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Forensic Engineering Investigation and Analysis of Crack Formation in Acetal Resin Nuts Used for Water Supply Lines

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Abstract

Non-destructive and destructive techniques were used to document and model crack formation in acetal resin nuts used for household toilet water supply lines. The morphologies of creep rupture and overload failure were documented using optical microscopy and scanning electron microscopy (SEM). The forensic investigation stemmed from litigation between a homeowner, plumbing contractor, and parts supplier related to a failure at a single residence. Fortuitously, 447 fittings in service for approximately two years under similar conditions were available for examination. In many properly installed fittings, cracks had initiated at the notch created by the sharp thread root radius, as predicted by engineering mechanics and finite element analysis. This study found that the cracks had propagated via plastic creep.

Keywords

Acetal resin nut, plastic nut, threaded nut, stress concentrations, creep rupture, scanning electron microscopy (SEM), liquid dye penetrant, fracture morphology

Introduction

A plumbing contractor was sued by a homeowner related to the failure of an acetal resin nut that was part of a water supply line to the toilet tank (**Figure 1**). The plumbing contractor subsequently filed a third-party lawsuit against the supplier of the water line, alleging negligent design and manufacture of the acetal resin nut.

The subject nut failed at the base of the thread. This type of failure has occurred in similar water supply lines from other suppliers and has been the subject of previous litigation and debate among experts, mainly focused on diverging opinions of installation error versus design defect[1,2]. Very often, the nuts are embossed with lettering on the end cap, advising to "hand tighten" only. In previous lawsuits (and in the subject lawsuit), the defendant suppliers — and experts retained by their attorneys — took the position that the nuts failed because they were overtightened by installation with a tool[3]. The opposing view expressed by plaintiffs — and experts retained by their attorneys — was that the nuts failed due to creep rupture of the plastic material caused by a combination of design and manufacturing defects related to the thread and the material used to make the nuts[4].

In the subject investigation, the authors were provided with 447 water supply lines with a common use history. Installation involved connecting the lines to residential toilets. The installation was within new home construction in a single neighborhood in South Florida. They were removed by the plumbing contractor after three identical supply line nut failures occurred within two years of installation.

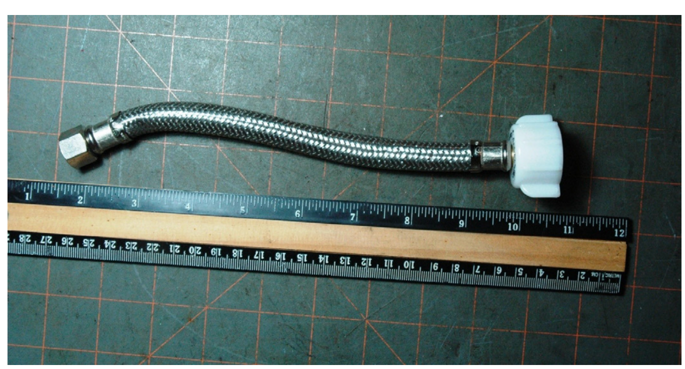

Figure 1
As-received photo of toilet supply line.

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Non-destructive and destructive techniques were used to detect cracks. Nuts with cracks were then inspected using optical microscopy and SEM. The stress concentrations in the threaded connection where the cracks originated were the relative stress concentrations in the threaded connection that was qualitatively modeled using Finite Element Analysis (FEA) to determine regions of high stress.

Fourier-transform infrared spectroscopy (FTIR) was performed on the subject nut to identify the polymer. It was determined that the material was polyoxymethylene (acetal).

Scope of Work

The following tasks were performed:

- Examination of plastic nuts that had been in service for approximately two years.
- Optical microscopic examination of the nuts to determine the presence of tool marks.
- Excluding nuts with any surface marks.
- Application of liquid dye penetrant to the interior of the nuts that had no tool marks.
- Cutting some of the dyed nuts in cross-section.
- Applying a torque to some of the dyed nuts to cause overload failure.
- Examination of the fracture surfaces of the failed nuts using an optical microscope.
- Examination of the fracture surfaces of a subset of nuts with cracks using SEM.
- 3D modeling and qualitative FEA.

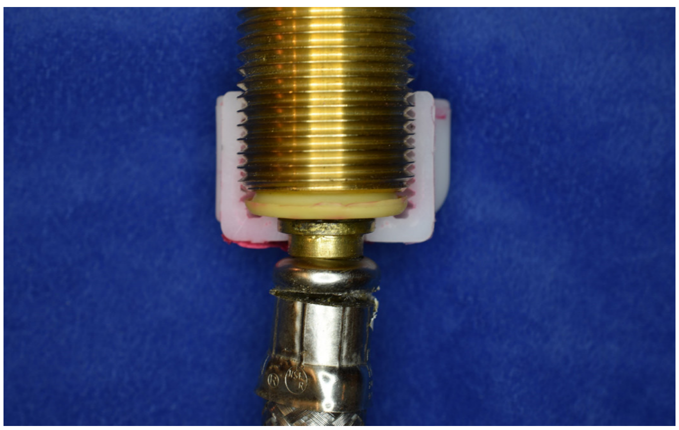

Figure 2
Cross-section showing connection to male-threaded fitting at base of toilet tank.

