The Evaluation of Appliance Hose and Tubing Failures

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ABSTRACT

Polymeric hoses and tubing, like all assembly components, are subject to failure. The failures can be related to four primary factors, including the part material, the overall design, the production, and the service environment. This paper focuses on the investigation of appliance hose and tubing failures, including the determination of their nature and cause. This is illustrated through the presentation of case studies from appliance applications. These case studies review failures associated with chemical interaction, ultraviolet radiation degradation, contamination, and manufacturing defects.

INTRODUCTION

Flexible hose and tubing, hereby referred to synonymously, are a mature product and unfortunately too often viewed as commodity items. Their use within appliance applications is widespread, and because of their familiarity, these components are often taken for granted. Frequently, however, failure within hose and tubing has catastrophic consequences on the appliance and potentially on the surroundings. Flexible tubing can fail through many of the same mechanisms that affect other polymeric-based components, including:

- Ductile rupture
- Brittle fracture
- Molecular degradation
- Environmental stress cracking
- Creep
- Fatigue
- Deformation

Selected for many reasons over metal tubing alternatives, polymeric flexible tubing offers a price advantage, unique design features, and corrosion resistance. However, like other polymeric components, flexible tubing has weaknesses that need to be recognized.

As with any component, the performance of polymeric hose and tubing is related to four primary factors:

- Material
- Design
- Processing
- Service Environment

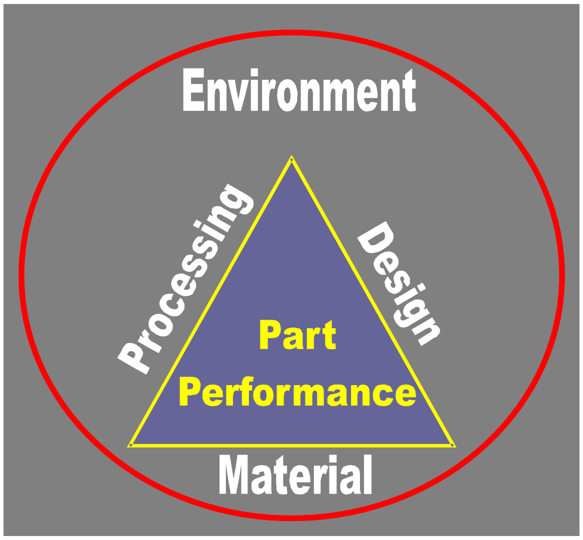

Figure 1 – Graphical representation of the factors affecting product performance.[1]

Poor performance or failure is most often not linked to a single factor, but commonly is a combination of two or more of these influences that affect the overall function of the component. This is particularly true in the case of hose and tubing.

Material

The selection of an appropriate material is the most critical consideration that will affect performance in a tubing application. A wide range of materials are available within three broad categories; thermoplastic resins, thermoplastic elastomers (TPE), and rubber. Each of these materials has distinct advantages and liabilities that must be understood. The material must be selected to match the anticipated service requirements, with particular consideration to thermal exposure, chemical contact, and applied stresses. The composition of the tubing material extends beyond the identification of the base polymer, and performance is greatly influenced by other formulation constituents, such as antioxidants, impact modifiers, stabilizers, filler materials and even pigments. The specification of a proven hose and tubing material is important to the reliability of the system. Many problems have arisen from a vague part drawing, such as specifying simply polyurethane tubing.

Design

The design aspects of a flexible tubing application are often less significant than they are with other polymeric applications; not because they are unimportant, but because this application is by nature a simple design. The primary considerations will be the diameter and the wall thickness. Matching these with the applied internal and external stresses is of major importance when selecting the proper hose and tubing for the appliance.

Processing

Hose and tubing are almost exclusively produced through extrusion. Unlike other polymeric applications, there is little choice on the production technique. However, aspects associated with the extrusion process will certainly have an impact on the performance of the product. Pertinent considerations include temperature, back pressure and die design. The design of the die is particularly important as it relates to weld lines or defects within the tubing. Weld lines, running down the longitudinal axis of the tubing will inherently represent the area on the product with the lowest mechanical integrity. Beside the extrusion process, the compounding of the resin is also included with processing. The resin must be handled in such a way to homogeneously disperse the formulation constituents throughout the resin, without imparting excessive heat or shear that could lead to molecular degradation.

