISMS

In practice, the most important factor determining the long term behaviour of uPVC is its processing.

PVC used to make pressure pipe is normally suspension polymerized and starts its life as a fine white powder. Each grain of the powder is an irregular shaped particle generally 100-200  $\mu$  in diameter. Each grain has a complex microstructure as shown in Fig. 2. The terminology followed is that summarized by Geil (Ref. 4). The structure is essentially agglomerates of primary particles, each primary particle being  $\sim 1 \mu$  in diameter. The aggregated primary particles form subgrains (50  $\mu$ ) and grains while within each primary particle, finer structure of domains (200 nm) and microdomains (20 nm) can be identified.

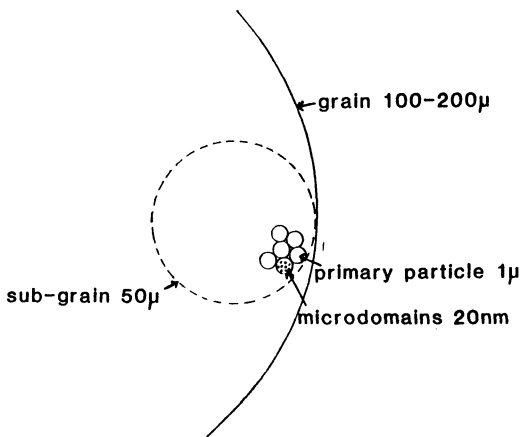


Fig. 2. Structure of PVC grain.

Commercial PVC is predominantly an amorphous polymer although it may contain a few percent of crystalline material. Consequently, it does not exhibit a distinct melting point but gradually softens above its  $T_g$ . Since the grains do not strictly melt, the production of an homogenous melt from the PVC powder must be achieved by the action of heat and mechanical shear in the extruder.

The first stage of processing usually involves premixing the polymer powder with additives such as stabilizers and lubricants. This can be done in a high speed mixer which is taken above the melting temperature of one of the additives to ensure a good distribution of additives around the grain. This dry blend is fed to the extruder which converts it into a rigid pipe.

The most commonly used extruders have twin screws and Allsop (Ref. 5) has studied the processes that occur during processing by stopping an extruder during production and stripping the machine down as quickly as possible to examine the material around the screws. He has shown that the PVC grains are initially compacted and densified and then fused and elongated into an homogeneous mass. Memory of the original grains and primary particles exists well down the extruder barrel. If the extrusion is not performed carefully, memory of the initial particles and grains can be maintained into the final product and this can have a severe effect on the mechanical properties of the pipe.

Homogenisation of the melt is promoted by high temperature and a high degree of shearing of the PVC. However, under these conditions, the PVC can approach the region where it will undergo dehydrochlorination. This is clearly shown in Fig. 3. This figure shows the results for isothermal mixing in a Brabender of a typical pipe dry blend. The Brabender was set up in a low shear mode in order to minimize comminution of the PVC grains down to primary particles which is usually associated with the action of a Brabender. Consequently the action of a twin screw extruder could be mimicked. The torque on the Brabender was measured as a function of time for different temperature settings. The torque, Fig. 3a, was initially constant until the onset of gelation where it rises to a plateau value which corresponds to a fully gelled melt. The homogeneous melt stage is found after this point. A second rapid rise in the torque is found with the onset of degradation.