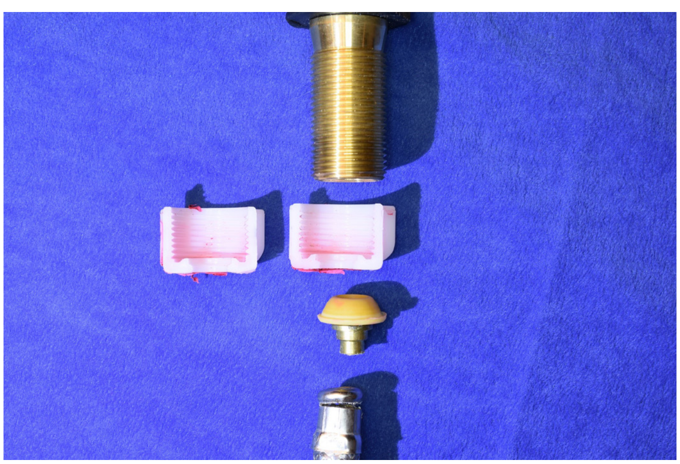

Figure 3
Exploded view of cross-section of connector components.

Observations

In use, the toilet connector threads onto a male pipe at the bottom of the toilet tank, compressing a rubber gasket between the interior surface of the connector and the end of the male pipe to prevent water leakage (**Figures 2** and **3**). The contact between the end of the male pipe and the connector creates an outward-directed longitudinal force on the interior surface of the connector. This force creates a shear stress and bending moment within the wall of the connector, with the highest stress located at the interior surface at the bottom of the wall (as shown in **Figure 4**). In addition, the threaded wall of the cap is subjected to a

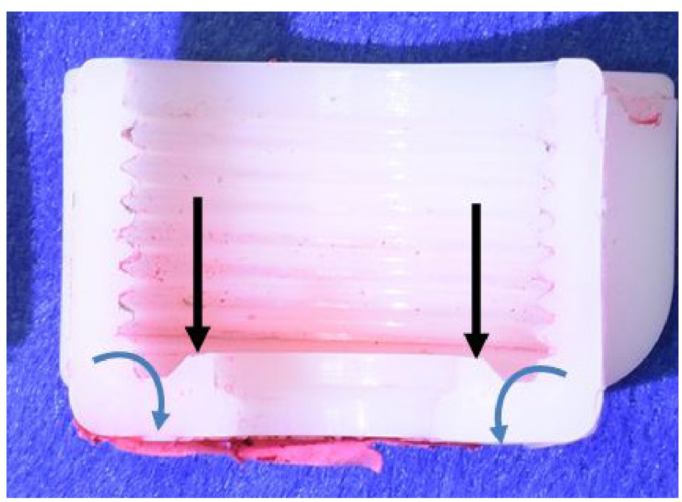

Figure 4
Cross-section of nut with crack, showing force and bending moment at end-cap.

combination of shear and radial stresses from the threaded connection.

The interior thread extends to the base of the cap. The sharp-edged roots of threads are known as stress risers, which lead to local stress concentrations many times greater than the stress that would be present without the stress riser[5]. **Figures 5** and **6** show a cross-section of a nut examined during this investigation that revealed the presence of a crack that formed at the root of the base thread, as predicted by static analysis of the applied forces and illustrated in the output of FEA performed during this investigation (shown in **Figure 7**).

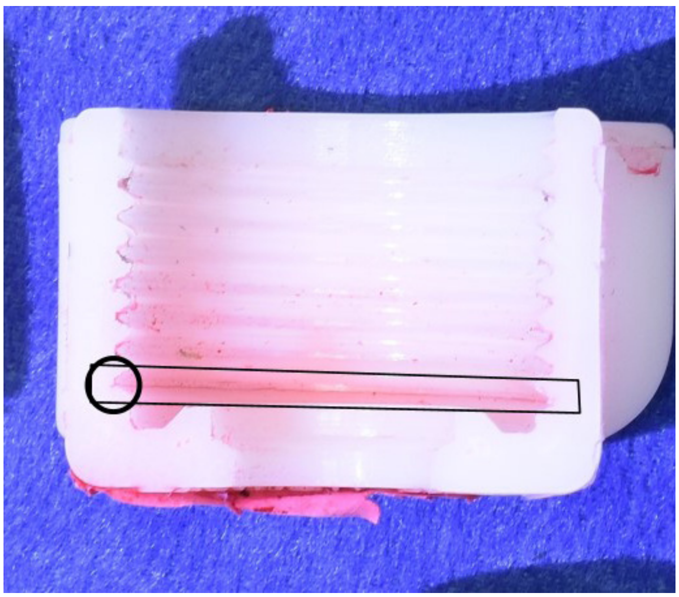

Figure 5
Cross-section of nut, showing crack at root of base thread.

