Advanced Analysis Techniques for Root Cause Polyurethane Failure

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Abstract

Determining the root cause of premature failure in a polyurethane part requires analysis of the physical, mechanical, and chemical nature of the failure.

In this paper we will review common analysis for basic type failures as well as new advanced capabilities to determine root cause of the failures. We will also provide real world examples of failure root cause analysis which include mechanical and chemical failures. These failures will range from the most simplistic mechanical failures to extensive failure analysis that require advanced mechanical and analytical techniques. These include Finite Element Analysis (FEA), Fourier Transform InfraRed (FTIR) spectroscopy, Scanning Electron Microscopy (SEM), and Nuclear Magnetic Resonance (NMR).

Introduction

Striving for perfection is the goal of every manufacturing organization. The implementation of engineering controls, personnel training, and quality assurance procedures helps to reduce the number of quality control incidences. Figure 1 illustrates a common root cause analysis technique to identify all possible causes when a failure occurs. These can range from process-related, both operator and machine, to materials, to even design flaws, making the ability to correctly identify the root cause of a failure or insufficient performance of a part a critical task.

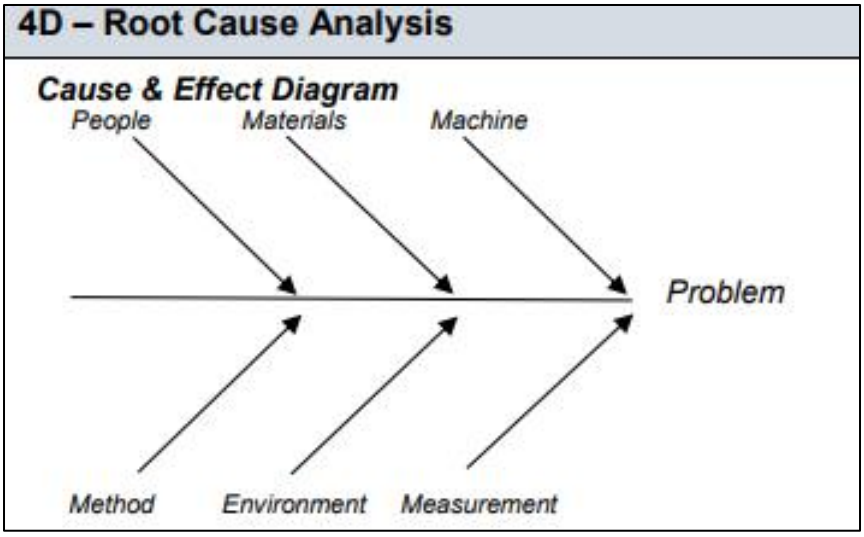

Figure 1: Common 8D Quality Root Cause Analysis "Fishbone" Diagram

Some issues that may result in potential failures are found in the early processing stages. Others are difficult to detect until parts have already reached the field. In every case, it is necessary to know the tools and techniques that are available to assist in failure root cause analyses and implement the proper corrective actions at the appropriate level. Urethane systems can be complex with many variables that play into how a part performs. Therefore, a variety of analytical methods may be required to determine which variables are contributing to a failure. Table 1 provides a brief overview of methods discussed in this paper and summarizes their benefits and limitations.

Method Name	Main Applications	Benefits	Limitations
Fourier-Transform Infrared Spectroscopy (FTIR)	PU Backbone determination Evaluation of contimant Presence of adhesives, mold release, etc Ratio	Quick/simple test Relatively low cost	More qualitatitive than quantitative in many cases
Nuclear Magnetic Resonance (NMR)	Composition analysis Evaluation of contaminants Ratio	High resolution spectra More detailed and conclusive than FTIR	Prohibitive cost/size Highly skilled analysis
% Chlorine	Ratio (MOCA or MCDEA cures)	Robust and repeatable Direct measurement of curative	Requires special equipment and skilled analyst Limited to MOCA & MCDEA cures
Scanning Electron Microscopy (SEM)	High resolution imaging Elemental mapping Composition Analysis Visual inspection of defects	Powerful optics tools Built-in measurement capabilities Cost is becoming more reasonable	May need to be combined with other methods for conclusivity
ASTM Physical Properties	Validation of parts/properties	Can indicate processing issues Feasible equipment for many processors to have ASTM methods exist for definition	Physical properties aren't always indicative of key performance areas
Dynamic Properties	Validation of parts/properties Application simulation	More applicable to part performance in cyclic or dynamic applications	Requires understanding of dynamic properties (tan δ, G') Sensitive equipment
Finite Element Analysis (FEA)	Material behavior predictions Design evaluations Determination of engineering criteria (stress/strains)	Quicker for iterative design ideas Saves costs on prototyping	Software can be costly Analysis can be time-consuming to set-up Characterizing elastomers can be challenging Requires skilled personnel

Table 1: Summary of Analytical Methods and their uses, benefits, and limitations

Fourier-Transform Infrared Spectroscopy (FTIR)

Fourier-Transform Infrared Spectroscopy is a tool used to gather a spectrum of the absorption vs. frequency of infrared light as it passes through a specimen. This spectrum can be analyzed to determine compositional information about the sample in question. Analyzing the spectra in any depth requires training and study, but it is possible to make the process user-friendly with the generation of a reference library of known compositions to match unknown samples against. Simply creating reference traces of incoming raw materials and outgoing formulations is enough to get a library started. Continually adding environmental exposures, process related variances, or known errors will quickly build a valuable set of spectra to compare against. The instrumentation is relatively size and cost efficient, and the process to generate the spectrum of a specimen is very straightforward and only requires a small sample amount to cover the diamond cell, as shown in Figure 2.