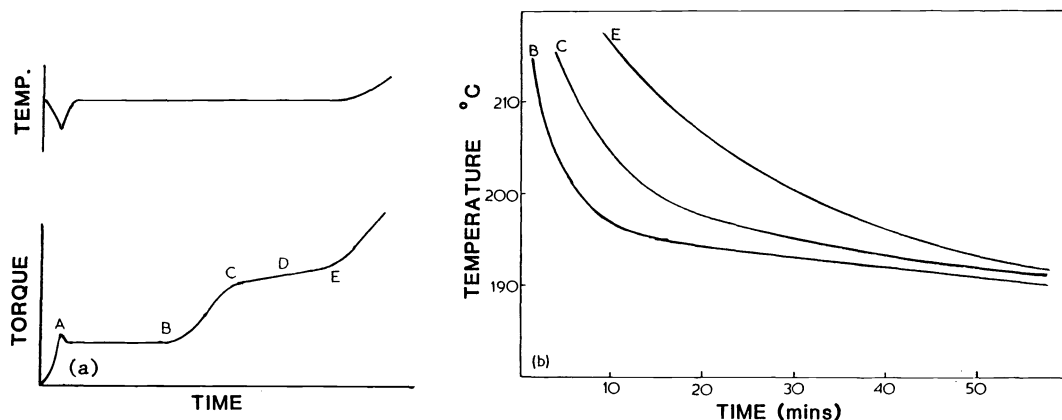


Fig. 3. Torque-temperature curves for gelation of PVC in low shear Brabender test a) torque against time b) time for the onset (B) and completion (C) of gelation, the homogeneous melt stage (D) and the onset of degradation (E) as a function of temperature. A is an initial loading peak.

The temperature as a function of time which corresponds to the onset and completion of gelation, and the onset of degradation is shown in Figure 3(b). Since residence time of PVC in the extruder for large diameter pipes may be 30 minutes, it can be seen that there is less than a 5°C gap between the line representing the fully gelled melt and the onset of degradation. Consequently, very careful control of extrusion conditions is required to obtain the best quality pipe.

#### MEASUREMENT OF PROCESSING

Since, as will be seen later, the level of processing is critical to the long term performance of PVC, some test to measure the level of processing is required. It would be advantageous if such a test be quick and simple to perform so that it could be used as a quality control test in a production environment. Several have been proposed and are discussed briefly below.

##### a) Solvent attack

In this method, the finished PVC product is immersed in a solvent such as acetone or methylene chloride for a given time after which the product is examined for surface attack. Although this method readily distinguishes poorly processed pipe, its interpretation can be subjective and difficult to quantify. The attack of PVC by methylene chloride is very sensitive to temperature and this has been proposed as a means of quantifying the test by varying the solvent temperature to obtain a temperature of no attack (Ref. 6).

Unfortunately, the solvents used can also attack some of the processing additives that are sometimes added to the PVC formulation. Thus although the mechanical properties of the pipe may be improved by the addition of the additives, a negative result may be obtained on the solvent immersion test. In addition, the result of the solvent attack test can be affected by the way the pipe surface was prepared.

b) Capillary rheometer test

A method described by a number of workers (Ref. 7 to 10) involves measurement of the die pressure during extrusion of a sample of the pipe through the capillary of a rheometer. This pressure,  $P$ , is related to the pressures,  $P_0$  and  $P_{100}$  measured for reference samples corresponding to zero and 100% gelation. The gelation level,  $G\%$ , is given by

$$G\% = \frac{P - P_0}{P_{100} - P_0} \times 100$$

Although the reference pressures are not universal and must be established for each PVC formulation, this technique does give a quantitative answer. It, however, gives an average result and does not take into account variations in gelation around the circumference of the pipe.

c) Microscopy

Gotham and Hitch (Ref. 11) used dark field optical microscopy to examine thin sections cut from pipe. Under these conditions, PVC shows as dark areas while the additives appear bright. In well processed polymer, the additives are evenly distributed while in the poorer processed material, there are clearly defined dark areas which are undispersed polymer grains. This technique is again qualitative although it can be made semi-quantitative if each sample is compared to reference samples graded 1 to 5.

An alternative microscopy method was used by Summers and Rabinovitch (Ref. 12). They swelled PVC specimens in acetone and then subjected them to shear between glass slides. Well processed PVC which has been swelled and sheared shows fibrils and an absence of primary particles while PVC processed at lower temperatures showed primary particles with only a few interconnecting fibrils.

EFFECT OF PROCESSING LEVEL ON MECHANICAL PROPERTIES

Table 1 lists the effect of processing on the mechanical properties of PVC pipe (Ref. 3). It can be seen that the tensile strength does not show a marked dependence on processing level increasing only slightly from 32% to 90% gelation level. This work by Benjamin also showed that the time dependence of the yield stress was relatively independent of the level of processing.