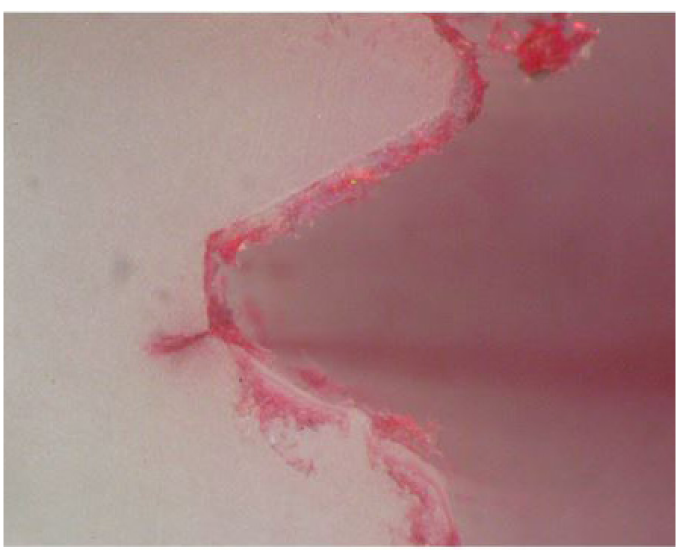

Figure 6
Close-up of crack in cross-section.

FEA was conducted to provide qualitative predictions of stress risers and their locations relative to the internal thread profile. Several sample nuts were cross-sectioned on various planes to facilitate detailed measurements and the internal geometry of the nut. These measurements were used to create a three-dimensional mesh model of the plastic nut.

FEA analysis was performed using a standard simulation software. The geometry of the fitting was based on measurements of a cross-section. Material properties were obtained from material datasheets. A tensile force was applied to the base of the fitting. The goal was not to determine stress values but to identify the most probable location for stress risers in this type of loading. The static simulation performed on the resulting model revealed a stress riser in the root of the base thread of the nut (**Figure 7**), consistent with both the physical findings and predictions based on engineering mechanics.

Since these nuts are made of an acetal resin plastic, they are susceptible to creep — the mechanism by which

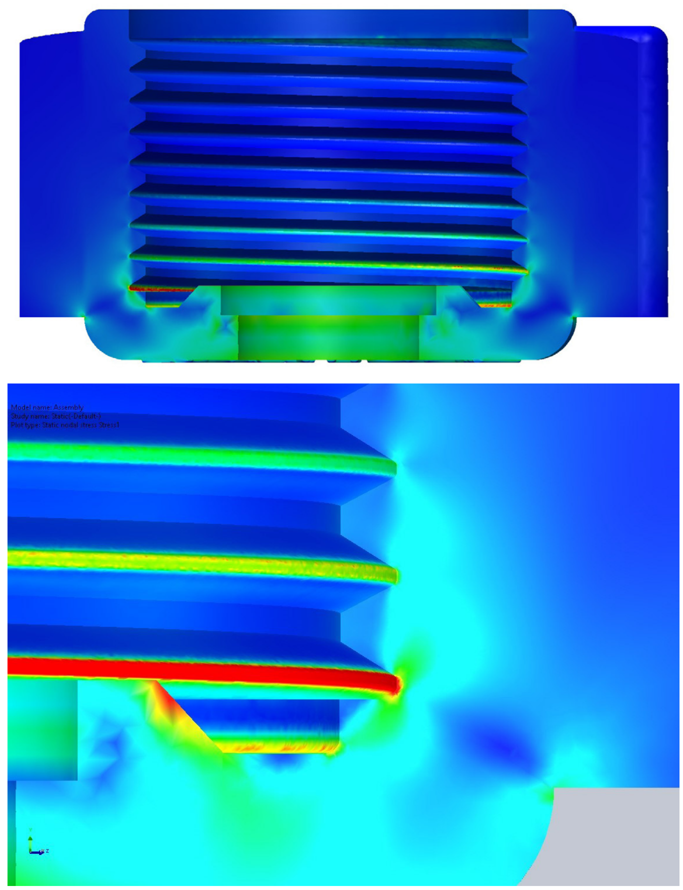

Figure 7
Qualitative FEA image, showing peak stress at root of base thread in red.

Figure 8
End of nut embossed with instruction to "hand tighten only," which has been colored for this photograph.

a plastic material will deform over time when subjected to a continuously applied load[6,7].

The subject nut in the original case appeared to have tool marks on the outer surface. Experts opined that the nut had been over-torqued, causing creep to occur and leading to the failure. Raised lettering on the end of the nut cap stated "HAND TIGHTEN ONLY" (**Figure 8**). However, this is not a reliable or accurate torque specification. Several studies have identified many factors that determine torque when hand tightening a nut[3,4], including age, gender, strength of the individual doing the tightening, and the location of the nut being tightened. Arguably, this means there is no torque specification for these nuts.