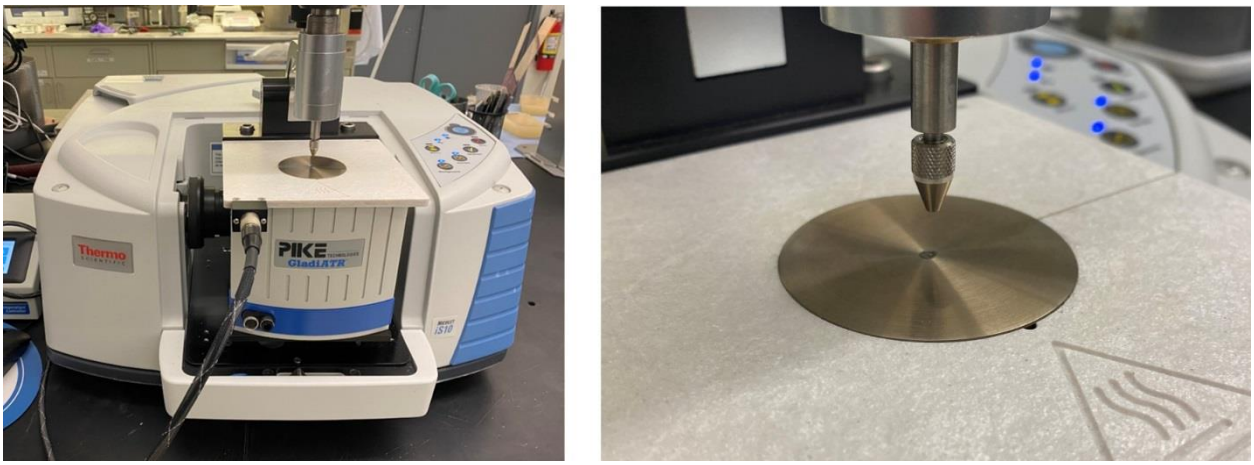

Figure 2: FTIR Instrumentation and collection area

FTIR Case 1: Material Identification

The most common application for FTIR is identification of an unknown material sample. In the design stages of a project it is commonly used to evaluate an incumbent material as a benchmark. In a failure analysis it is often the first step to verify the stated identity of the failed material. There have been cases where an ether-based part failed quickly in a humid or water-rich environment only to find out that the failed part came back as an ester-based PU leading to degradation due to hydrolysis. Given the busy nature of a production environment, mix-ups are possible and traceability is easy to lose once parts are shipped and put into the field. Being able to confirm material identity is always an important place to start in a failure investigation. An general example is shown in Figure 3, where an unknown sample is analyzed and strongly matched to reference spectra indicating it is a TDI PTMEG prepolymer cured with MOCA. This information can then be used to determine a material system equivalent or decide if a superior material choice exists that may improve performance.

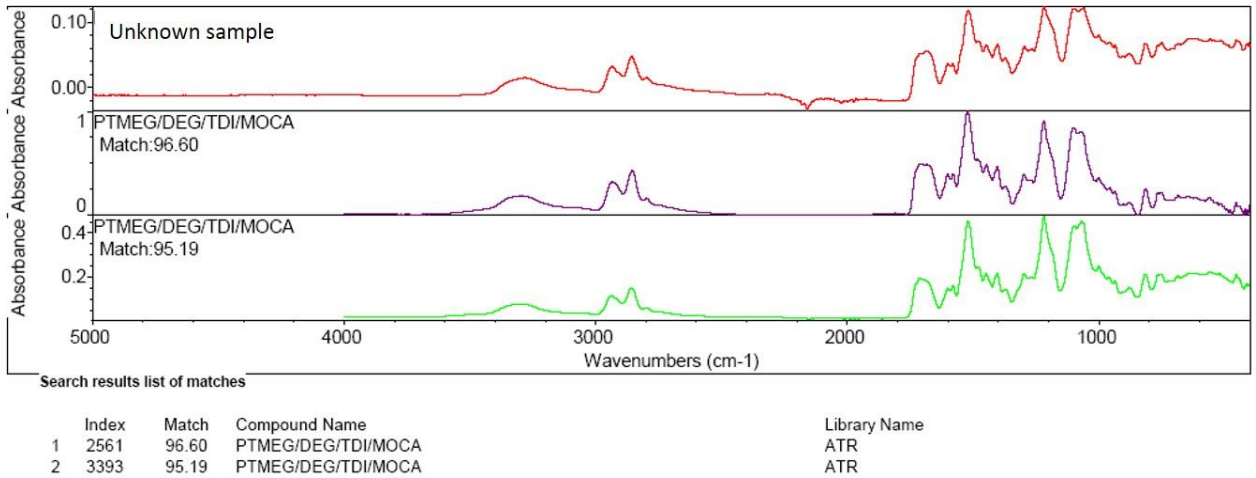

Figure 3: Example of an FTIR spectra and library match.

FTIR Case 2: Evaluation of an Unknown Contaminant

FTIR has built-in manipulation tools to assist with generating matches or to help with the evaluation of a sample. One common technique is spectral subtraction, which allows the user to subtract the trace of a known component present in the sample to isolate an unknown component. This can then be analyzed or matched independently. These techniques allow FTIR to be applied towards the evaluation and identification of possible contaminants and unknown artifacts within a PU sample. For example, a prepolymer sample was submitted with spherical particles throughout the liquid material (Figure 4). These were noticed after loading material into tanks but before processing. FTIR was utilized as a first step in attempting to identify the particles to direct the investigation to which analyses might be needed. However, this step proved more conclusive than originally intended. Analyzing the spectra compared against a control of the known prepolymer type showed a reduction in the peak around 2300cm^{-1} relating to unreacted NCO and an increase in peaks associated with urea chains forming. As no curative was present in the system, a second comparison spectra of a similar prepolymer cured with moisture was added. Utilizing spectral subtraction, those peaks were shown to be indicative of gelling and curing due to moisture. Drops of moisture were suspected of creating localized gelling within the prepolymer. This could be recreated and additionally confirmed that the spherical nature of the particles, which at first was still unexplained, was found to be related to the agitation of the material. This resulted in the “polishing” of these gelled areas as they tumbled through the tanks.

