FRACTOGRAPHIC CHARACTERIZATION OF PIPE AND TUBING FAILURES

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Abstract

Plastic piping systems are an important commercial product used in a wide variety of applications. Because of the diversity of applications and wide range of material used to produce pipes, many different types of failures can result in service. Evaluating these failures through a systematic analysis program allows an assessment of how and why the pipes failed. An essential portion of the failure analysis process is the fractographic examination, which provides information about the crack origin location, and the crack initiation and extension modes. The focus of this investigation was to characterize the surfaces of intentionally cracked laboratory samples in order to gain a more thorough understanding of pipe fracture mechanisms. This paper will document some of the key fracture features associated with overload of various materials used to produce commercial piping systems.

Background

Piping systems find wide utility in the world today and are used in a variety of applications including:

- Gas Distribution
- Water Distribution
- Sewer
- Drainage Systems
- Cable Protection
- Communication
- Industrial Applications

The evolution of piping systems has paralleled that of the development of materials. As metals were first developed, they found use in pipe-related applications. In fact the chemical symbol for lead, Pb, has its origins in the Latin word plumbus, the root for the English words plumbing and plumber. Today pipe systems are constructed from metals, concrete, plastics, composites, and rubber. The 1960s and 1970s saw a rapid increase in the use of plastic pipes with the advance of polyethylene and poly (vinyl chloride) in pipe applications.

With the current diversity of applications for piping systems, the distinctions between pipe, tube, and hose have become somewhat blurred. Plastic pipe is generally specified by the outer diameter (OD) and the wall thickness. Tubing is usually described simply by the outer diameter. An informal concept is that pipe is rigid and cannot be formed, while tubing is small in diameter and somewhat less rigid and thus can be shaped. While the terms pipe and tubing give an expectation of stiffness, hose on the other hand implies flexibility or portability. For the purposes of this evaluation, polymeric pipe, tubing, and hose have been considered and are described as piping.

When considering pipe, it is important to recognize its role pipe as part of a system. That system is made up of a series of subsystems, including all of the components within the system. This includes pipes, fittings, valves, pumps, and any other component online in the delivery system. All of the components of the piping system must be taken in account when evaluating performance or suitability. Additionally, the systems need to be recognized relative to the environments in which they operate.

The specific material selected for use for in a pipe application is based on many parameters depending on the specific performance expectation of the application and the requirements of the system. Careful consideration must be given to mechanical properties such as strength, ductility, stiffness, impact resistance, and fracture toughness; long term properties including creep resistance, vibration resistance, and thermal stability; and environmental properties such as chemical resistance, aging characteristics, fire resistance, and biological resistance.

Failure within components can be defined a number of ways. Most commonly one of three classifications is used:

- The part has become completely inoperable
- The part is operable, but is not fully functional
- The part is functional, but is unreliable or unsafe

For the purpose of this evaluation, failure has been defined as the presence of a crack or rupture in the pipe that would disrupt the flow of the contents or allow the contents to unexpectedly exit the pipe. This most closely resembles the first definition above.

While each pipe failure is unique, cracking is simply a response to stresses placed on the part, both from internal and external sources. A crack forms within the pipe as a response to relieve the stresses. This can happen in one of two general ways, ductile or brittle fracture. Ductile fracture is a bulk response of the polymer. As part of the ductile failure mechanism, yielding takes place. Yielding represents the large scale rearrangement of the molecular structure of the material as a response to relatively high stresses. Given sufficiently high stresses, cracking occurs through disentanglement. Conversely, brittle fracture is a localized response of the polymer. Like ductile failure, cracking takes place through disentanglement. However the cracking is related to molecular reorganization without yielding.

The exertion of mechanical loads, both internal and external, induces stresses within the pipe. If these stresses are sufficient, cracking will occur. The type of failure is a function of a number of parameters including:

- The pipe material
- Source of the stress – internal vs. external
- Magnitude of the force
- Force loading angle
- Pipe geometry
- Pipe support

The principle stresses that act on a pipe are the result of tensile and compression loading, as illustrated in Figure 1. Often this loading results in bending, a mixed mode including both tensile and compressive stresses. The third type of stress, shear, is usually not applicable to pipe, with the possible exception of twisting.