Figure 9
Composite photograph of cross-section of subject nut; interior thread ends at a notch in the upper left of image.

Investigation

The subject nut was examined by experts retained by the parties involved. The joint examination included visual examination under optical microscope and SEM. **Figure 9** is a composite photograph of the fracture surface of the subject nut. Failure initiated at the notched end of the interior thread at the base of the fitting, consistent with the location of the highest stress as shown by FEA.

Fortunately, the number of fittings that had been installed in the previous two years by the plumbing company involved were removed from service. As part of the forensic investigation, the supply lines were sent to the laboratory for inspection. A non-destructive technique called Liquid Dye Penetrant (LDP) testing was used to determine if any of the previously installed nuts possessed cracks[10].

This technique uses dye applied to the interior threads of the nuts. If a crack exists, the dye will migrate into the crack surface by capillary action and then can be detected visually or with a microscope. Post Emulsifiable Red Dye Penetrant was sprayed on the interior surfaces of the sample nuts, according to the directions of the manufacturer. After a 30-minute dwell time (to allow the dye to penetrate any small cracks in the sample), the dye was removed using soft cotton swabs followed by a small cotton tip to ensure there was no dye remaining on the internal threaded surfaces. Each nut was numbered and documented.

During the first phase of the investigation, 43 fittings were cut in cross-section. Incipient cracks were present at the root of the base thread in 11 of these, as seen in the sample shown in **Figures 5** and **6**. The onset of cracks in 25 percent of the samples with no evidence of tool marks, along with the three prior known failures of the same parts associated with this installation, provided strong evidence of a design or manufacturing defect specific to this lot of fittings. At this point in the study, deposition testimony was provided by experts for the various parties, and the suits were settled.

After the resolution of the legal cases, the authors decided to continue the investigation. The initial approach was modified by developing a method to expose the fracture surface. To do so, a hole in the shape of the nut was machined into a block of wood, and the male thread from a toilet fixture was attached to the socket of a torque wrench with epoxy. Using a calibrated torque meter, 0 to 600 inch-pounds, each nut was torqued to failure,

Figure 10
Torque wrench and nut in wood block.

and the load required to do so was recorded (**Figures 10** through **12**). The required torque to cause the part to fracture ranged from 14 to 22 nanometers (nm) 125 to 200 inch-pounds, consistent with data reported by Timpanaro, Shcerzer, Keifer and Eason[4], who reported torque values of 16.9 to 26.8 nm (150 to 237 inch-pounds).

The thread base of an additional 100 supply line nuts was then examined microscopically to determine if any cracks had started over the two-year in-service period. These nuts had no signs of tool marks. As shown in **Figures 13** and **14**, Sample #17 had red dye penetrant on the inside of the fracture surface, indicating the presence of a crack. Of the 100 parts examined in this phase, 10 were found with cracks at the base of the last thread, corresponding to a crack formation rate of 10 percent.

The fracture surface of Sample #17 was examined by means of Scanning Electron Microscopy, using an

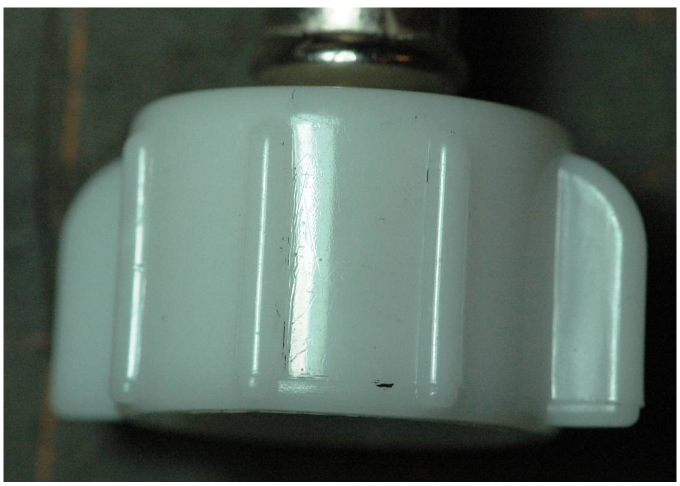

Figure 11
Before torque to failure — no tool marks.

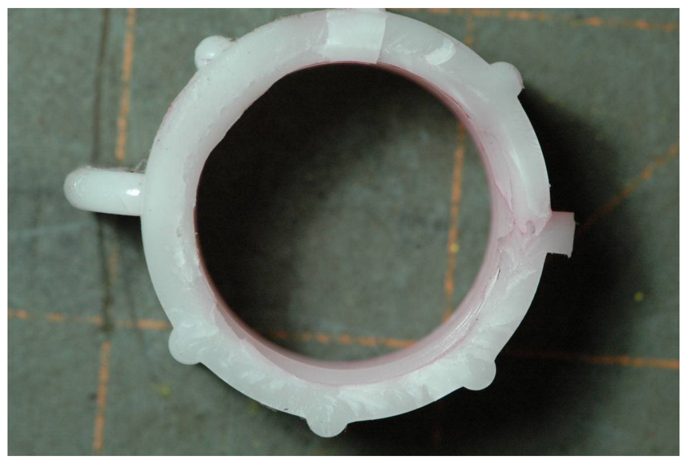

Figure 13
Fracture surface of Sample #17.