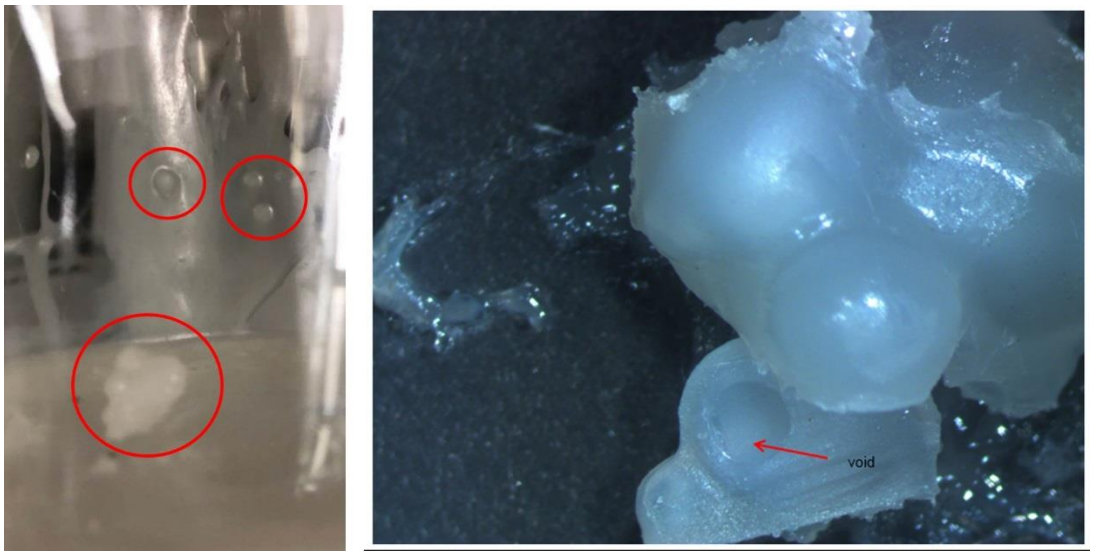

Figure 4: Image of spherical particles (left) and under magnification (right)

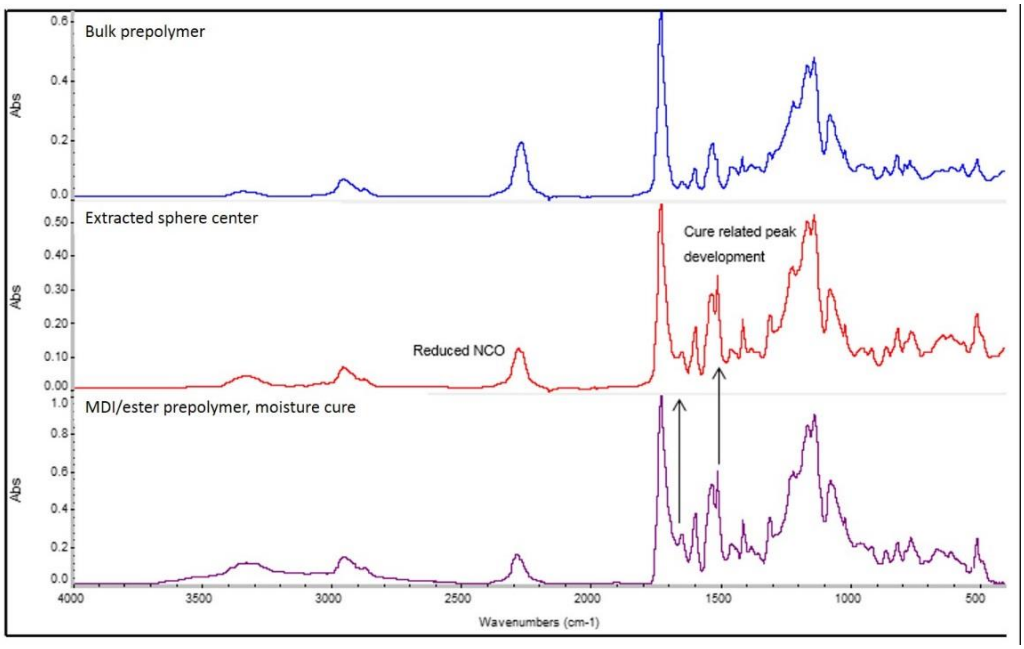

Figure 5: FTIR trace of particles, compared with bulk prepolymer and moisture cured prepolymer

FTIR Case 3: Evaluation of Part Defect

In a part presenting with cracks and voids (Figure 6), surface scrapings from the inside of the voids were analyzed and subtracted from a trace of the urethane itself. Searching for a match to this trace showed the presence of polydimethylsiloxane (PDMS), indicating that excess mold release was likely present at the time of molding. Based

on similar failures observed in the past, the excess mold release was likely trapped during the casting operation causing the formation of cracks and voids during the curing process.

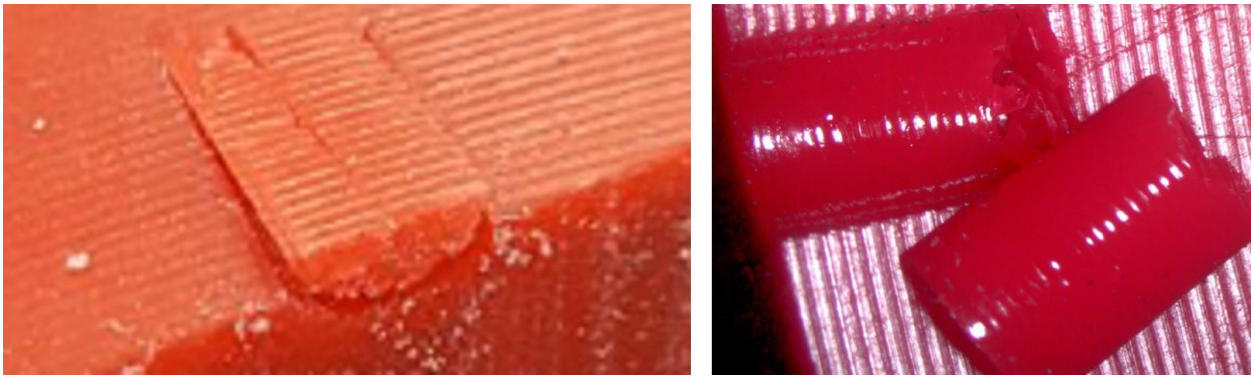

Figure 6: Image of crack defect on surface of part (left), sample preparation isolating the inside of the void inside the crack (right)