Table 1. Effect of processing level on mechanical properties

Attack by methylene chloride	Severe	Slight	None	None
Homogeneity by microscope technique	Inhomogeneous	Some Inhomogeneity	Homogeneous	Homogeneous
Gelation level rheology technique	32%	44%	68%	90%
Yield stress MPa	54	55	56	56
Elongation to break %	108	133	115	58
Tensile impact energy 0°C, N mm/mm <sup>2</sup>	381	706	711	656

On the other hand, Table 1 indicates that impact toughness and ductility initially increases with processing level to a peak at 44 to 68% gelation and then decreases above this level. The drop off in properties at 90% gelation was probably a result of degradation of the pipe since signs of overheating were reported. Alternatively, similar results obtained by Summers et al (Ref. 13) were attributed to melt fracture producing a roughening of the pipe surface and a consequential loss of impact performance.

Brittle failure of materials can often be described in fracture mechanics terms. The basis of fracture mechanics is that all materials contain flaws from which brittle failure can initiate. The severity of a flaw of length,  $2a$ , in a specimen subjected to a stress,  $\sigma$ , is characterised by the stress intensity factor,  $K$ , given by

$$K = Y\sigma(\pi a)^{1/2} \dots(1)$$

where  $Y$  is a geometric factor. Specimens cut from lengths of pressure pipe have been subjected to different levels of  $K$  by notching the samples and testing them in 3 point bend jigs under different loads. Fig. 4 shows the time to failure of these samples as a function of applied stress intensity factor. It can be seen that the plots for good and poorly processed pipes have similar slopes but that the poorly processed pipe fails at significantly shorter times for a given value of  $K$ . Similar results have been obtained by Marshall and Birch (Ref. 14).

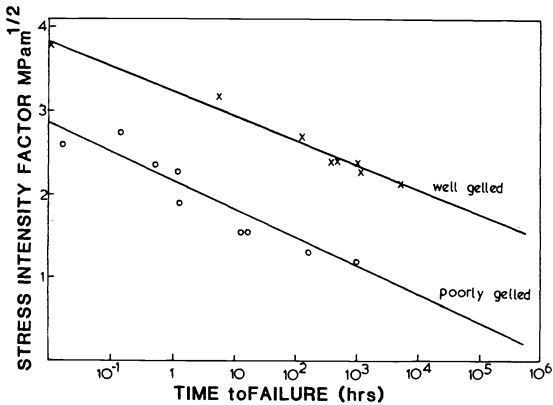


Fig. 4. Time to failure for different stress intensity factors for well and poorly processed pipe

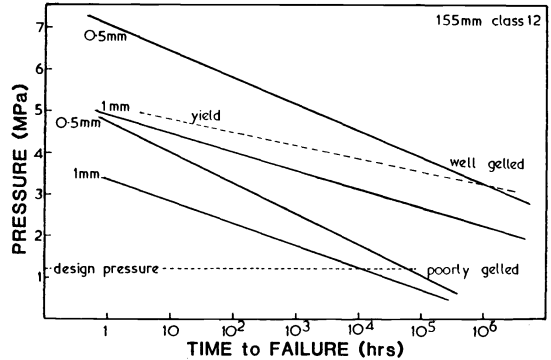


Fig. 5. Time to failure for different stresses and notch depths (155 mm class 12 pipe)

Surprisingly, the level of processing does not appear to affect the fatigue crack propagation rate in PVC. Gotham and Hitch (Ref. 11) gave plots of the number of cycles to failure against the stress amplitude of the fatigue load (S-N curves) for notched and unnotched pipe sample with different levels of processing. The results for the notched pipe samples which had been well and poorly processed fell on the same line while the unnotched results showed significantly greater times to failure at a particular stress amplitude for the well processed pipe over the poorly processed pipe. This implies no difference in the fatigue crack propagation rate as a result of processing level but differences in the initiation time for the fatigue crack to start propagating or a larger inherent flaw size in the poorly processed pipe. Direct measurement of fatigue crack propagation rates in PVC with different levels of processing in recent unpublished work by Kim and Mai has confirmed the relative insensitivity of fatigue crack propagation rate to processing level.