Figure 12
Torqued to failure.

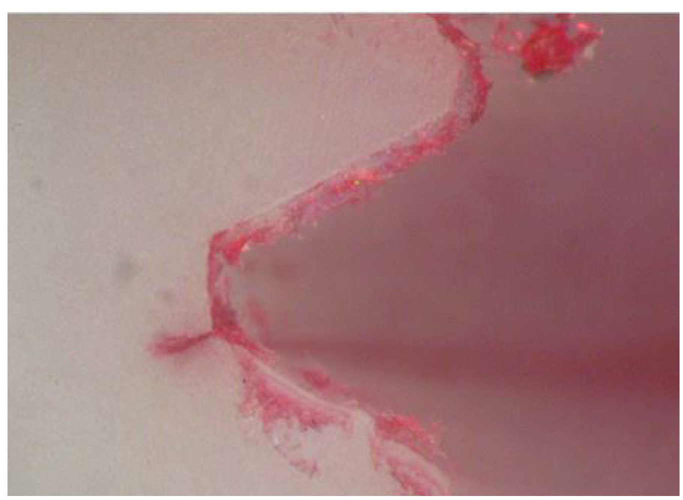

Figure 14
Red dye penetrant in crack on the fracture surface of Sample #17.

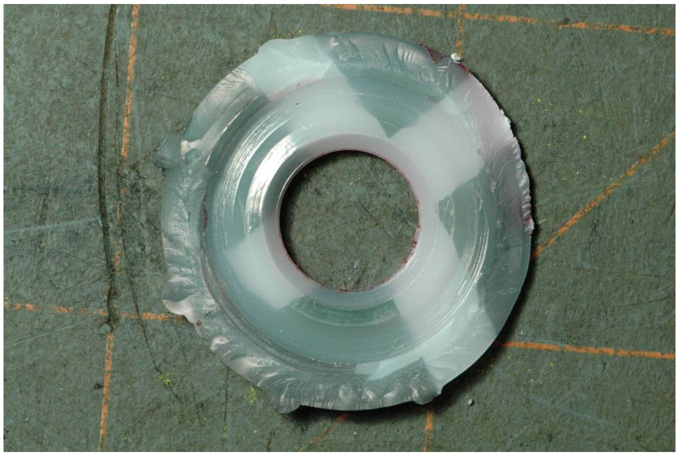

Figure 15
Sample #17, sputter coated.

analytical SEM. The fracture surface was imaged in an uncoated state, using a 5kV accelerating voltage, and spot size of between 96 and 117 nm with the average spot size of 100 nm with a resulting absorption current of 0.58 pascals, to avoid sample charging. After imaging the fracture surface at multiple magnifications, the sample was removed and coated with gold, using a vacuum sputtering system (**Figure 15**). The sample was placed back in the analytical SEM, and the series of fractographs was replicated with respect to location and magnification, at 5kV accelerating voltage, and slightly higher absorption current to illustrate the ability of gold coating to permit higher quality imaging (without changing the features and morphology of the fracture surface). Note that at 20,000 times magnification, the gold coating is invisible

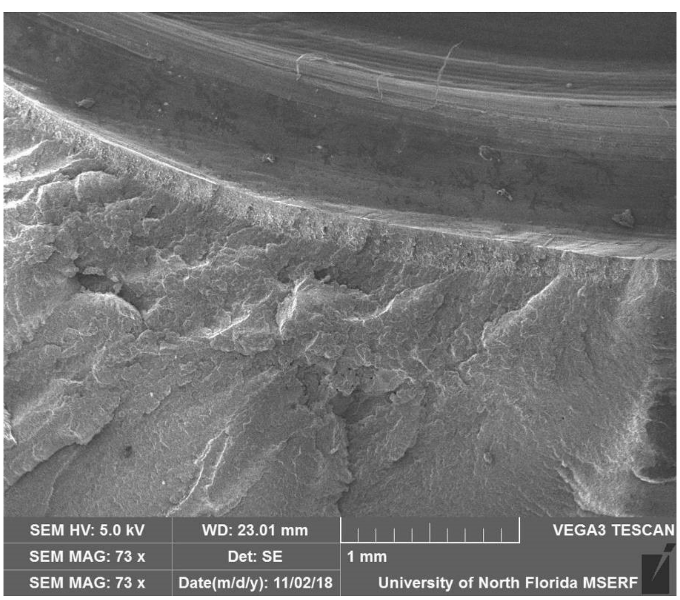

Figure 16
Medium magnification, Sample #17.

to the viewer, as its thickness of approximately 50 angstroms falls below the resolution of the microscope.