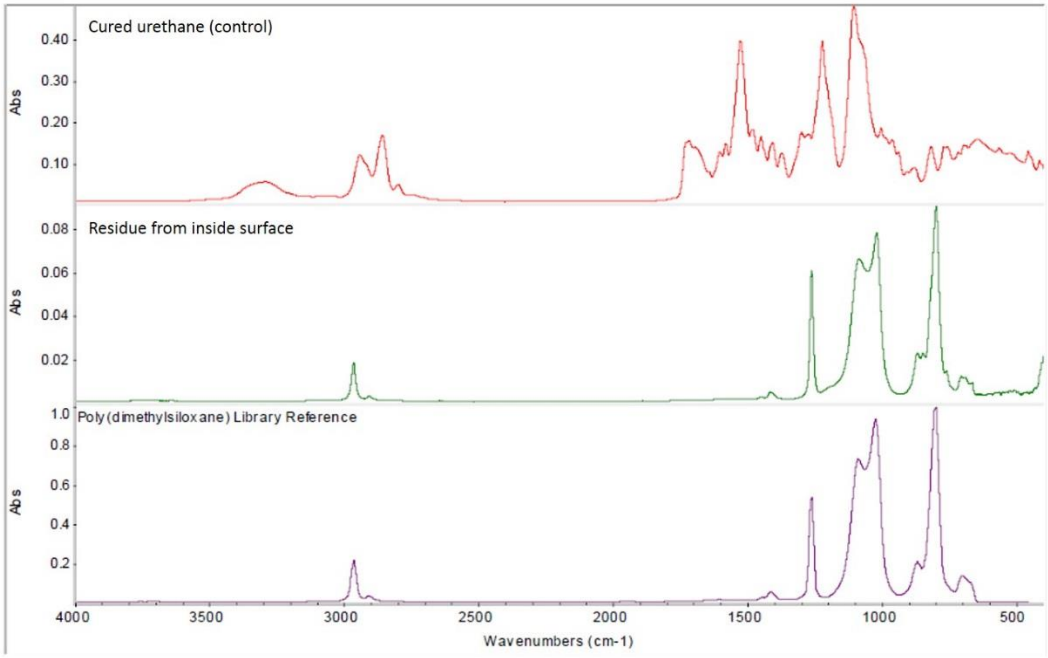

Figure 7: FTIR comparison showing the residue from the inside surface of the crack matched to PDMS

FTIR Case 4: Tires & Wheels

Comparable analyses are often performed on the surfaces of wheel hubs to check for the presence of bonding agents or mold release at the site of bond failures, or from the surfaces of parts where unknown contamination is present. For example, an unknown film-like sample was taken from the surface of a wheel on two separate occasions. FTIR analysis assisted the determination of two distinct root causes in these two cases that presented similarly.

In the first instance, the film was found to be polyethylene. This likely was a piece of the packaging from the wheel that was not removed properly and had melted to the surface of the wheel as it heated up due to use.

In the second, the film was proven to be the same composition as the urethane wheel. Running additional wheel capacity calculations indicated a potential risk for hysteretic blowout failures. This can result in overheated urethane from the center of the cross-section escaping and coating the track. The wheel subsequently ran over this urethane on its next pass and created the film on the surface. Proving the film to likely have originated from the wheel itself pointed to the wheel being underdesigned or overloaded. The design was then adjusted and the max load and speeds were re-communicated to the end user before a higher quantity of failures occurred.

FTIR Case 5: Ratio Analysis on Failed Part

FTIR can be used to determine whether a part is off-ratio, especially if the theory is off by a significant amount. Typically, calibration curves or control samples are needed to give a quantitative result. In one recent example, users noticed that molded parts did not “feel” or “behave” correctly when handled. Most noticeably, the parts were observed to crack and break apart by hand when flexed. Typically this type of behavior could be indicative of a material issue or parts being processed far off-ratio. As part of the investigation, control samples were cast at 50%, 70%, 95%, and 130% for use during the analyses required. Figure 8 shows the N-H and C-H regions of the FTIR trace. A trace of the curative is also shown corresponding to peaks in the original sample related to the amount of curative present.

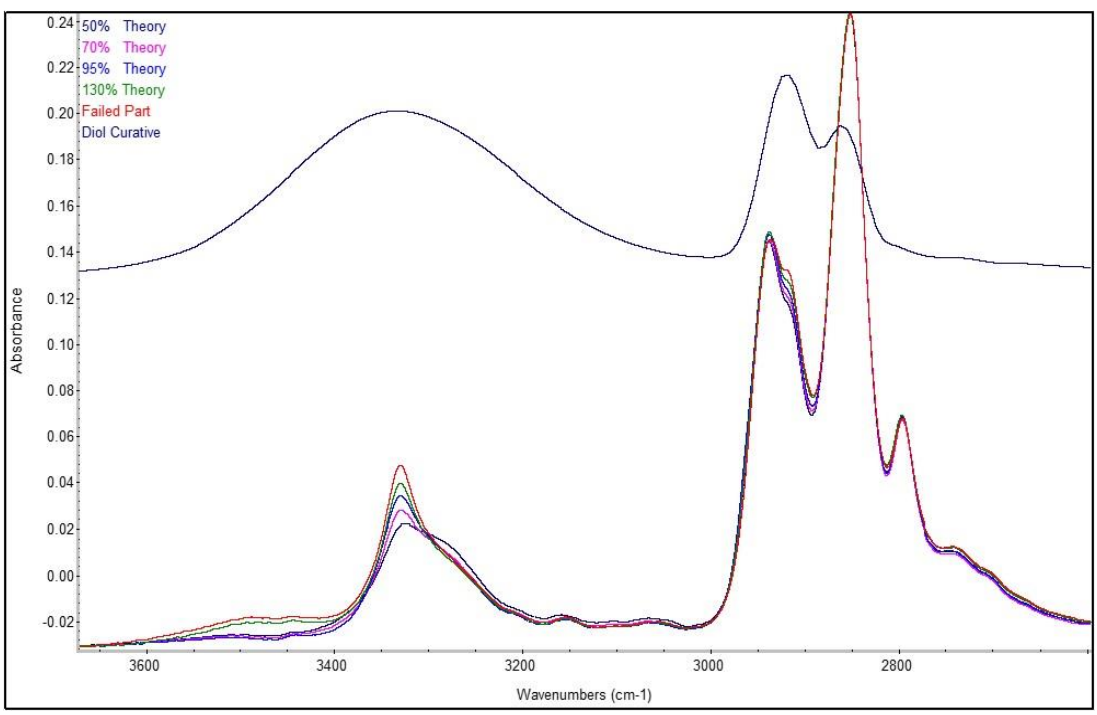

Figure 8: N-H and C-H stretch of FTIR trace for controls and failed part. Trace of curative is overlaid above with corresponding peaks

In this case the diol curative has a strong absorbance near 2917cm^{-1}. This peak is related directly to the "backbone" structure, independent of cure. As shown in Figure 9, this peak intensifies as cure theory is increased. A calibration curve can be generated by measuring the absorbance for this peak and dividing by the total C-H peak near 2900 cm^{-1}, shown in Figure 10. This allows the estimation of the ratio of the failed part, which given how much excess curative is indicated was likely "double-dosed" with curative resulting in a ratio well above the 130% control.

