Fatigue Crack Growth Process in CPVC Pipe Couplings

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Abstract: An investigation of the influence of temperature and loading frequencies on the morphological features found on the fatigue fractured surface of chlorinated polyvinyl chloride (CPVC) has been conducted. Single edge notched rectangular coupons obtained by flattening schedule 80 CPVC pipe couplings were subjected to fatigue loading at different temperatures of 0, 23, 40, and 70 °C and frequencies of 0.1, 1, and 50 Hz. Crack growth in CPVC, involved a combination of shear yielding and crazing processes. At the test temperature of 0 °C and 23 °C, the fatigue crack growth was noted to occur predominantly by shear yielding while crazing played a secondary role. On the other hand at 40 °C and 70 °C, the fatigue crack growth process appeared to predominantly involve a crazing process while shear yielding played a less significant role. Filler material particles played a major role as brittle second phase stress-raiser particles and facilitated craze initiation. Discontinuous crack growth bands (DGBs) indicating repeated crack arrests were also noted on the fracture surface.

Key words: CPVC, pipe couplings, fatigue, crack growth, temperature, frequency

Introduction

Understanding of the macroscopic and microscopic details of the fracture surface morphology in CPVC is of interest because they reveal valuable information on the mechanism(s) with which the cracks growth occurs under given cyclic stress and environmental conditions. Among various conditions, temperature and loading frequency is of the primary interest in applications of CPVC as a pipe line material used for transport of potable, sewage, and sea waters as well as other corrosive liquids. Despite of the fact that the failures of CPVC pipe and pipe fittings are being reported at an increasing rate, the investigations to determine the causes of such failures and understanding the mechanism(s) of fracture process in these materials have been few and far between. A large number of studies, however, have been conducted, which addressed the mechanism(s) of fatigue crack growth in many other engineering polymers including some on PVC [1-10]. A general finding of these studies conclude that under stress states where the maximum principal stress is tensile, polymers may, at the beginning of the deformation, exhibit only a small or even no macroscopic inelastic deformation due to shear-yielding. The mechanism of inelastic deformation then switches to crazing. Crazes form in a two step process, first the highly stressed region decays into voids, and second, after localized necking is initiated, micro fibrils form, which bridge the craze gap. The crack growth occurs by fracturing the craze zone, which advances the crack tip to the boundary of the craze zone. After this crack tip advancement, the crack is arrested and waits for the next craze zone to develop and crack advancement by fracturing the craze zone is...
repeated. The fracture thus occurs by a sequential repetitive process of crack tip inelastic deformation (characterized by micro void formation), craze zone development, and craze zone fracture leading to crack growth. Craze zone fracture may occur by scission of the craze fibrils or pull out failure of highly oriented chains in the craze zone. Fibril scission is favored at lower temperatures as well as high strain rate (high frequencies), while chain pull out is expected at high temperatures and low strain rates (low frequencies).

Although slow crack growth under both cyclic (fatigue) and static (creep) loading conditions have been a subject of study of a large number of investigators, to our best knowledge, the only work available in the literature till date, on the subject of fatigue crack growth in CPVC pipes and fittings are just a few papers authored by Merah et al, Khan et al, Saghir et al and Mezghani et al [11-18]. These authors have investigated the effect of temperatures ranging from −10 to 70 °C on the mechanical properties of CPVC. They found that the yield strength and elastic modulus decrease linearly with temperature. Brittle fracture occurred at temperatures below room temperature while ductile fracture occurred at room temperature and temperatures above RT. It is shown that the crack propagation in CPVC pipe fittings occurs through a crazing process, which involves void formation and molecular orientation hardening.

The work presented here aims at investigating the mechanism(s) involved in the crack growth process in CPVC pipe fittings subjected to fatigue loading at different temperatures and test frequencies.