The SEM images after gold coating clearly show two different types of fracture morphologies present in the surface of the same sample. One has plate-like fracture zones corresponding to a fast overload fracture achieved with the torque wrench, while the other (crack that visually showed as red in color) has a tufted appearance associated with sustained loading over time, resulting in creep rupture morphology. See **Figures 16** through **20**. Under sustained

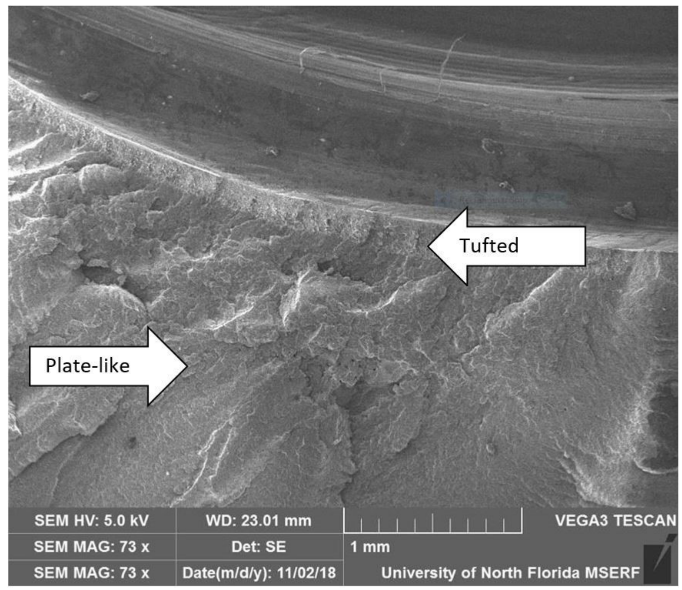

Figure 17
Medium magnification, Sample #17,
gold coated showing fracture morphologies.

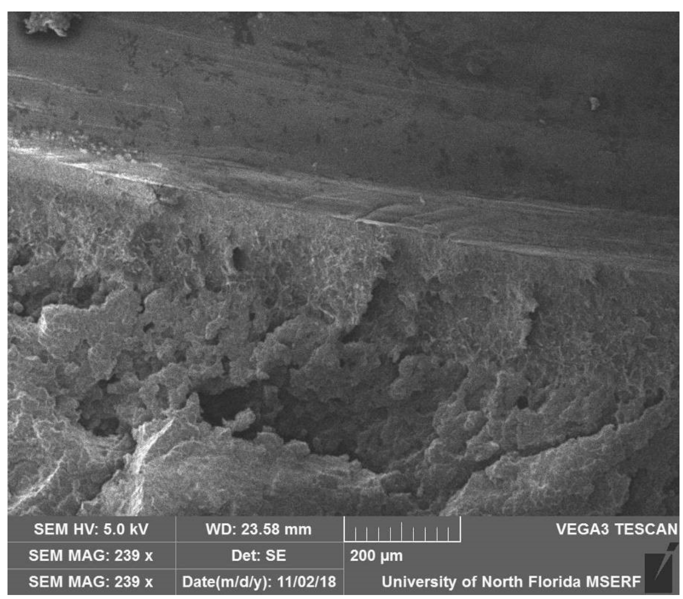

Figure 18
Higher magnification, Sample #17.

loading, this material undergoes slow, stable crack extension, resulting in the development of a tufted fracture surface appearance. These tufts represent fibril extension and subsequent rupture in various polymers[9].

SEM was also performed on two more cracked parts, Sample #9 and Sample #27, which were picked at random from the 10 parts with visible cracks. The SEM photographs for these two samples reveal the same two types of fracture morphology (plate-like and tufted), as described above and shown in **Figures 21** through **24**.

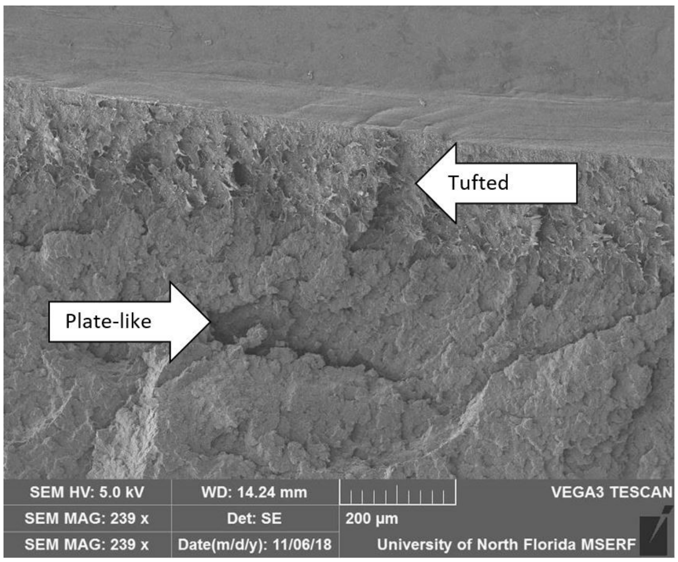

Figure 19
Higher magnification, Sample #17,
gold coated showing fracture morphologies.