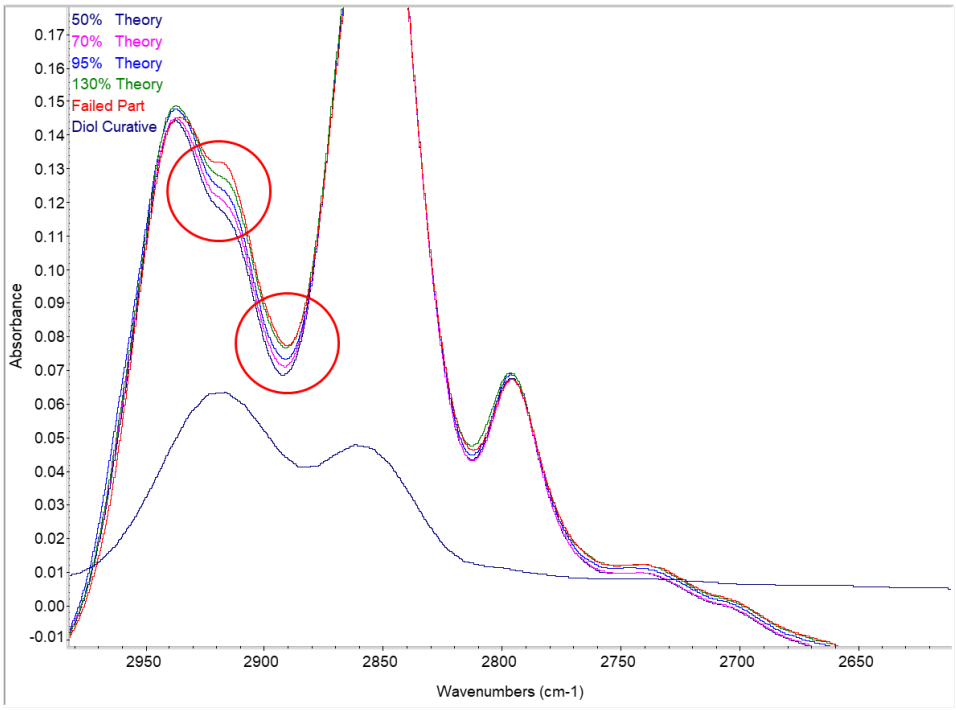

Figure 9: Zoomed in FTIR trace on Diol Curative peak

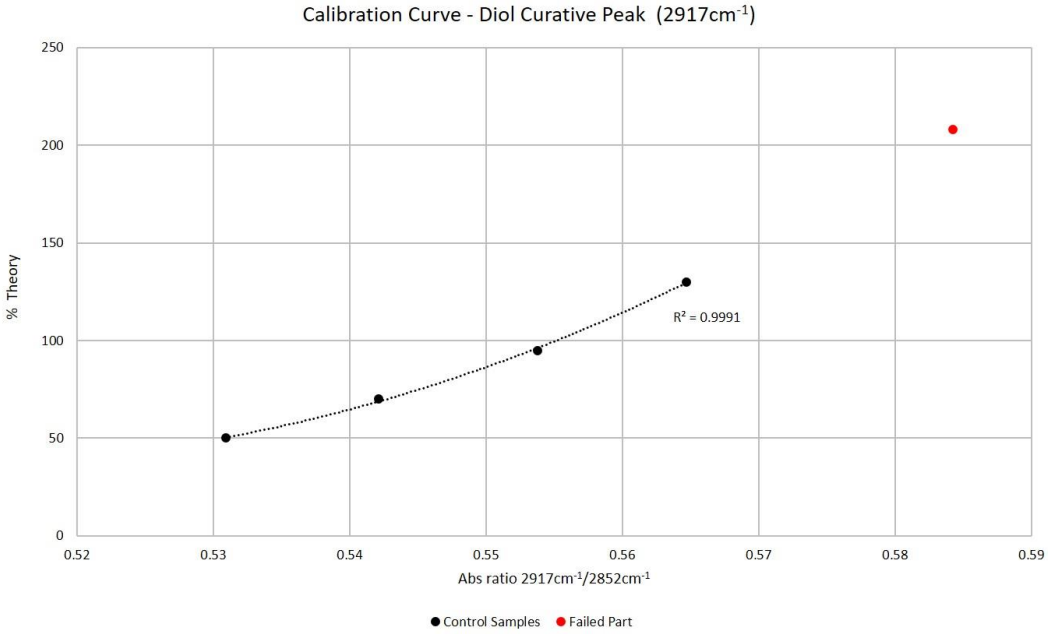

Figure 10: Calibration curve of curative peak

A similar approach can be used for the urethane N-H peak developed during cure as shown in Figure 11, and a similar calibration curve generated in Figure 12. This calibration suggests the failed part was over 170% theory, consistent with the double-dose theory.