**Results and Discussion**

**Fatigue Test Results**

Figure 1 shows typical variation of da/dN with ΔK for different temperatures and frequencies at a stress range of 13.3 MPa. As reported in earlier work by Merah et al [12] reasonable data scatter is observed at all conditions. The effect of frequency on the crack growth rates at different temperatures is provided in Figure 2 and the effect of temperature on crack growth rates at different frequencies is shown in Figure 3. The da/dN vs. ΔK curves shown in figure 2 and 3 are the average of two or three tests performed at condition. Results on these figures illustrate two important points. First, for a given ΔK, the crack growth rate da/dN increases with increasing temperature. For example, at the frequency of 1 Hz (Fig. 2-b) at ΔK = 2.0 MPa√m, da/dN of 4, 4.9, 12 and 27 μm/cycle were observed for test temperature of 0, 23, 40 and 70 °C, respectively. A similar result is found at 50 Hz (Fig. 2-c). As explained in earlier work by Merah et al [12], at the frequency of 0.1 Hz however, there is an appreciable enhancement in da/dN when the temperature is increased from 40 to 70 °C. This decrease in the crack propagation resistance at higher temperatures can be explained by the fact that due to the temperature induced molecular vibrations the molecular chain disentanglement in CPVC becomes much easier and promotes a higher rate of crack growth. On the other hand at low temperatures the molecular chains are expected to be more rigidly packed and do not undergo easy disentanglement. The crack growth rates at lower temperatures are expected to be low.
The effect of frequency on crack growth rate in CPVC presented in Figure 3 (a-d) display the variation of $da/dN$ with $\Delta K$ for different frequencies at the four temperatures of interest (0, 23, 40 and 70 °C). The results obtained reveal two important points. First, the fatigue crack growth rates in CPVC are sensitive to frequency changes at 40 and 70 °C and show only a negligible sensitivity to the frequency changes at lower temperatures ($T \leq 23$ °C). This observation is in agreement with the result reported in a related work [29, 51]. In this work the authors show that the transition form shear yielding dominated crack growth to craze dominated crack growth occurred between 23 and 50 °C. Second, at higher temperatures the frequency sensitivity appears to be dependent on the frequency
level. Higher frequency sensitivity is observed in the 0.1 to 1 Hz range than in 1 to 50 Hz range.

**Fig. 3.** Effect of frequency on fatigue crack growth rates of CPVC at different temperature (a) 0 °C, (b) 23 °C, (c) 40 °C and (d) 70 °C.

**Crack Growth Process**

-Macroscopic Fracture Surface Analysis

Macro photographs of fracture surface were taken by a low power optical microscope to examine the fracture process as affected by the changes in temperature and frequency. Representative fracture surface macrographs from CPVC samples fatigued at 0, 23, 40 and 70 °C and at different frequencies of 0.1, 1.0, and 50 Hz are presented in Fig. 4 to 7.
The effect of frequency change on the fatigue crack growth process is clearly evident when macro fractographs of samples fatigued at a given temperature but at different frequencies are compared. An examination of the fracture surfaces of three CPVC samples fatigued at 0 °C at different frequencies of 0.1, 1, and 50 Hz (Fig. 4) shows a much flatter fracture surface at the frequencies of 0.1 and 1 Hz as compared to the fracture surface observed at 50 Hz. At 50 Hz the fracture surface assumes a much rougher appearance especially from the mid way to the end of the crack growth process. The flat fracture surfaces at 0.1 and 1 Hz indicate that at these frequencies the major portion of the fatigue crack growth has occurred under a shear yield control process. On the other hand at the test frequency of 50 Hz, the roughness of the fracture surface suggests that the fatigue crack growth must have occurred mainly under a craze growth control process.

Fig. 4. Macro-fractographs of CPVC samples fatigued at 0 °C. (a) 0.1 Hz, (b) 1 Hz, (c) 50 Hz; Magnification 2X.

Fig. 5. Macro-fractographs of CPVC samples fatigued at 23° C. (a) 0.1 Hz, (b) 1 Hz, (c) 50 Hz; Magnification 2X.