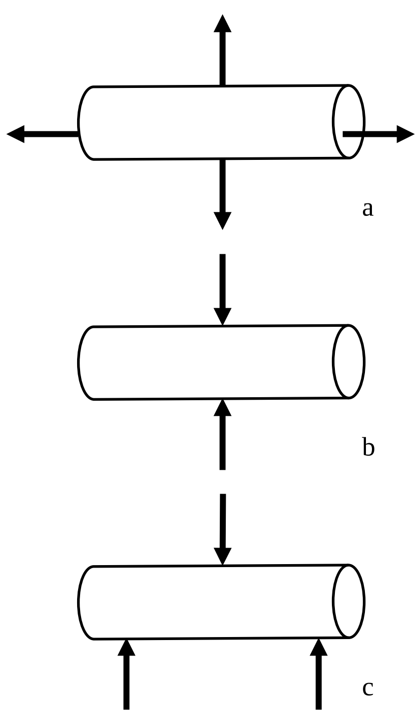

Figure 1 - Pipe loading demonstrating tensile stress (a), compressive stress (b), and bending stress (c).

Considering simply the implications of internal pressure, pipe is adequately modeled as a thin wall cylinder. In this case, there are three principal stresses on the pipe wall, the shell of the cylinder. These are circumferential or hoop stress, longitudinal stress, and radial stress. The cylinder shown in Figure 2 has an internal diameter *d* and a wall thickness of *t*. If the applied internal pressure is *p* then the hoop stress is represented by F1, the longitudinal stress by F2, and the radial stress by F3.

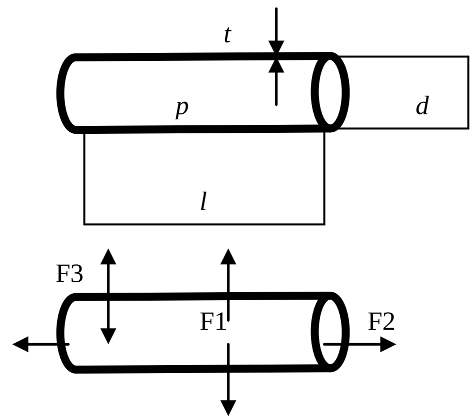

Figure 2 – The three principal stresses on the pipe wall are illustrated.

Using the approximation of the pipe as a thin wall cylinder, the following equations define the hoop stress and the longitudinal stress:

$$F1 = p \times d / 2t \qquad (1)$$

$$F2 = p \times d / 4t \qquad (2)$$

Where F1 is the hoop stress, F2 is the longitudinal stress, p is the internal pressure, d is the internal pipe diameter, and t is the pipe wall thickness. Under these conditions F3, the radial stress is generally considered negligible. (Ref. 1)

Based upon the stresses exerted on the pipe the crack will have a longitudinal or circumferential orientation, as illustrated in Figure 3.

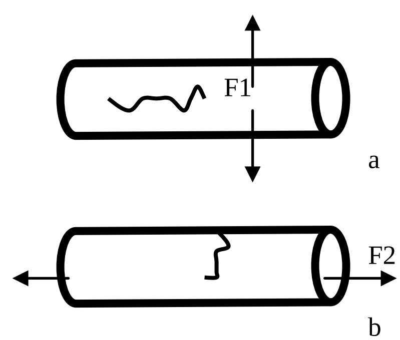

Figure 3 – Longitudinal cracking (a) and circumferential cracking (b) are illustrated within a pipe.

Cracking represents the partial fracture of a solid material. This results in the creation of two mating fracture surfaces. The examination and interpretation of the features present on the fracture surfaces is a discipline known as fractography. Fractographic studies involve a combination of visual, microscopic and scanning electron microscopic (SEM) examinations. A thorough understanding of the mechanisms of pipe failure is important. Fractography is used to characterize the mode of the failure and can provide invaluable information regarding the stresses and conditions leading to the failure. In this investigation, commercial pipe samples fabricated from different materials were stressed through overload to intentionally create laboratory failures. A fractographic examination was subsequently conducted in order to understand and document the resulting fracture surface features. This study was conducted to further the understanding of the failure mechanisms routinely observed with plastic pipes.