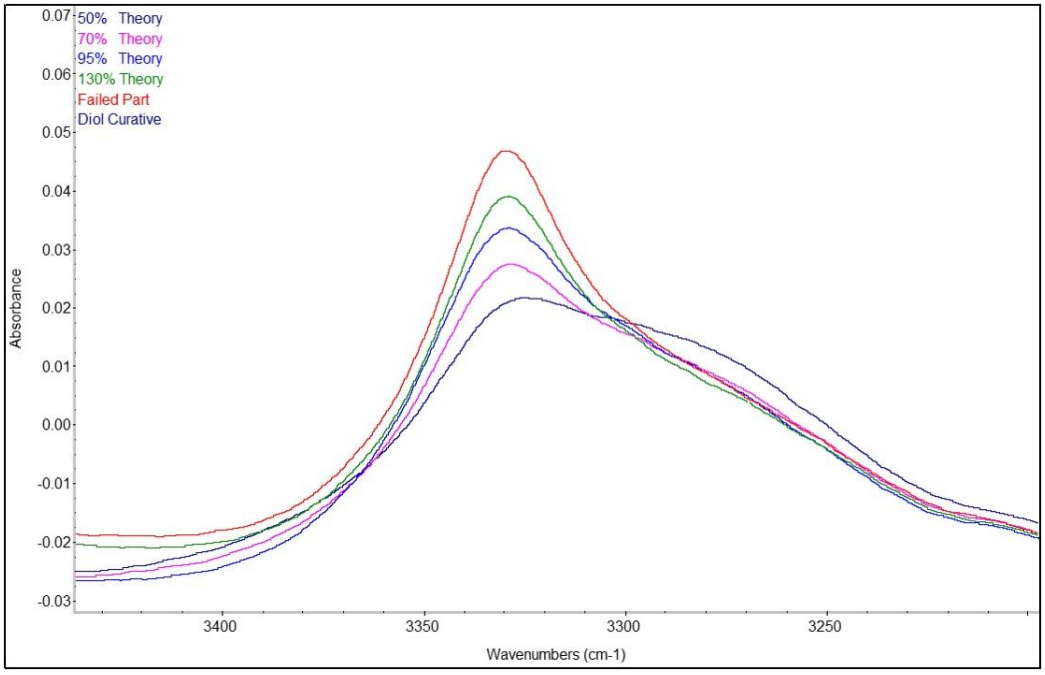

Figure 11: N-H peak from FTIR trace

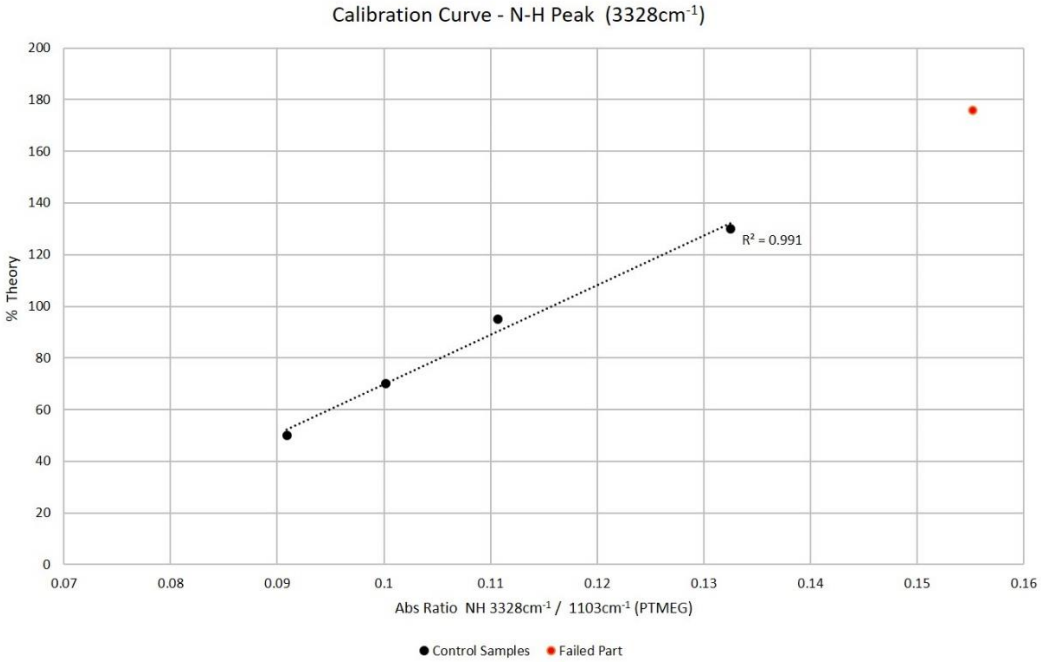

Figure 12: Calibration curve from N-H peak

Nuclear Magnetic Resonance (NMR)

While FTIR analysis is versatile and can provide useful analytical information as shown in the previous examples, often there is a need for higher resolution analysis that results in additional detail. Nuclear Magnetic Resonance (NMR) has become a valuable tool building on the information available analyzing by FTIR through additional capabilities including:

- High resolution spectra allowing for more detailed composition analysis, including specific backbones and mole ratios of polyols (Figure 14)
- Identification of components with smaller or trace amounts
- Able to quantify percentage of components, allowing for ratio analysis or determining additive levels
- Evaluation of contaminants or unknown material
- Compare urea group levels between good and questionable samples to determine hydrolysis

Figure 13: NMR Instrumentation

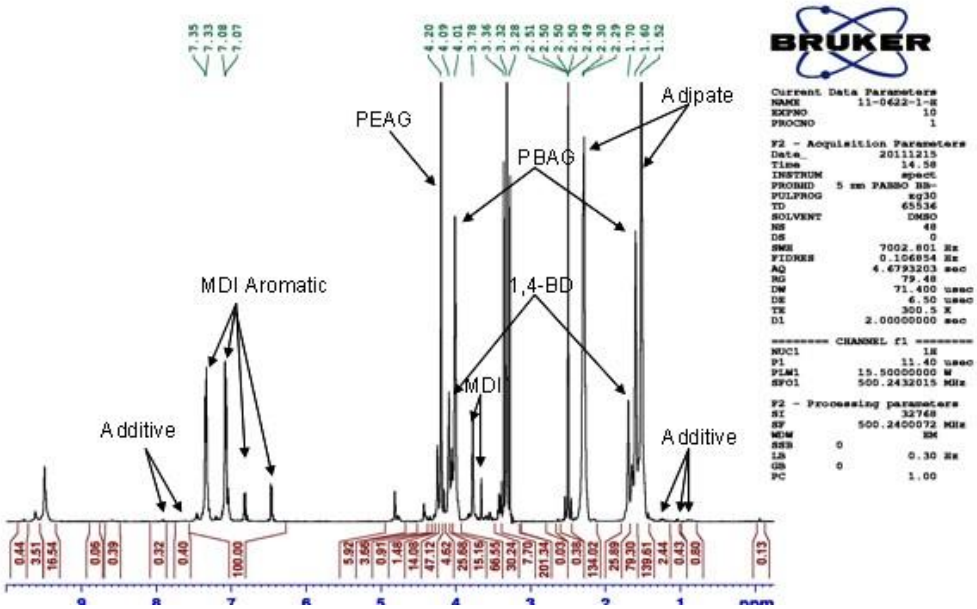

Figure 14: Example of spectrum generated by NMR analysis of MDI ester / BD system with trace amounts of secondary components

Since the percentages of components can be quantified, ratio calculations can be carried out. Calculating ratio via NMR results is especially important for systems using curatives that lack chlorine or sulfur and has found great usefulness for systems cured with 1,4-butanediol. Two approaches can be used when performing this type of ratio analysis.