PREDICTING PIPE LIFETIMES

The above discussion can now be applied to the all important question of 'can the premature brittle failure of uPVC pipe be predicted?' As mentioned earlier, brittle failure can be a result of either static or fatigue loadings and these will be considered in turn.

a) Static loads

The results shown in Fig. 4 can be converted into the time for brittle failure for different internal pressures using eqn. 1 and the relationship of the wall hoop stress,  $\sigma$ , to the internal pressure,  $P$

$$P = \frac{2\sigma t}{D - t}$$

where  $t$  is the wall thickness and  $D$ , the outside diameter. To do this, values for the notch depth,  $a$ , and  $Y$  must be assumed.  $Y$  is a geometric factor and will vary with the class of pipe considered and the type of notch.  $Y$  is tabulated for many geometries in Ref. 15.

As an example, assuming a 155 mm class 12 pipe (AS1477), with a scratch down the inside, the calculated brittle times to failure for different applied pressures is shown in Fig. 5. Also shown on this graph is the ductile failure line calculated from Fig. 1. It should be noted that the mode of failure will be determined by which failure process will occur at the lower stress. Thus the poorly processed pipe will fail at all times in a brittle fashion even with a quite small scratch. With increasing time under pressure for the well processed pipe, the brittle failure pressure becomes lower than that required for ductile failure and this pipe will undergo a transition from ductile failure at short times

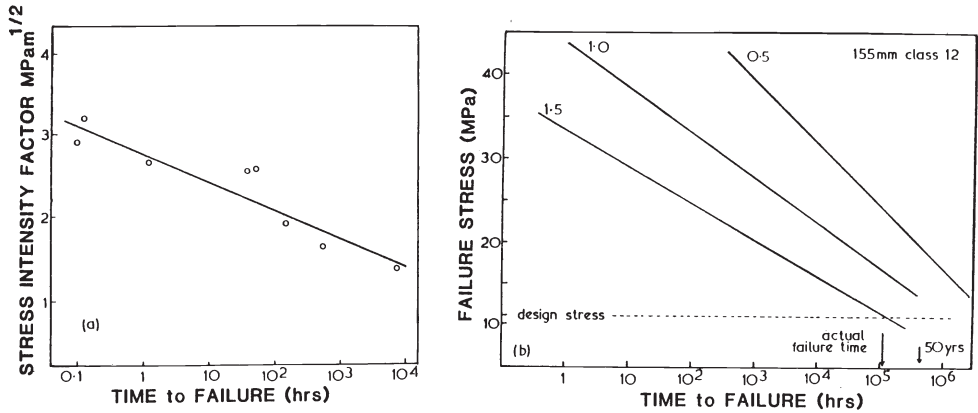


Fig. 6. Brittle failure data on actual failed pipe  
 a) stress intensity factor versus time to fail  
 b) brittle failure stress against time to fail for different notch depths

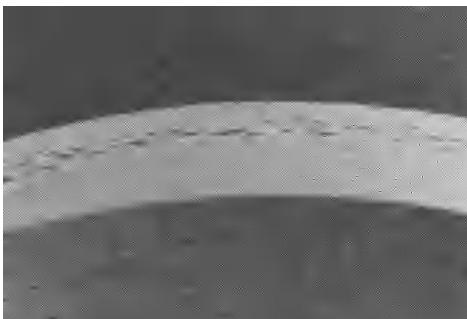
to brittle behaviour at long times under pressure. Fortunately, for well processed pipes without large imperfections, this transition occurs at long service lives beyond the design life. Such a knee in the failure regression line is well known in polyethylene pipe but has rarely been reported in uPVC except by Benjamin (Ref. 3).

Extrapolation of the failure stress lines can be used to predict the service life of a pipe under static pressure since when the failure stress falls below the design stress, failure would be anticipated. This approach was checked by testing pipe which had failed in service after 10 years. Specimens cut from this pipe were subjected to different stress intensity factors in 3 point bend jigs and the time to failure was recorded. Fig. 6a is a plot of  $K$  versus time to failure while in Fig. 6b,  $K$  has been converted to a brittle failure stress for different notch depths. In order for the brittle failure stress to decrease below the design pressure of 11MPa, a flaw size of ~ 1.5 mm would be required.