Experimental

Commercially available pipe, tubing and hose samples representing a range of materials were selected for the investigation. Each sample was mechanically tested by applying high pressure with water until failure. High pressures were achieved by using a mechanical pump, which is capable of producing pressures up to approximately 3000 psi by hand. All failures occurred within 3 minutes of the initial application of pressure with the pump. The prepared fracture surfaces were examined using a Keyence digital microscope.

Tests and Results

Crosslinked Polyethylene (PEX) Pipe

The PEX specimens were cut approximately 13 in. in length from stock ¾ in. diameter piping. Push lock fittings were used to attach and cap the PEX specimens during testing. The line was pushed into the fitting and, upon reaching the appropriate insertion depth, small metal teeth in the fitting engage the tubing. These teeth prevent the tubing from slipping out of the fitting. The fitting used to attach the PEX pipe to the pump water supply was a ¾ in. Push Lock x ¾ in. FNPT (female national pipe thread). The pipe was then filled with water and capped with the ¾ in. Push Lock end stop. High pressure was then applied with the mechanical pump. During pressurization noticeable deformation took place throughout the pipe, increasing the diameter of the pipe. This deformation typically took place over 800 psi, while additional water volume was added to compensate for the dimensional change. For all specimens tested, failure occurred at approximately 1000 to 1050 psi.

An examination of the specimen showed a single longitudinal crack on the pipe sample. Significant macro-ductility in the form of stress whitening and permanent deformation, as illustrated in Figure 4, was evident. While the level of apparent ductility was significant, measurements showed that the level of elongation was well below the elongation at break expected from a standard tensile test. The reduction in elongation is the result of the rapid overload mechanism. Examination of the fracture surface showed that the crack initiated at an included discontinuity, likely present as a gel particle. The morphology at the crack origin was relatively smooth, as presented in Figure 5. Fracture surface locations remote to the origin also showed smooth surface features, as represented in Figure 6. The lack of apparent micro-ductility is further evidence of the brittle fracture mechanism.

Polyethylene (PE) Tubing

Several specimens, ranging from 24 to 30 in. were cut from a stock roll of ¼ in. x .170 in. (O.D. x I.D.) polyethylene tubing. Generally, this tubing is constructed from linear low-density polyethylene. One end of the specimen was attached to the water supply line from the pump using a plastic push lock style. A similar push lock fitting with a integral valve was used to cap the specimen. The push lock fittings are similar in function to those used for the PEX pipe. With the end cap valve open, water was supplied to evacuate all of the air inside the tubing; the valve was then sealed. The specimen was checked for leaks at system pressure. High pressure was then applied until failure. Several specimens were tested and all failed at approximately 600 to 650 psi.

Inspection of the failed tubing samples showed longitudinal cracking, which exhibited a significant level of macro-ductility, as illustrated in Figure 7. The overall appearance of the cracking was generally similar to that produced within the PEX pipes. Further examination of the fracture surface reveled a lack of micro-ductility, showing an absence of stretch flaps or fibrils. A typical surface of the fracture is included in Figure 8.

Chlorinated Poly(vinyl chloride) (CPVC) Pipe

Specimens constructed of CPVC were cut from stock ¾ in. diameter pipe. All specimens were approximately 18 in. in length. A ¾ in. Slip x ¾ in. MNPT (male national pipe thread) was attached to each end of the pipe by solvent cement joining. An appropriate primer was applied to both the pipe end and fitting. The CPVC solvent cement was then applied to the pipe end and installed into the fitting, utilizing a quarter turn while pushing the pipe in to ensure bottoming. The fitting and pipe were held together by hand for 30 seconds thereafter. The specimens were allowed to cure for a minimum of 4 days prior to pressure testing to allow adequate time for the volatiles to dissipate from the cemented area. Several wraps of Teflon® tape were applied to the MNPT threads. One end was threaded onto the pump water supply. The pipe was filled with water and capped with a ¾ in. FNPT PVC cap. High pressure was then applied with the mechanical pump. During pressurization no noticeable deformation took place. For all specimens, fracture occurred at approximately 2000 to 2150 psi.