- Control samples can be submitted to generate a calibration curve, against which the sample in question can be compared.
- A mock formulation using lot NCO can be created, varying ratio until it matches the percentages returned by NMR.

With the increased sensitivity of NMR compared to FTIR, exact percentages of individual components can be more accurately determined, differentiating between ratios that are closer together where such distinctions might not have been possible with FTIR.

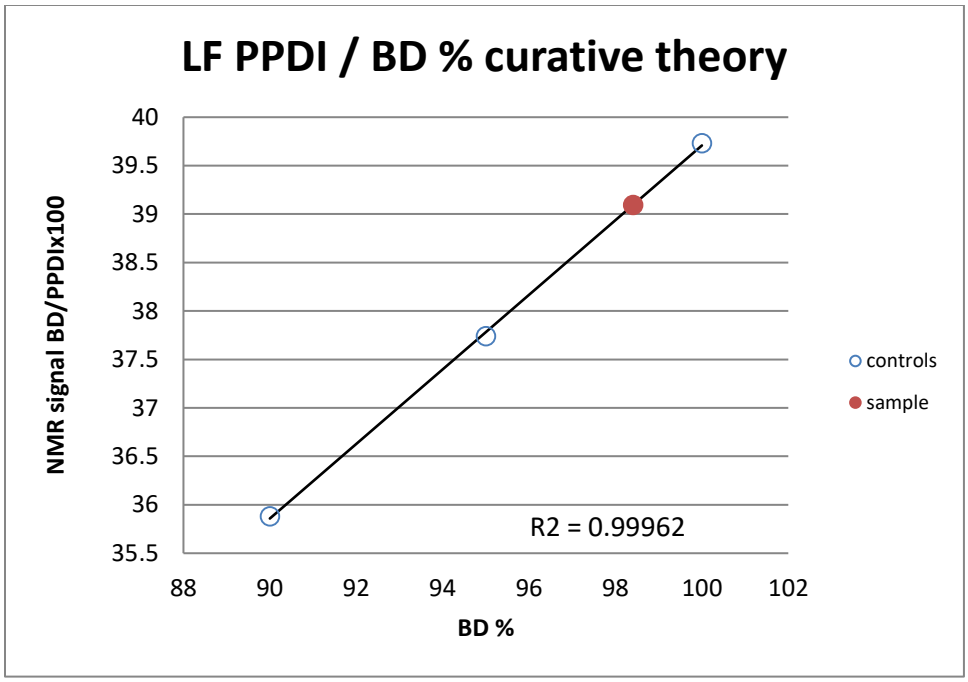

Figure 15: Example of calibration curve generated by NMR analysis of control samples at 90%, 95%, 100%, and a submitted sample targeting 98% is evaluated and found to be on-target

Percent Chlorine Analysis – Schöniger Combustion (%Cl)

It is possible to determine the ratio of parts cured with specific curatives through the direct measurement of the amount of chlorine present in the cured part. For simplicity this section refers to calculations dealing with MOCA, but the same method applies to MCDEA cures with modified equations. To quickly summarize the method, a sample is combusted in a specially designed flask, absorbed in a solution, and titrated to determine the level of chlorine. As MOCA contains a known percentage of chlorine this translates to a direct measurement of concentration of MOCA present in the original sample.

When formulating, the amount of curative needed in a part is calculated based on the target ratio and the %NCO of the prepolymer (Equation 1).

$$Pph_{MOCA} = \frac{\%NCO * EW_{MOCA} * \%Theory}{4202}$$

Equation 1: Calculation to determine amount of MOCA (parts per hundred parts of prepolymer) as a function of %NCO, Equivalent weight of curative, and desired theory

Ratio can be determined by using this same concept in reverse. The amount of curative is now known through direct measurement of chlorine and ideally %NCO is known from lot traceability. In the event that NCO of the original prepolymer is not known, it is possible to do the same calculation with an assumed value of NCO. This is often the mid-point or the end-points of the specification to get an estimate or a range of stoichiometries that the part will fall in. Although this assumption limits the determination of the exact ratio, often it is enough to make reasonable conclusions about the likelihood of parts being on- or off-ratio.

$$Pph_{MOCA} = \frac{\%Chlorine * 100}{26.5 - \%Chlorine}$$

$$\%Ratio = \frac{Pph_{MOCA} * 100}{\%NCO * 3.18}$$

Equation 2: Calculation of amount of MOCA from measured % Chlorine, and Calculation of ratio as function of MOCA content and %NCO

Scanning Electron Microscopy (SEM)

The crux of Scanning Electron Microscopy (SEM) technology involves bombarding a sample's surface with a high-energy electron beam on the surface of a sample. When the electrons interact with the surface of the part, it generates signals that can be interpreted by the instrumentation to provide information about the elemental composition of the sample. Historically the use of SEM was limited to research settings due to the size and cost of the instrumentation. However, the recent advent of benchtop SEM units has reduced equipment size down to that of a suitcase (Figure 16) and cost down to approximately $100k. These changes allow SEM techniques to be more broadly used to help solve practical problems in commercial laboratories. Although cost may still be prohibitive in some cases, it is more feasible for some potential users looking to add to their analytical toolbox.