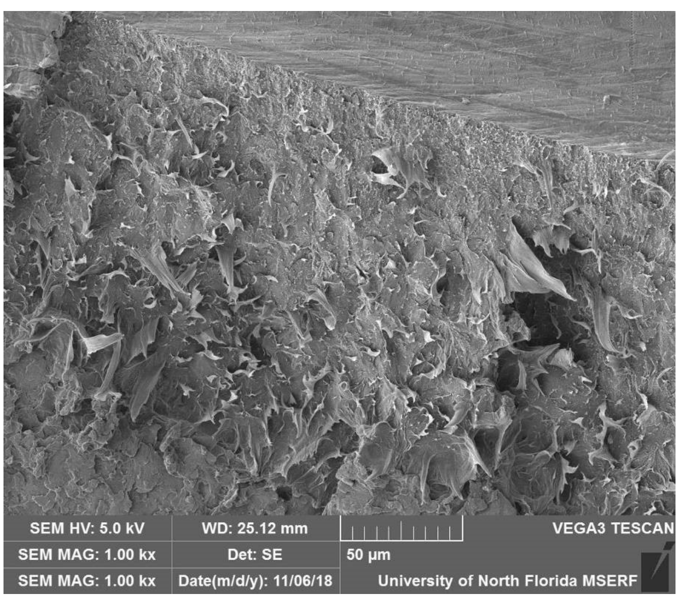

Figure 20
Even higher magnification, Sample #17,
gold coated showing tufted appearance of fracture surface.

The authors also attempted to quantify the meaning of "hand tighten" as applied to the installation of these nuts. The torque recorded during the hand tightening tests was within the range of 2.0 to 3.4 nm (18 to 30 inch-pounds), consistent with data reported by Timpanaro, Shcerzer, Keifer, and Eason[4], who reported torque values of 1.1 to 3.4 nm (10 to 30 inch-pounds). When compared to the torque to cause overload failure, the values are approximately seven times the values achieved by hand tightening.

Conclusion

This study provided a unique opportunity to examine

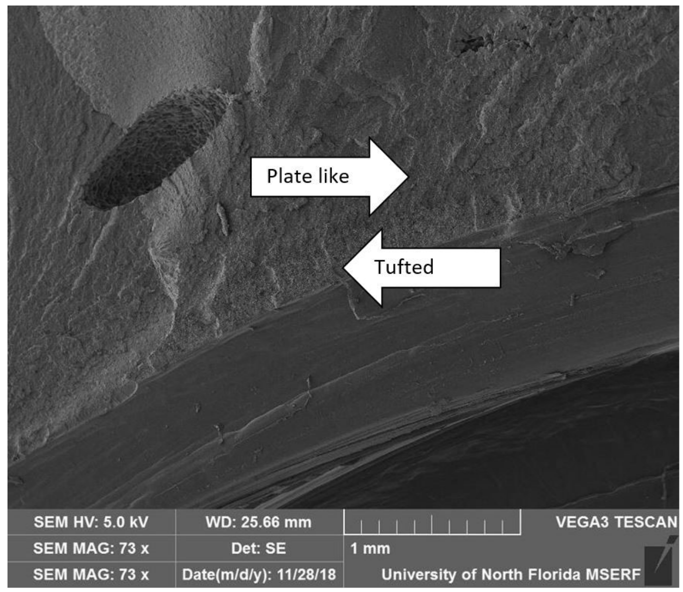

Figure 21
Sample #9, medium magnification.

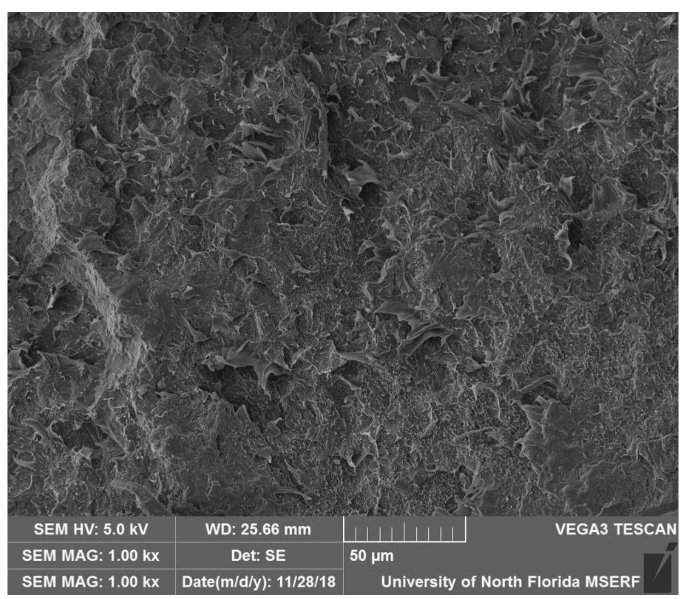

Figure 22
Sample #9, higher magnification of tufted area.