Service Environment

The service environment is the most important of the factors that affect the performance of a tubing application. Unfortunately it is the hardest to anticipate and control. Obvious service aspects include the temperature and pressure to which the tubing will be exposed. Other foreseeable service conditions include contact with chemical agents, possible oxidation, and exposure to ultraviolet radiation. These need to be considered as part of the material selection process. Less obvious, but equally important, concerns include the external stresses imparted onto the tubing. These can originate from bending, interference with mating fittings, and vibration from other appliance components. It should be remembered that it is these stresses, together with the applied pressure that provide the total stress that can drive cracking, tearing, or rupture.

The factors that effect the performance of flexible hose and tubing are illustrated in the case studies presented below. These case studies represent real life failures and illustrate the importance of carefully considering the selection, manufacture, and use of hose and tubing.

MATERIAL RELATED FAILURE

Example 1 – Failure of Plasticized Poly(vinyl chloride) Tubing [2]

Numerous pieces of clear polymeric tubing failed while in service in an appliance application. While in use, the tubing had been exposed to periods of elevated temperature as a normal part of the operation. The tubing was specified to be a poly(vinyl chloride) (PVC) resin plasticized with trioctyl trimellitate (TOTM). The failures occurred through splitting of the tubing at an interference fitting, and were associated with apparent embrittlement of the material. The failed tubing represented a recent increase in the number of in-service failures, which had been linked to a particular lot of tubing. No failures had been reported outside of the identified tubing lot.

Samples representing the suspect tubing that was tied to the field failures, and the reference tubing were analyzed using micro-Fourier transform infrared spectroscopy (FTIR). The spectrum obtained on the older, reference tubing material was characteristic of a PVC resin containing a trimellitate ester plasticizer. This was consistent with the described specified material. The results obtained on the suspect tubing material, however, differed substantially. While the obtained spectrum contained absorption bands characteristic of PVC, the results indicated that the material had been plasticized with an adipate ester material, such as dioctyl adipate.

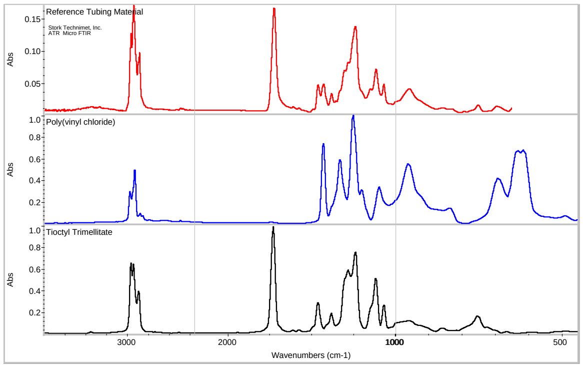

Figure 2 – The FTIR results obtained on the reference tubing were consistent with a PVC resin plasticized with trioctyl trimellitate.

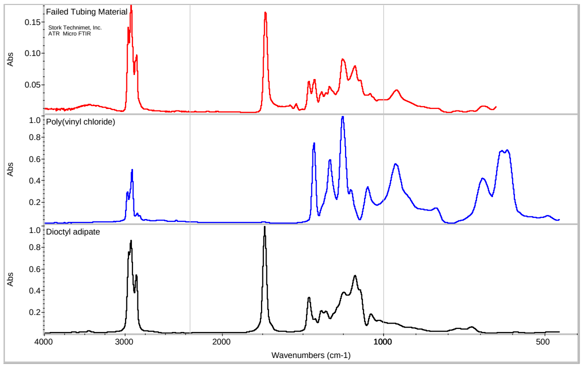

Figure 3 – The FTIR results produced by the failed tubing material differed from those represented by the reference material and were indicative of a PVC resin containing an adipate-based plasticizer.

The two tubing materials were further evaluated via thermogravimetric analysis (TGA). Both sets of results exhibited complex weight loss profiles, consistent with those expected for plasticized PVC resins. The thermograms representing the reference and suspect sample materials showed comparable plasticizer contents of 28% and 25%, respectively. A direct comparison of the weight loss profiles showed that the suspect material, containing the adipate-based plasticizer, underwent initial weight loss at a significantly lower temperature relative to the reference material, formulated with the trimellitate-based plasticizer. The elevated weight loss onset temperature exhibited by the reference tubing material was consistent with the observed performance and greater thermal stability of this tubing material. These results indicated that the reference material exhibited superior thermal resistance compared with the failed material.