Examination of a failed test specimen showed multiple cracks and a significant crack bifurcation pattern, as illustrated in Figure 9. The cracking was generally oriented longitudinally. This fracture pattern is consistent with rapid crack propagation and indicated that the fracture was traveling rapidly in order to dissipate a significant level of energy. Multiple apparent crack origins were noted within the straight sections of the crack, with subsequent extension resulting in bifurcation. No signs of macro-ductility were apparent, with the features being characteristic of brittle fracture.

Crack origins were observed along the fracture surface at both the inner diameter and outer diameter walls, with a typical origin area shown in Figure 10. The morphology within the origin area was coarse and generally consistent with a moderate level of micro-ductility for CPVC. Conversely, areas remote to the crack origins displayed a relatively smooth morphology showing sharp, distinct crack directionality features. These features, as presented in Figure 11, are consistent with brittle cracking.

Poly(vinyl chloride) (PVC) Pipe

PVC specimens were cut from stock ¾ in. diameter pipe. All specimens were approximately 18 in. in length. A ¾ in. Slip x ¾ in. MNPT (male national pipe thread) fitting was attached to each end of the pipe by solvent cement joining. The steps for joining were the same as those in the CPVC, except solvent cement appropriate for PVC was used. The pipe was attached to the water supply from the pump, filled with water and capped with a ¾ in. FNPT PVC cap. High pressure was then applied with the mechanical pump. During pressurization no noticeable deformation took place. For all specimens, fracture occurred at approximately 2000 psi.

An examination of the failed test specimen showed an overall appearance that closely matched that of the CPVC specimen, as illustrated in Figure 12. The specimen exhibited multiple cracks and a distinct and widespread crack bifurcation pattern. The cracking was oriented longitudinally and the pattern was characteristic of rapid crack propagation. Similar to the features on the CPVC pipe, the pattern indicated that the fracture was traveling rapidly in an attempt to dissipate a significant level of energy. Multiple crack origins were found within the straight sections of the crack, with subsequent extension resulting in bifurcation. No signs of macro-ductility were apparent, with the features being characteristic of brittle fracture.

Multiple crack origins were observed along the PVC fracture surface. The crack origins were present at both the inner diameter and outer diameter walls, and a typical origin area is shown in Figure 13. The morphology within the origin area was generally coarse, indicative of a moderate level of micro-ductility for PVC. The morphology at locations remote to the crack origins displayed a contrasting smooth morphology, which included sharp and distinct crack directionality features. These features, as represented in Figure 13, were consistent with brittle cracking.

Discussion

Based upon the evaluation of laboratory fracture surfaces created on different pipe materials, the corresponding responses to relatively rapid over-pressurization have been documented. The obtained fracture surfaces could easily be used to separate the bulk macro responses as ductile and brittle. The PEX and PE samples displayed a significant level of deformation and distinct yielding. Conversely, the CPVC and PVC samples showed extremely brittle characteristics including substantial crack bifurcation. These macro responses correlate with the inherent tensile and impact properties of the materials.

Interestingly, the observed fracture surfaces showed the opposite response on a micro level. The PEX and PE displayed almost no evidence of micro-ductility, as would be indicated by the presence of stretched fibril or flap formation. Conversely, the CPVC and PVC fracture surfaces showed a relatively coarse textured morphology indicative of micro-ductility at the crack origin locations. Further work will need to be performed in order to indentify the mechanism responsible for this contrasting behavior. In all cases the longitudinal cracking predicted by the elevated level of hoop stress was observed, as opposed to circumferential cracking caused by longitudinal stress.

Further Work

The current work has raised questions regarding the mechanisms pertaining to the cracking with pipe, tubing and hose materials. Additional investigations are being undertaken to further evaluate failure through overload in other materials and alternate failure mechanism such as creep and environmental stress cracking. Further experiments will be performed to assess these failures and will be added to the paper as time allows and to the final presentation.