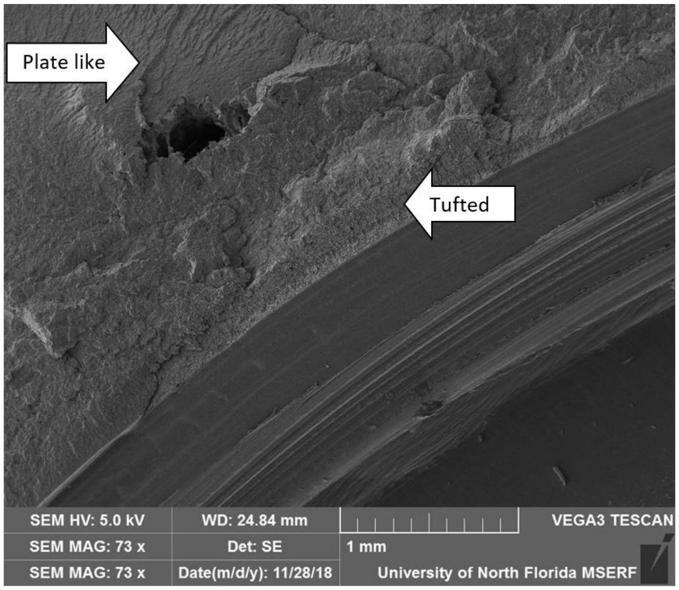

Figure 23
Sample #56 with two fracture morphologies.

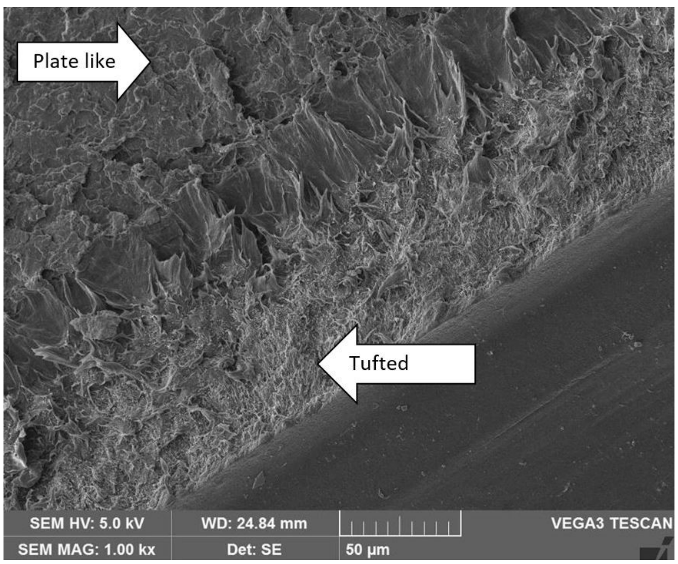

Figure 24
Sample #56 at higher magnification.

a statistically relevant sample size of acetal resin toilet nuts that had been subjected to remarkably similar installation and in-service conditions. They were installed by the same plumbing contractor, in the same newly constructed neighborhood, and had the same water supply. Additionally, they were all removed at the same time after approximately two years of service.

In this investigation, 143 fittings with no evidence of external tool marks were examined after the application of liquid dye penetrant to the interior threads. Of these, 43 were cut in cross-section, and cracks were observed in the base thread in 11 samples, corresponding to a rate of crack formation of ~25 percent. An additional 100 fittings were torqued to failure, exposing the entire fracture surface. Of these, 10 percent had cracks at the base thread. Thus, based on these two different studies, the rate of crack formation in these plastic nuts was concluded to be in the range of 10 to 25 percent (**Figure 25**). In addition, there were three known failures of nuts during the two-year period these fittings were in use.

Method	Number Examined	Crack Frequency
Cross Section Cut	43	25%
Torque to Failure	100	10%

Figure 25
Number of samples and crack frequency.

The torque achieved by hand tightening was approximately seven times less than the torque required to cause the nut to fracture in overload. Of the nuts examined in which there was no evidence of tool marks, the high rate of crack formation indicates that cracks formed even when the nut was hand-tightened — and that crack formation did not require installation with a tool.

Although this is well known in the industry, it bears repeating in this study. SEM was performed on cracked areas. It was observed that gold coating presents clear advantages in fracture surface imaging and causes no deleterious effects on the surface morphology. The 10-nm layer of conductive material protected the polymer sample from the highly energetic beam during its interaction with the sample.

The SEM study revealed the presence of a tufted surface morphology, which is associated with slow stable crack extension due to sustained loading over time defined as plastic creep[8,9].

This study confirms that these acetal resin plastic toilet nuts were prone to crack formation by creep deformation with no evidence of over-tightening. All cracks formed at the root of the base thread, which served as a stress riser at the location of the greatest stress in the part. This failure mode is recognized and warned against by manufacturers of acetal resin plastic. Consequently, it is the opinion of the authors that the crack formation in these nuts was the result of a defective design of the thread geometry and the inappropriate use of acetal resin plastic for the material of construction. Notably, this part is no longer available in the United States.

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