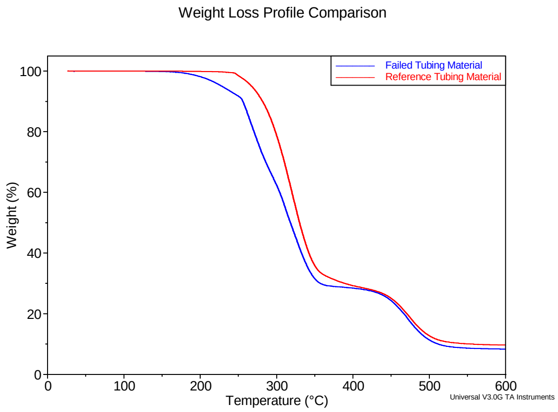

Figure 4 – The TGA results showed that the reference tubing material demonstrated greater thermal stability compared with the failed tubing material.

It was the conclusion of the evaluation that the failed tubing had been produced from a formulation that did not comply with the specified material. The failed tubing material was identified as a PVC resin with an adipate-based plasticizer, not trioctyl trimellitate. The obtained TGA results confirmed that the failed tubing material was not as thermally stable as the reference material because of this formulation difference. The adipate ester underwent migration and evaporation, rendering the PVC tubing stiffer and relatively embrittled, and that this was responsible for the observed failure. Clearly, the primary factor related to the failure of the PVC tubing was exclusively related to the material.

DESIGN RELATED FAILURE

Example 2 – Torn Flexible Draw Tubing

A high rate of tearing occurred during the installation of draw tubing into a type of major residential appliance. The tubing was co-extruded from hard and soft poly(vinyl chloride) (PVC) compounds. The design resulted in a tubing that was sturdy, but flexible. The failures had been reported with a new production lot of the tubing, after conversion from one supplier to another. It had been suspected that changes in the PVC compound formulations were responsible for the failures.

A visual examination of the failed tubing confirmed spiral tearing within the soft PVC material. The tubing did not exhibit significant macro ductility, with no observed stretching or deformation. During the visual examination a clear difference was apparent between the construction of the failed tubing compared with a sample of the older, reference tubing.

A typical section of the tubing was further examined via scanning electron microscopy (SEM). The tear surface exhibited features associated with overload of a soft polymeric material. A moderate level of micro ductility was apparent in the form of an overlapping morphology. No evidence was found to indicate molecular degradation of the tubing material.

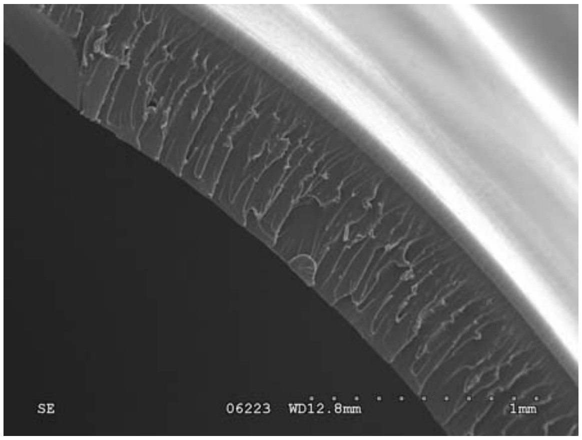

Figure 5 – The failed tubing fracture surface exhibited features associated with mechanical overload.

The hard segments of the draw tubing from the reference and failed tubing samples were analyzed using both FTIR and TGA. The materials produced comparable results, characteristic of a PVC compound containing calcium carbonate filler. No variation was observed in the relative loading of the filler, and the two materials were consistent in formulation. Correspondingly, the soft segments of the two tubing samples were also analyzed. Again, the results were consistent across the two materials. Both samples generated results indicative of PVC compounds plasticized with a phthalate-based oil. No significant compositional differences were found between the two soft segment materials.

In order to more comprehensively evaluate the observed appearance differences, cross sections were prepared through the two types of the draw tubing. Examination of the cross sections revealed substantial variation in the design of the two tubing samples. These differences included the thickness of the soft segment, the size and geometry of the hard segment, and most importantly the angle between the hard and soft segment bands. Specifically, the failed tubing contained a series of sharp corners, absent in the references tubing. These corners acted as notches, producing a point of severe stress concentration.