Fig. 6. Macro-fractographs of CPVC sample fatigued at 40° C, (a) 0.1 Hz, (b) 1 Hz, (c) 50 Hz; magnification 2X.
Similar observations can be made at all other test temperatures of 23, 40, and 70 °C, where the fracture surfaces are noted to have also gradually changed from a flat appearance at 0.1 Hz to a rough appearance at 50 Hz. It can thus be safely assumed that at all four test temperatures of 0, 23, 40, and 70 °C, an increase in the test frequency from 0.1 to 50 Hz alters the fatigue crack growth process from one which involves growth by shear yielding (at 0.1 and 1 Hz) to one that involves growth by predominantly a crazing process. It must however be noted that the frequency effect on the fracture surface is not as pronounced at 0 and 23 °C as it is at 40 °C (Fig. 6) and at 70 °C (Fig. 7). At 40 and 70 °C, the appearance of fracture surface suggests that at these temperatures only a small portion of the total crack growth takes place under shear yielding and the bulk of the crack growth occur under a craze growth controlled process. Since the crazing process involves appreciable amount of inelastic behavior in the vicinity of the crack tip region, it is expected that due to this inelastic condition present at the crack tip, the craze dominant process should result in lowering the crack growth rates much more significantly at 40 and 70 °C than at 0 and 23 °C when the test frequency is increased form 0.1 to 50 Hz. The da/dN versus ΔK curves shown in Fig. 2 (a, b, c) confirm that indeed a much more pronounced effect of frequency on the crack growth rates is observed at 40 and 70 °C as compared to 0 and 23 °C. It may be worth noting that at 0.1 Hz and 70 °C, where the specimen spend a very long time (under very low frequency of 0.1 Hz) at relatively high temperature of 70 °C, the fracture surface shows a very fibrous morphology (Figure 7-a) which may be suggestive of the crack growth occurring perhaps under a mixed fatigue-creep conditions.

The change in the test temperature at a given frequency also produces a noticeable change in the fracture surface morphology in CPVC material. A comparison of the fracture surfaces of samples tested at 23 and 40 °C at the test frequencies of 0.1 and 1 Hz (Fig. 5 and 6) reveal that the stepwise crack front advancement at 23 °C seems to occur at a slower rate than at 40 °C, as indicated by the spacing of the crack arrest markings present on the respective fracture surfaces. It is evident that the crack front in the case of 40 °C is advancing with a larger jump step than at 23 °C. This means that when the crack growth rates at a given frequency are compared one should expect that at higher test temperatures the crack growth rates will be higher than at lower test temperatures. The da/dN versus ΔK data shown in Figure 2 (a, b, c) once again confirm that the fracture surface morphology studies are in conformity with the fatigue crack growth test results. At higher temperatures the material becomes less...
resistant to advancing crack front and promotes a rapid craze formation and craze zone rupture than it does at lower temperatures. When test temperature is further raised from 40 to 70 °C, the material loses much of its structural integrity and offers very little resistance to crack growth process. The crack propagates rapidly under a craze growth dominant process. The fracture surface examination in Figure 7 provide clear evidence that the material undergoes an appreciable thermal degradation and offers marginal resistance to fatigue crack growth at test temperature 70 °C. The crack growth rates are thus expected to be the highest at 70 °C among all other test temperatures. The da/dN versus ∆K curves in Figure 2 shows this to be indeed true.

SEM Fracture Surface Analysis

SEM (Scanning Electron Microscopy) analysis of the fracture surface revealed the existence of several characteristic features such as shear lips, conical shaped patterns, and discontinuous crack growth bands (DGBs) on the fracture surfaces of the CPVC samples fatigued at different test temperatures and test frequencies. The fracture surface morphology indicates the presence of three different crack growth zones. The first zone, in the vicinity of the starter notch indicates that the early stages of crack growth occurs under a shear yielding process as evidenced by the presence of shear lips (Figure 8). This shear yielding is expected in the vicinity of starter notch root due to the presence of high stress concentration, which is expected to exceed the yield strength of the material. After this initial crack growth under shear yielding process, the crack growth process changes to growth by a crazing process. This crack growth mode is marked by the conical shaped patterns found on the fracture surface (Figure 9).

Fig. 8. Shear yielding at the vicinity of the machined notch in CPVC. (a) Sample fatigued at 0 °C and 50 Hz, (b) sample fatigued at 23 °C and 0.1 Hz.