Acknowledgements

The authors wish to sincerely thank their colleagues at The Madison Group for the assistance in putting this work together.

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Keywords

fractography, failure analysis, pipe, tubing

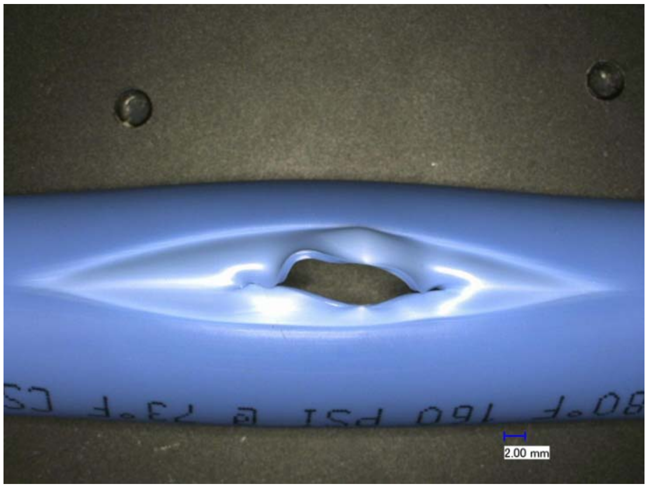

Fig. 4 - Photomicrograph showing the deformation on the PEX pipe sample.

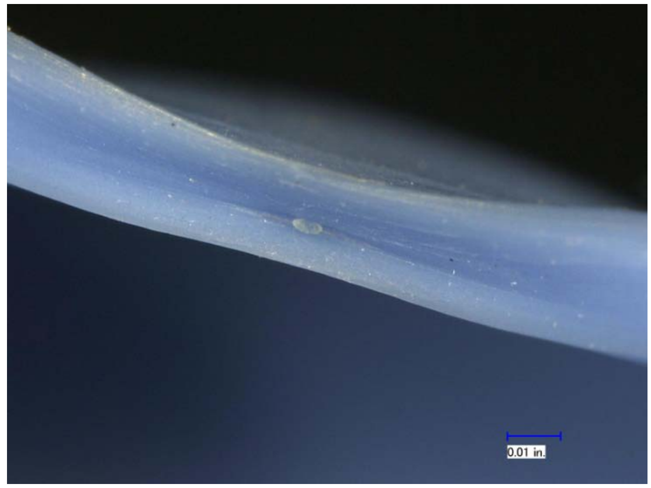

Fig. 5 - Photomicrograph showing the crack origin at a discontinuity.

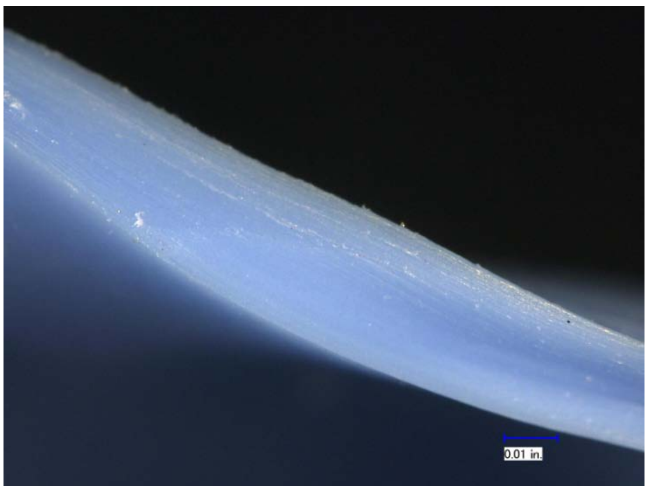

Fig. 6 - Photomicrograph showing a typical area on the fracture surface remote to the origin.