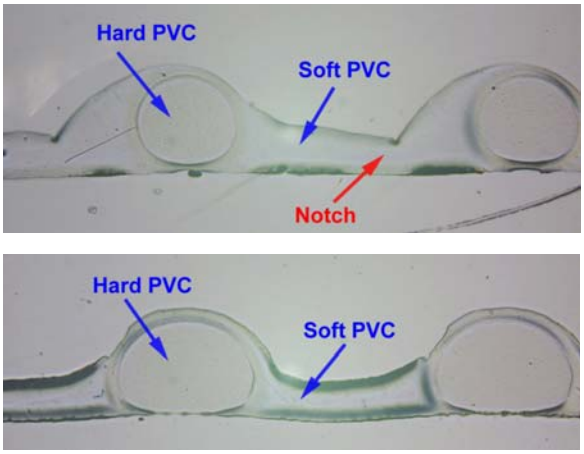

Figure 6 – Cross section showing that the failed tubing (lower) exhibited a sharp notch between the soft and hard segments. This is significantly different that the design of the reference tubing (upper).

It was the conclusion of the evaluation that the failed tubing had been designed in such a way as to impart severe stress concentration within the soft segment. The stresses placed on the tubing section during installation exceeded the strength of the notched material. As such, the fundamental design differences between the two types of draw tubing were responsible for the observed variation in performance. Analysis of the hard and soft segment material produced very consistent results across the two types of tubing. The outcome of the testing showed that design of the draw tube was the leading factor in the failures.

PROCESSING RELATED FAILURE

Example 3 – Contaminant Inclusions within Rubber Hoses

Rubber hoses used in appliance applications had been rejected during quality control inspection prior to installation into the final assembly. The hose sections were rejected because of the presence of included contaminants, which were thought to be detrimental to the integrity of the parts. The hoses had a multilayer design and been produced from a chloroprene rubber inner tube layer and a chlorobutyl rubber cover layer.

Examination of the hose sections confirmed the presence of included white contaminant material in both the inner tube and cover layers in different samples. Typical contamination samples were excised from the hoses and analyzed. Both contaminant materials were white in color and exhibited a powdery texture. Analysis of the contamination present within the inner tube layer via micro-FTIR produced results characteristic of a silicate-based mineral. The white contaminant was further evaluated using energy dispersive X-ray spectroscopy (EDS). The resulting elemental profile included relatively high concentrations of silicon, calcium and oxygen, consistent with calcium silicate.

The contaminant material removed from the hose cover layer was also analyzed using micro-FTIR. The resulting spectrum exhibited absorption bands characteristic of calcium carbonate.

Figure 7 – White included contaminant material was present within the hose cover layer.

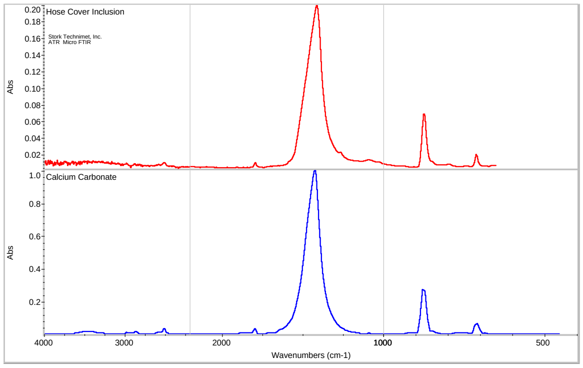

Figure 8 – The included material from the hose cover produced an FTIR spectrum characteristic of calcium carbonate.

The results obtained during the analysis indicated that different included contaminant materials were present within the hose inner tube and cover layers. The inclusion within the inner tube was identified as calcium silicate, a mineral filler commonly used in the formulation of rubber compounds and a major constituent of the chloroprene rubber compound. The included material from the cover layer was determined to be calcium carbonate. Calcium carbonate was the primary filler material used in the chlorobutyl rubber hose cover layer formulation. Given the appearance and composition of the included contaminants, both sets of defects were likely the result of incomplete dispersion of the filler materials within the respective rubber compounds, making this principally a processing related failure. Such inclusions can occur if the rubber mixing process does not impart proper shear with the rubber, or if hard particle agglomerates are present within the fillers.