These conical shaped features result from the fracture of the crazed zone at its mid rib and advancement of the crack front. The remainder of the crack propagation occurs through the primary and secondary craze formation and craze zone fibril rupture. Discontinuous crack growth bands (DGBs) indicating repeated crack arrests were also noted on the fracture surface. Such DGBs were mainly found on the fracture surface of samples fatigued at the test frequency of 50 Hz. Fig 10 shows the DGBs observed on the fracture surface of samples fatigued at 50 Hz at two different temperatures of 0 °C and 40 °C.
**Fig. 9.** Crack growth by crazing process in CPVC. (a) Sample fatigued at 0 °C at 1 Hz, (b) sample fatigued at 23 °C at 1 Hz.

**Fig. 10.** Discontinuous growth bands (DGBs) in a CPVC samples fatigued at 50 Hz (a) 0 °C and (b) at 40 °C.

The existence of DGBs on the fracture surface is suggestive of local crack arrest and results in increased resistance to crack propagation. The density of the DGBs was noted to increase with increase in temperatures from 23 to 70 °C. The crack propagation rate is thus expected to decrease with increase in frequency at high temperatures, which confirms the da/dN vs ΔK results discussed earlier.

**Fig. 11.** Fatigue striation in CPVC sample fatigued at (a) 23 °C and (b) 70 °C.
The crack growth process in CPVC is however found to be different in two ways from other glassy polymers. First the crazing process takes place with minimal inelastic deformation and without noticeable micro void formation (cavitation) as found in other polymers such as polyethylene [5, 7]. The second difference is that the fracture surface in CPVC exhibits typical fatigue striations suggesting that the crack growth in CPVC also occurs through an incremental crack growth with each load cycle much the same way as in metallic materials. Figure 11 shows such striations on the fracture surface of a CPVC sample fatigued at 23 and at 70 °C at a frequency of 1 Hz. It was also found that the crack growth in CPVC takes place in a discontinuous manner involving repeated crack arrests in much the same way as the other glassy polymers.

Fig. 12. Additive particles providing the necessary stress concentration for the craze zone initiation. (a) Sample fatigued at 50 °C and a frequency of 0.1 Hz, (b) sample fatigued at 50 °C and a frequency of 50 Hz.

Another interesting and worth noting observation is the role of the propriety additive material particles (which are usually added by the manufacturer to enhance certain mechanical properties of the polymeric materials) in the crack growth process. In the present material these additive material particles played a role of brittle second phase stress-raiser particles and facilitated craze initiation. Thus in CPVC micro void formation (cavitation) as a necessary step toward craze zone formation was no longer necessary and the stress levels required for craze zone initiation were provided by the additive particles, which acted as stress raisers. The initiation site of a craze zone associated with these particles can bee seen on the fracture surface of a sample fatigued at 40 °C and a frequency of 0.1 Hz (Fig. 12 a and b). The remnants of the fibril structure of the craze zone points converge at the long needle like additive particles which were responsible for the craze zone initiation.

A change in the test temperature did not produce any significant change in the overall crack growth mechanism in CPVC, which remained one of a combination of shear yielding and crazing processes. Evidence of such a mixed mode fracture process is provided in Figure 13. The temperature however played a major role in determining the predomination of one fracture mode over the other. An examination of Figure 13 shows that a shear yielding dominates the fracture process in CPVC at test temperatures of 0 °C and 23 °C, while crazing plays a secondary role at these temperatures. On the other hand at 40 °C and 70 °C, the fatigue crack growth process predominantly involves a crazing process while shear yielding plays a less
significant role. Figure 13-c shows evidence of craze dominant fracture process in a CPVC sample fatigued at 40 °C. It can thus be assumed that a fracture mode transition from shear yielding dominant process to craze formation and fracture dominant process occurs in CPVC at temperatures above room temperature (23 °C).

Further ahead from the notch area region the effect of temperature is once again reflected by the difference in the amount of predominance of one fracture mode over the other with temperature change. Figures 14 (a) and (b) provide a comparison of the shear deformation/craze regions for two samples fatigued at the same frequency (0.1 Hz) but at two different temperatures of 23 °C and 70 °C.