This particular length of pipe did contain quite large impurities, although probably not of this magnitude. Other failed lines have not had gross inclusions to which failure could be attributed. However, it is conceivable that poorer processed pipe could have areas of weakness within its structure of this magnitude. If a poorly processed pipe is heated in an oven at 180°C for 1 hour, large voids and delaminations can form often extending for several mm, Fig. 7a. SEM examination of the surface of these delaminations clearly shows the existence of primary particles which have survived through the extrusions, Fig. 7b. Well processed pipe is unaffected by this test. This suggests that in poorly processed PVC, the original PVC powder grains are not properly fused together during extrusion and that this can create areas of weakness within the pipe wall which can support little stress and hence act as quite large cracks from which brittle fracture can initiate.

b) Fatigue

Fatigue data have traditionally been presented graphically as stress amplitude or peak stress of the cyclic load versus the number of cycles to failure (S-N curves). Recently, Joseph (Ref. 16) has collected many of the published S-N curves for PVC pipe and plotted them on a single graph. By drawing a lower bound line through this data, and assuming 10



a) x2



Fig. 7. Voiding and delamination in poorly processed uPVC pipe held at 180°C for 1 hour

a) overall view b) SEM of void surface.

pressure surges per hour, he obtained a reasonable correlation with service failures of PVC pipelines under fatigue. Each S-N curve is specific to a particular class of pipe and level of processing. The lower bound lifetime of Joseph would be quite conservative for larger diameter pipes since his data was based on pipes with diameters from 25 mm to 457 mm and wall thicknesses from 1 mm to 22.5 mm. Obviously, a fatigue crack will take longer to grow through a thick wall of 22.5 mm than through one of 1 mm, provided of course that the critical flaw size to cause catastrophic failure is not less than 1 mm. Such should be the case for well processed pipe

Since S-N curves are tedious to obtain, an alternative method of generating them could be useful. It has been found in practice (Ref. 17) that the fatigue crack growth per cycle,  $\frac{da}{dN}$ , in PVC is given by

$$\frac{da}{dN} = A (\Delta K)^n \quad \dots(2)$$

where A and n are constants and  $\Delta K$  is the amplitude of the stress intensity factor. This equation can be integrated to give the number of cycles to failure,  $N_f$ , as a function of the stress amplitude,  $\Delta \sigma$ ,

$$N_f = \int_{a_0}^{a_c} 1/A (Y \Delta \sigma)^{-n} (\tilde{n} a)^{2/n} da \quad \dots(3)$$

where  $a_0$  is the initial crack length,  $a_c$  is the critical crack length for failure and  $\Delta K = Y \Delta \sigma (\tilde{n} a)^{1/2}$ . The critical crack length can have either of two values. If the crack penetrates the wall, the pipe will have failed and  $a_c$  equals the wall thickness. Alternatively, the crack will reach a length where it will propagate catastrophically in one cycle. This condition is reached when the peak stress and the crack length are such that the stress intensity factor, given in eqn. 1, exceeds a critical level. This critical stress intensity factor will depend on the time under load.

Using eqn. 3 to predict the S-N curve for a class of pipe must be done with some caution. It assumes that the lifetime of the pipe is governed by growth of a fatigue crack and takes no account of any possible crack initiation stage. Crack initiation in fatigue of PVC has received little attention. However, it is likely that a number of cycles will occur before a sharp crack will form at the blunt tip of a flaw or imperfection in the material. Eqn. 3 would thus give a lower limit to the lifetime of the pipe.

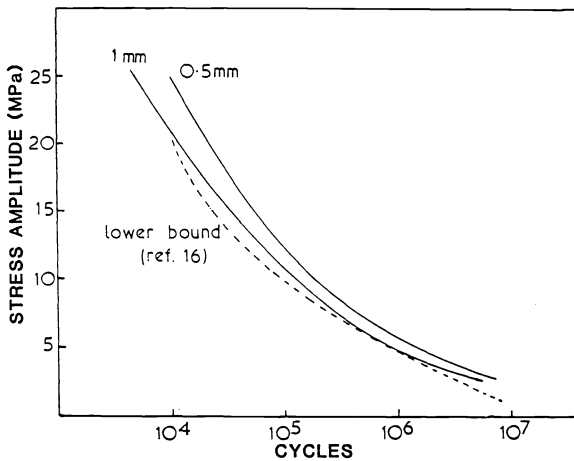


Fig. 8. Calculated S-N Curves for 155mm class 12 pipe based on eqn. 3. --- line is lower bound from Ref. 16.