Example 4 – Failure Analysis of a Tube Assembly

A tube assembly used in an appliance application failed while in service. The assembly included a section of tubing in conjunction with a nozzle fitting. The tubing had been produced from a heat stabilized, extrusion grade of nylon 6 resin.

A visual examination of the assembly revealed a circumferential crack within the tube. The crack extended approximately 270 degrees around the tube. The tubing exhibited a substantial level of stress whitening, which was particularly evident on the outside diameter, adjacent to the crack. Areas of tubing that were remote to the crack also demonstrated a high level of ductility in the form of stretching and deformation. The examination showed that the while the tip of the nozzle fitting was tapered, the base was sharply angled.

A section of the tubing was further evaluated using scanning electron microscopy. The SEM examination revealed multiple apparent crack origins along the outer diameter of the tubing wall. The crack origin areas exhibited a relatively smooth morphology, and the observed features were generally consistent with brittle fracture. Within the crack origin region, additional features indicative of pre-crack initiation sites were also evident. These features also exhibited a morphology associated with brittle cracking. The form of pre-cracks was generally consistent with the crack origins, except that they had not extended significantly into the tubing wall. Increased ductility was apparent within the mid-wall fracture region. This ductility was apparent in the presence of formed fibrils and stretching. The crack surface morphology adjacent to the inner diameter included a smooth texture, indicative of brittle fracture during the final mechanical overload of the tubing wall. Throughout the SEM examination no evidence was found to indicate defects, such as voids or inclusions, with the tubing wall. Further, no signs of molecular degradation, such as chemical attack or thermal deterioration were evident.

Figure 9 – The tube assembly exhibited significant macro ductility adjacent to the failure.

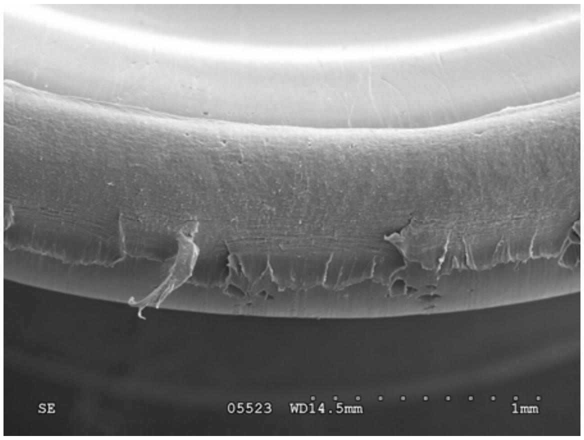

Figure 10 – Multiple apparent crack origins were present along the outer diameter of the tubing.

Further SEM evaluation was conducted on the outer diameter of the tubing, adjacent to the apparent crack origins. The inspection revealed multiple linear indications, which were characteristic of extrusion damage, on the outer diameter surface. The examination showed that these indications directly corresponded to the crack and pre-crack initiation sites observed on the fracture surface.

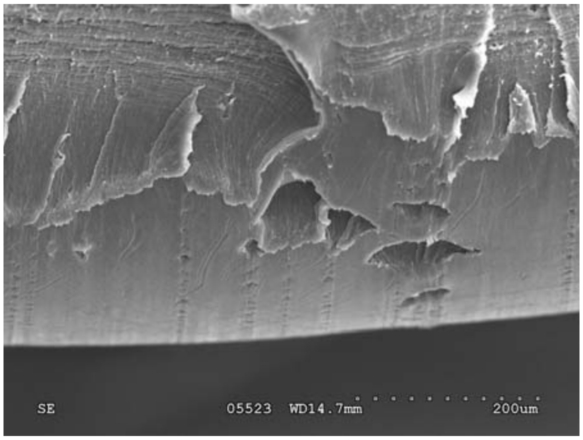

Figure 11 – The outer diameter surface of the tubing exhibited indications that corresponded to the crack origins.

Analysis of the tubing material via FTIR and differential scanning calorimetry (DSC) produced results characteristic of a nylon 6 resin. No evidence was found to suggest contamination or degradation of the tubing material.