**Fig. 13.** Fracture surface of a sample fatigued at a frequency of 1 Hz (a) at 0 °C, (b) at 23 °C, and (c) at 40 °C.

**Fig. 14.** Fracture surface of sample fatigued at (a) 23 °C and a frequency of 0.1 Hz, (b) 70 °C and a frequency of 0.1 Hz.
A comparative examination of the two figures shows that at 70 °C, the cellular structure appears considerably more drawn than the ones observed at 23 °C suggesting that the fracture process at 70 °C is overwhelmingly controlled by the craze growth probably interacting with creep process, while at 23 °C the craze growth plays much less significant role in the fracture process.

**Conclusions**

Fatigue crack growth rate tests for schedule 80 CPVC pipe coupling material have been carried out at different temperatures and frequencies. The analysis of the test results leads to following conclusions:

- The fatigue crack growth process in CPVC involves a mixed mode shear yielding and crazing processes. The initial fracture occurs through shear yielding, which is then taken over by fracture progress through crazing.
- At test temperatures of 0 and 23 °C, crack growth occurs predominantly under shear yielding, whereas at 40 and 70 °C, crack growth by crazing is more favored.
- Temperatures above 23 °C were found to be significantly detrimental. The fatigue crack growth rates increased by a factor of almost 5 at 40 °C and by a factor of almost 10 at 70 °C at 70 °C as compared to the crack growth rates at room temperature (23 °C).
- The frequency sensitivity of the fatigue crack growth was noticeable only at the temperature of 70 °C, where an increase in the frequency from 0.1 to 50 Hz lead to a decrease in the crack growth rate by almost a factor of 4.
- The craze zone formation in CPVC is initiated at the points of stress concentrations provided by the additive particles. No micro void formation (cavitation) was observed during the crack growth by crazing.

Fatigue striations were observed in samples fatigued at high frequency of 50 Hz.

**Experimental**

The specimens for monotonic and fatigue crack growth testing programs for CPVC were prepared from commercially available four inch injection molded couplings. 50-mm wide rings were cut from the couplings and slit into two equal semicircular halves. The couplings were slit in such a way that it eliminated the weldline from the test material. The half rings were heated at 105 °C in an electric oven for 20 minutes and flattened under compression to obtain flat plates. Tensile tests on the samples from the heated and flattened plates and on the ring type specimens from as received couplings were performed to find out whether or not the heating and flattening process introduced any changes in the material properties. The results of these tests showed the material’s tensile properties remained essentially unchanged and thus it was safely assumed that the heating and flattening process did not alter the material in any notable manner. Rectangular coupons having dimensions of 40 mm x 180 mm x 9.4 mm were machined from the flattened plates. A sharp razor blade was used to manually introduce a through-thickness 1-mm deep razor sharp starter notch at one edge of the coupons. It should be pointed out that the 1-mm depth of the notch acted merely as a crack starter notch and this depth was kept essentially constant in all test coupons.

An Instron material testing machine was used for fatigue testing. All tests were performed in load control mode using sinusoidal waveform loading. Two to three tests were conducted at 0, 23, 40 and 70 °C at three different frequencies of 0.1, 1.0
and 50 Hz. A stress ratio \( R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \) of 0.2, and two stress ranges \( \Delta \sigma \) 13.30 and 11 MPa were used. The mean stress was taken to be about 20 % of the yield strength of CPVC in order to keep \( \sigma_{\text{max}} \) below 50 % of \( \sigma_{\text{ys}} \) to minimize plastic yielding.

A Questar QM-100 microscope with a working range of 15-45 cm and resolution of 0.1 mm was used to observe the crack initiation and growth during the fatigue tests. For the long duration low temperatures and low frequencies tests, a video recording system was employed to record the entire crack growth process. Plexiglas chambers were used for conducting non-ambient temperature tests. The high temperature environmental chamber was designed to maintain temperatures up to 150 °C for extended periods of time. The chamber for low temperature testing circulated refrigerant solution through copper tubing placed inside the chamber. A window (30 mm x 60 mm) allowed optical observation and measurement of the crack. The fracture surface morphology of the failed specimens was studied using a Joel JSM scanning electron microscope.

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**References**