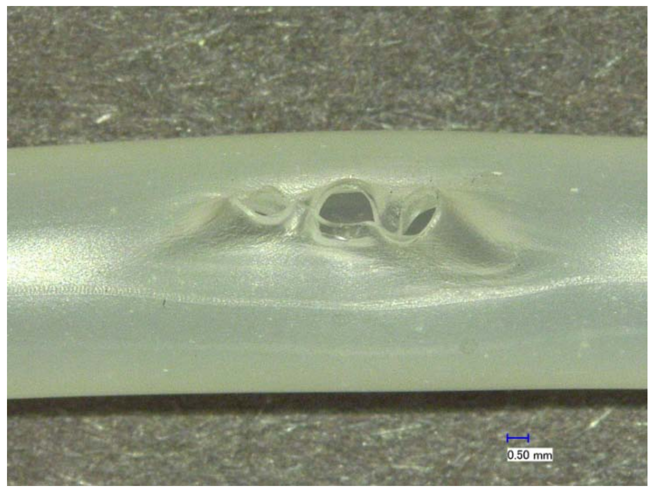

Fig. 7 - Photomicrograph showing the PE tubing deformation.

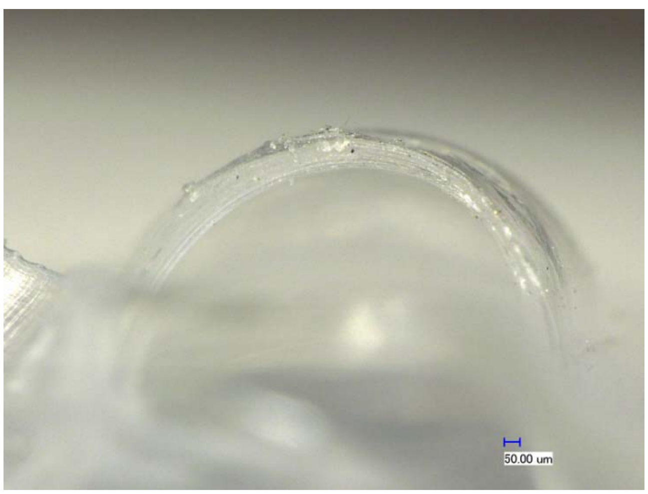

Fig. 8 - Photomicrograph showing a typical area on the PE tubing fracture surface.

Fig. 9 - Close-up view showing the crack pattern on the CPVC pipe.

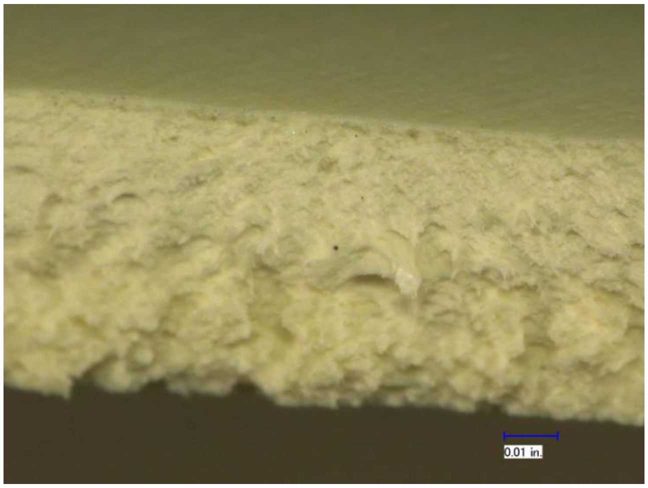

Fig. 10 - Photomicrograph showing an apparent crack origin on the CPVC fracture surface.

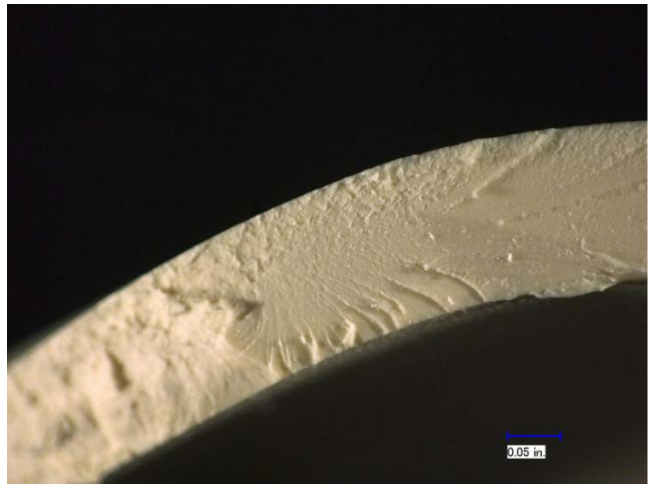

Fig. 11 - Photomicrograph showing an area remote to crack origins on the CPVC pipe.