It was the conclusion of the evaluation that the nylon tubing failed through mechanical overload. The fracture surface exhibited multiple crack origin sites along the outer diameter of the tubing. The crack origins and observed pre-crack features corresponded to linear indications present on the outer diameter surface of the tubing. These indications were likely produced during the extrusion process and represented surface defects and points of severe stress concentration. The driving stress responsible for the failure is likely associated with the natural bending of the tubing as it is configured in the appliance. It appears likely that the design of the nozzle fitting was also a factor in the failure because of the relatively sharp corners and the corresponding stress imparted onto the tubing. Once initiated, the cracking extended through the tubing wall and subsequently circumferentially around the tubing. Given the outcome of the investigation, the tube assembly failure was related to processing problems. However design considerations regarding the fitting are thought to be a contributing factor.

Example 5 – Failure of Nylon Air Line Tubing

Several pieces of air line tubing used in a medical monitoring device ruptured during routine over-pressurization testing. The tubing was specified to be extruded from a nylon resin. The over-pressurization testing was performed as part of a normal quality control procedure to randomly evaluate a number of the completed assemblies. In a successful test, the tubing will exhibit ductility and bulge, but not rupture.

A visual examination of the failed samples revealed relatively long longitudinal slits extending through the tubing wall. The tubing samples were sectioned and further examined with the aid of an optical stereomicroscope. The microscopic inspection of the fracture surfaces revealed little evidence of macro ductility, as would be apparent in the form stress whitening or permanent deformation. Conversely, the fracture surface exhibited features indicative of brittle cracking. The observed features suggested that the cracking had initiated within the mid-wall of the tubing. The examination of several reference tubing samples that had deformed, but not ruptured, during the evaluation showed significant ductility in the form of stress whitening and deformation.

A typical failed tubing sample was evaluated via scanning electron microscopy. The fracture surface examination confirmed that the cracking had initiated within the mid-section of the tubing wall. At the apparent crack origin location features suggestive of included material were present. The fracture surface morphology included an overlapping structure, indicative of a moderate level of micro ductility. Overall, the fracture surface features presented signs of mechanical overload of the tubing.

In order to further assess the failed tubing, several samples were evaluated via cross sectional examination. The randomly selected cross sections did not reveal any of the included material suggested through the SEM evaluation. However, several of samples exhibited discontinuities along the inner diameter wall. The discontinuities appeared as cut defects. Such defects would substantially reduce the tubing strength and lead to premature brittle failure. The cuts were likely produced during the extrusion process, possible through non-uniform operation.

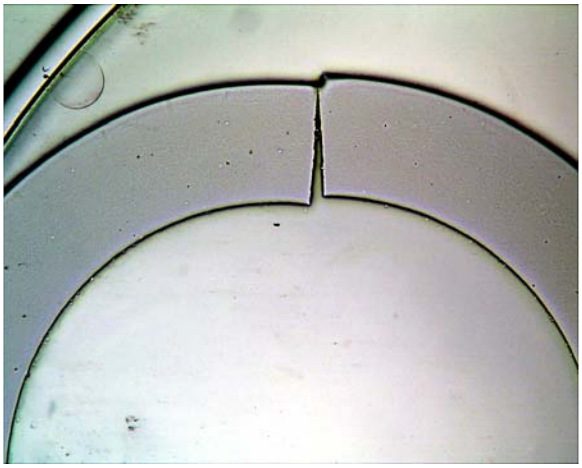

Figure 12 – The cracking within the tube exhibited no signs of macro ductility.

The failed tubing material was analyzed using FTIR. The resulting spectrum was consistent with a nylon resin, without evidence to show contamination or degradation of the bulk resin. Based upon the observations made during the SEM evaluation, an attempt was made to isolate any included particulate matter. Sections of the failed nylon tubing were dissolved in formic acid. After the dissolution, several included particles remained and these exhibited a relatively soft texture, suggestive of an elastomeric material. Representative particles were analyzed using micro-FTIR. The obtained spectra presented relatively strong absorption bands associated with hydrocarbon functionality and additional bands consistent with a chlorinated material, such as chlorinated polyethylene or chlorosulfonated polyethylene.