Figure 8 shows S-N curves calculated for a 155 mm class 12 pipe for different initial flaw sizes  $a_0$ . Typical values for n of 2.81 and A of  $6.04 \times 10^{-25} \text{ m cycle}^{-1}$  were used (Ref. 18). Although Y is a function of crack length, a, it was considered constant for ease of integration. The critical crack length,  $a_c$ , was taken as the wall thickness or the value calculated in the following way.  $N_f$  is calculated from eqn. 3 with  $a_c$  equal to the wall thickness.  $N_f$  was then converted to a failure time assuming 10 cycles per hour. The failure time was used to determine the critical stress intensity factor assuming the time dependence of the critical stress intensity factor is that of a well processed PVC shown in Fig. 4. The effect of the cyclic load is likely to be less than that of the continuous load and a conservative estimate of K will be obtained. Using eqn. 1, a new  $a_c$  was estimated. This procedure was continued until the value of  $N_f$  did not change significantly from one calculation to the next. The calculated S-N curves in Fig. 8 can be seen to have the right order of magnitude by comparison of the lower bound line produced by Joseph from the published literature.

It has already been noted that the level of processing has little effect on the fatigue crack propagation rate. Processing can however affect the fatigue life in a number of ways. Firstly, poor processing introduces large inherent flaws into the material and this will reduce the fatigue life as illustrated in Fig. 8 for different values of  $a_0$ . In addition, the critical crack size for catastrophic failure is reduced by poor processing, Fig. 4, and this will also reduce the fatigue life for thick walled pipe. Finally, the crack initiation time for poorly processed pipe may also be reduced but this has not yet been confirmed.

In service, a pipe is most likely to experience a combination of both static and fatigue loading with variable pressure due to pumping or water hammer superimposed on a constant pressure. The effect of mean stress on fatigue in PVC has received little attention. Gotham and Hitch (Ref. 11) found that ripple loads of + 25% superimposed on a mean stress of 35 MPa reduced the lifetime of PVC by 2 decades. A mean stress of this level would be unlikely in service and Joseph (Ref. 15) contends that low superimposed mean stresses have little influence on the fatigue lifetime. This is supported by the results reported by Stapel (Ref. 19). He considered that the allowable stress amplitude,  $\sigma_a$ , was reduced in a parabolic fashion with the mean stress,  $\sigma_m$ ,

$$\sigma_a = \sigma_{a_0} \left[ 1 - \left( \frac{\sigma_m}{\sigma_f} \right)^2 \right] \quad \dots (4)$$

where  $\sigma_{a_0}$  is the stress amplitude to give failure after a specified number of cycles with no mean stress and  $\sigma_f$  is the static failure stress. This relationship implies that the mean stress must be a substantial proportion of the static failure stress to reduce the allowable stress amplitude significantly.

The fracture mechanics approach to the mean stress is to modify eqn. (2) to take into account the mean stress intensity factor,  $K_m$ , so that

$$\frac{da}{dN} = A' (K_m \Delta K)^n \quad \dots (5)$$

This equation could also be integrated to give an S-N curve. The applicability of equation 5 for uPVC is at present under investigation.

#### CONCLUSION

Studies on the premature brittle failure of uPVC pipe have indicated that the most important factor governing the long term behaviour is the processing level. Processing level has little effect on yield behaviour but can drastically reduce the time for brittle failure both under static and dynamic load. Moreover, the improperly fused PVC grains can introduce large areas of weakness in the polymer from which failure can occur. On the other hand, uPVC which has been gelled and homogenized adequately during the pipe extrusion will give satisfactory service performance both under static and dynamic loading conditions.

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