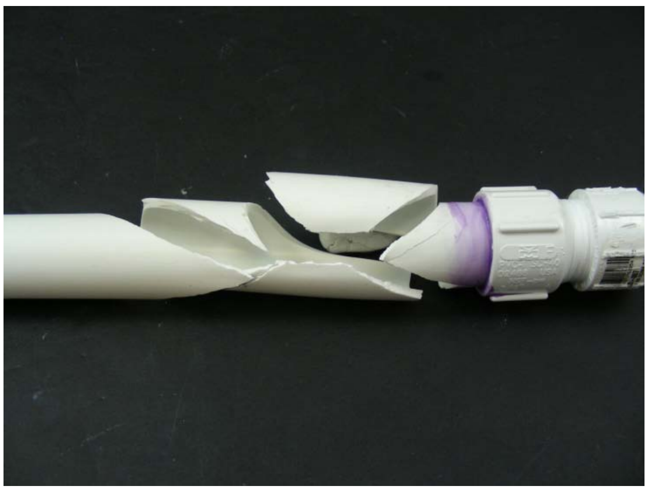

Fig. 12 - Close-up view showing the crack pattern on the PVC pipe.

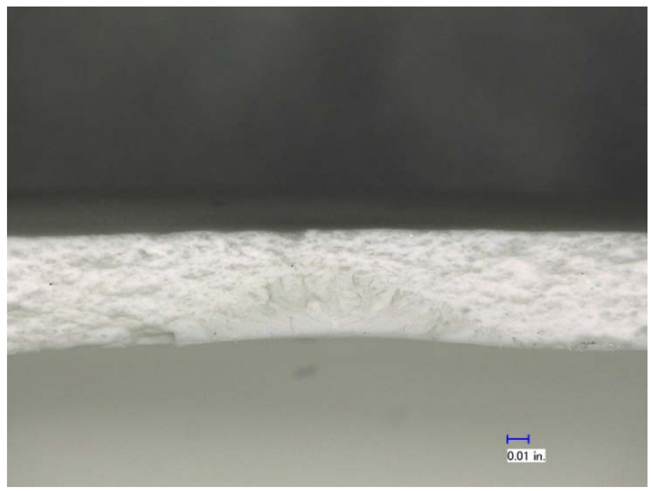

Fig. 13 - Photomicrograph showing an apparent crack origin on the PVC fracture surface.

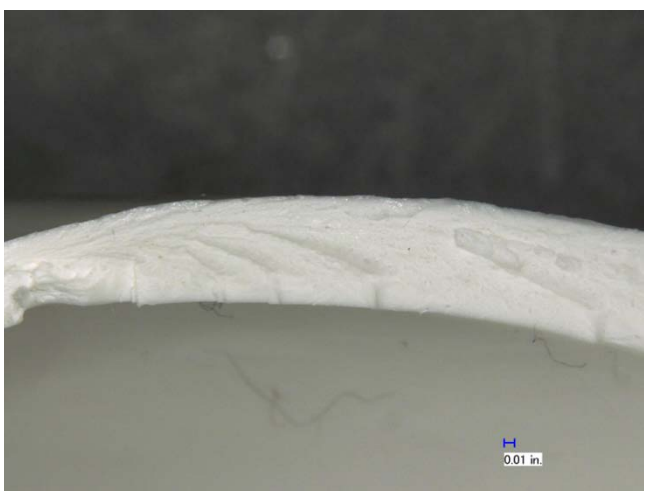

Fig. 14 - Photomicrograph showing the fracture surface remote to crack origns on the PVC fracture surface.