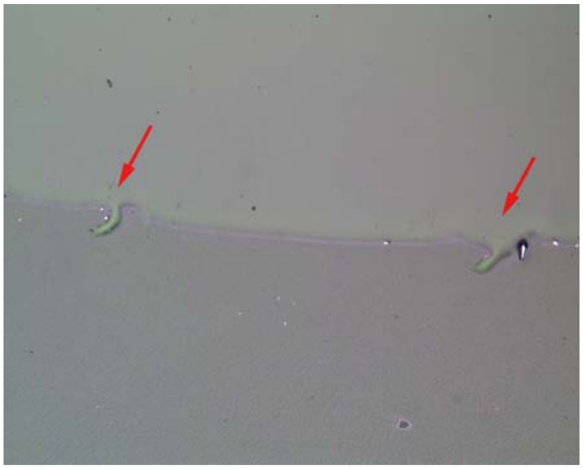

Figure 13 – Discontinuities were apparent along the inner diameter of the failed tubing.

The isolated particulate material was further analyzed via energy dispersive X-ray spectroscopy. The EDS results showed relatively high concentrations of carbon and chlorine, with lesser amounts of sulfur, oxygen, zinc, and magnesium. Overall, the analysis of the included particulate matter was indicative of a chlorinated polyethylene or chlorosulfonated polyethylene rubber compound.

It was the conclusion of the investigation that the tubing ruptures occurred as a result of the exertion of stresses beyond the strength of the extruded tubing, given two contributory factors. The failed sample contained included contaminant particles that reduced the integrity and strength of the tubing. Inclusions act as sites of crack initiation because of inadequate fusion and stress concentration associated with localized variation in mechanical properties. The source of the include rubber particles was not positively identified, but it was suspected that they may have originated from rubber articles used in conjunction with the resin and tubing processing equipment. The role of the discontinuities along the inner diameter is not apparent, but these may act as notches to reduce the ductility of the formed tubing. Processing, related to both the presence of the included contamination and the inner surface discontinuities, was the principal factor in the failures.

SERVICE RELATED FAILURE

Example 6 – Failure of a Power Equipment Fuel Line

A section of polymeric tubing used in conjunction with a piece of outdoor power equipment failed while in service. The tubing had been produced from poly(ether urethane) and was used in a gasoline fuel line application. The tubing section represented an isolated incident, with no other reported failures. In the application, the tubing was exposed to ambient conditions, including a wide temperature range, moisture, and sunlight.

A visual examination of the tubing section revealed massive catastrophic cracking. The sample was further examined with the aid of an optical stereomicroscope. Inspection of the outer diameter surface revealed a complex pattern of interconnecting cracks. This morphology is commonly referred to as mudcracking and is characteristic of substantial molecular degradation. Examination of the inner diameter surface showed the presence of cracks that extended well into the tubing wall. The form and concentration of the cracks differed significantly, and the cracks at the inner diameter surface were far less numerous. Additionally, the inner diameter surface did not exhibit the intersecting network of cracks present on the outer diameter.

Examination of the cracks that extended through the tubing wall showed a relatively smooth texture, with no evidence of macro ductility. The observed features indicated that the cracking originated along the inner diameter.

The tubing section was further inspected via scanning electron microscopy. Examination of the outer diameter surface showed the presence of a series of cracks characteristic of severe molecular degradation. The mudcracked morphology included a network of perpendicular cracks that covered the entire surface of the tubing that had been exposed while in service. Such degradation can be the result of chemical attack, thermal deterioration, or ultraviolet (UV) degradation.

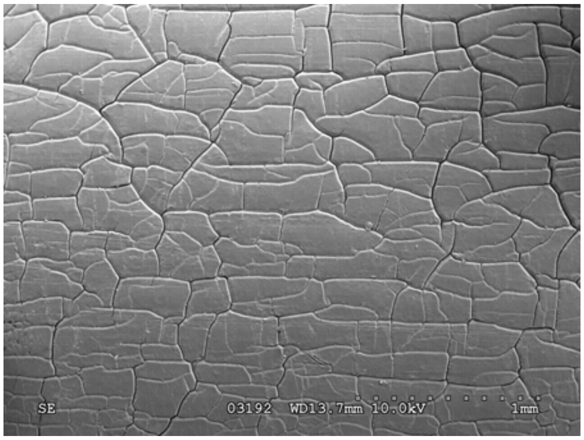

Figure 14 – The outer diameter surface exhibited mudcracking characteristic of molecular degradation.

Examination of the inner diameter surface revealed cracks that deeply penetrated the tubing wall, oriented at 90-degree angles. The overall appearance of the surface was suggestive of chemical interaction, but not molecular degradation associated with direct chemical attack. Examination of the fracture surface of a typical crack indicated that the initial cracking extended through approximately one-half of the tubing wall. The observed features confirmed that the cracking initiated along the inner diameter. Secondary cracking, suggestive of chemical interaction with the tubing material, was also evident. Examination of the crack surface toward the outer diameter revealed that the mudcracking did not extend significantly into the tubing wall. The fracture surface along the outer diameter exhibited features characteristic of final overload, associated with the exertion of stress beyond the strength of the tubing in a state of reduced wall thickness.

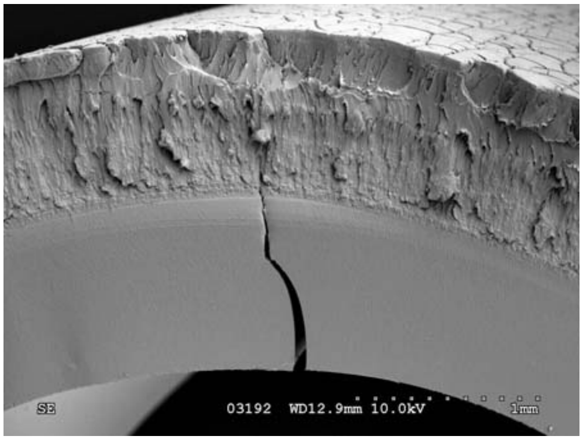

Figure 15 – The cracking extended from the inner diameter outward approximately one-half through the wall prior to final overload.

The tubing material was analyzed using FTIR. Analysis of a core specimen of the tubing remote to the apparent cracking produced results characteristic of poly(ether urethane). Analysis of the outer diameter surface, however, resulted in a spectrum that differed substantially. The outer diameter results exhibited absorption bands indicative of severe oxidation of the polymer. Conversely, analysis of the inner diameter surface produced results that closely matched those obtained on the core material. As such, the FTIR analysis generated a good correlation with the SEM results, indicating gross molecular oxidation of the outer diameter surface, without severe degradation of the inner diameter surface material.

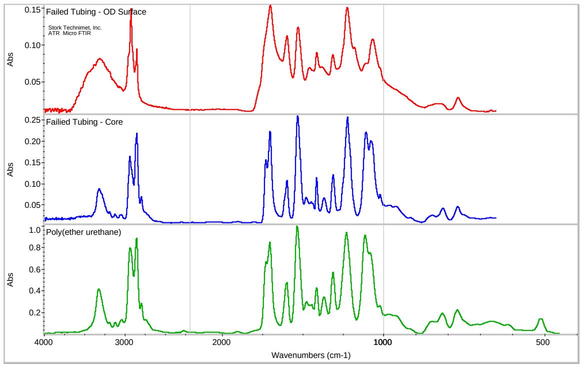

Figure 16 – The FTIR spectrum obtained on the tubing outer diameter surface showed evidence of oxidative degradation of the poly(ether urethane) resin.

It was the conclusion of the analysis that the fuel line tubing had undergone severe molecular degradation of the outer diameter surface. The location and form of the degradation was indicative of ultraviolet (UV) exposure associated with weathering. While the degradation was most apparent on the outer diameter surface, materials that are transparent can also be degraded at otherwise hidden, isolated areas, such as the inner diameter surface.[3] The appearance of the primary, deeply penetrating cracks, which extended from the inner diameter surface, was suggestive of chemical interaction with the tubing material. This was supported by the relatively low concentration of cracks. This interaction is distinct from chemical attack and the corresponding molecular degradation. Instead, the features were suggestive of a failure mode typified by partial dissolution of the crack tip by chemical agents. In this failure mechanism chemical agents dissolve the material at the crack tip, resulting in acceleration of crack extension. It was thereby concluded that the partial molecular degradation of the inner diameter surface material caused by the weathering and UV exposure was sufficient to allow catastrophic interaction within the gasoline contained within the fuel line. The isolated nature of the failure suggested that the equipment had been exposed to an anomalous condition. Given the results of the evaluation, the service condition appeared to be the primary factor related to the failure of the gasoline line. However, material selection, and particularly the UV and chemical resistance of the tubing, may have been a contributing factor.

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