Figure 16: Scanning Electron Microscopy (SEM) benchtop instrumentation

In addition to excellent imaging technology, these benchtop units usually come equipped with Energy Dispersive Spectroscopy (EDS). EDS can be used to determine the elemental composition of the sample and allow for the mapping of the elements present among other qualitative and quantitative analysis tools. SEM has many applications within urethane technology for troubleshooting processing issues or failure analyses, including:

- Clear imaging of parts or defects, including scale measurement
- Elemental composition of a part, contaminant, or unknown artifact
- Verifying FTIR analyses by confirming elemental markers such as chlorine or sulfur to prove the presence of specific curatives
- Identifying poorly dispersed curatives or additives by mapping and isolating elemental "hot-spots"

Case 1: SEM Imaging

The ability of SEM to provide high resolution and clear imaging of a defect, contaminant, artifact, or suspected area proves to be a valuable investigative tool by itself before even introducing the elemental analysis aspect of the technology. In one case, a prepolymer sample was provided showing particles throughout. Traditional microscopy showed only a fluffy white precipitate. A particle of the precipitate was isolated and rinsed with solvent to remove the bulk prepolymer. SEM was used to capture a very well-define image (Figure 17) of the particle which was then suspected to be dimer, even fully revealing the crystalline structure. This was subsequently confirmed by FTIR utilizing spectral subtraction techniques to remove peaks associated with bulk prepolymer and match against a known dimer spectrum in the reference library (Figure 18).

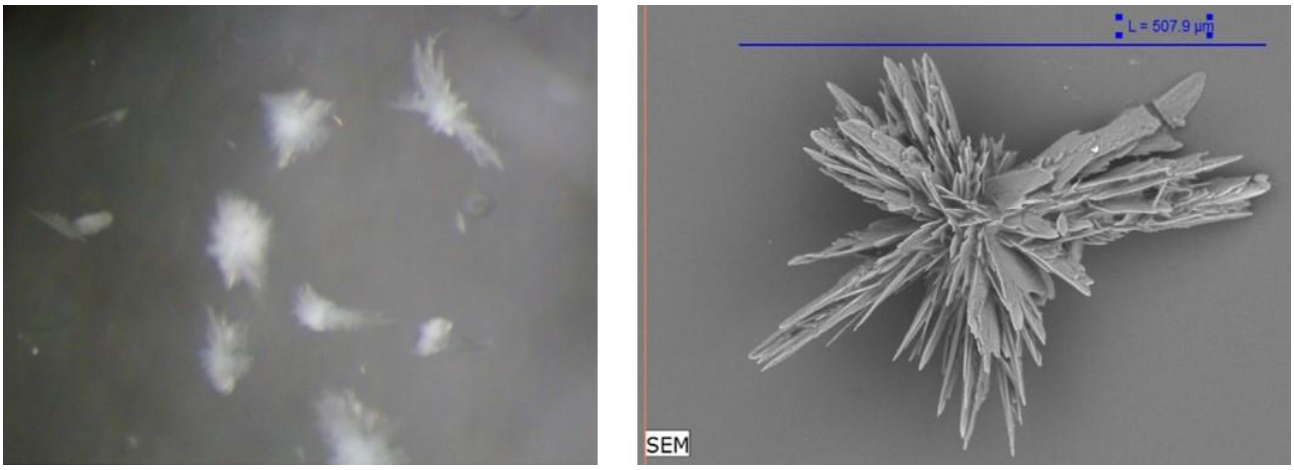

Figure 17: Particles floating in prepolymer under traditional microscopic imaging (left) and isolated particle under SEM imaging (right)

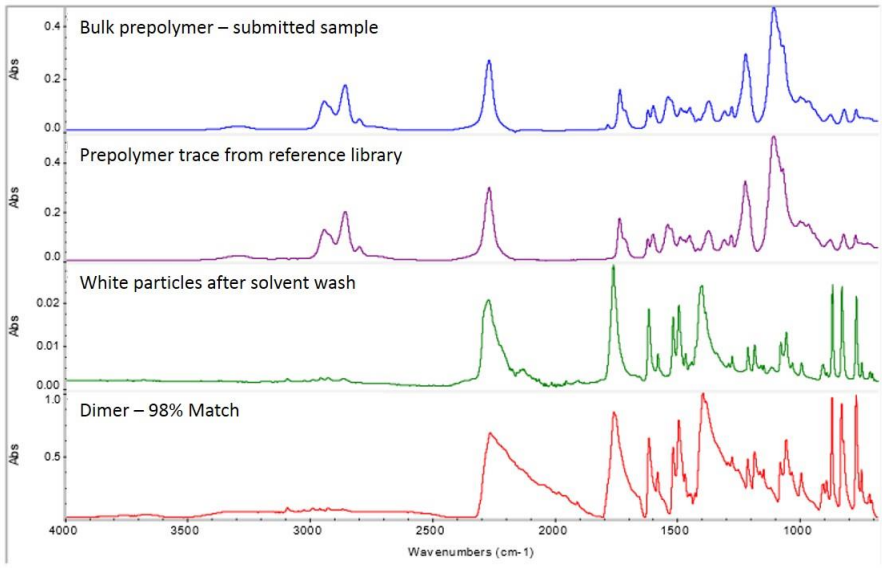

Figure 18: FTIR Comparison of bulk prepolymer and isolated particle against their respective reference spectra

Case 2: Metal Contamination

Elemental analysis is a basic, yet valuably informative tool that can aid greatly in determining the composition of an unknown artifact. In another simple case, metallic flakes were found in cured urethane after processing. In order to determine the likely source of the contaminant, or if it was indicative of a larger issue, a request to identify the type of metal was made. It was suspected that damage to the steel drum or the bung had occurred in transit and could possibly be where the pieces of metal originated. Performing EDS analysis on the metal identified it as aluminum. Comparing a piece of the bung side by side highlighted the expected iron in the steel bung and confirmed the two metals to be different (Figure 19). Quickly and simply identifying the elemental makeup of a container ruled out one potential root cause and pointed the investigation towards aluminum parts used in the process, allowing the true source to be found.

Figure 19: Metallic flake located in cured urethane (left), SEM element map of Aluminum flakes (Al – red) and steel-based bung containing iron (Fe - green) (right)

Case 3: Curative Dispersion

Curatives that contain sulfur or chlorine show characteristic peaks in the EDS spectra obtained by SEM analysis. SEM can therefore investigate issues related to the dispersion of these curatives. One recent example involved a defect in a cured part consisting of a visible, off-color "swirl," containing voids. Isolating the area in question with a razor allowed for evaluation by both FTIR and SEM-EDS. Since the part was known to contain MOCA, mapping the defect for chlorine content allowed for an immediate evaluation of chlorine distribution in and around the defect area.

The mapping revealed that there was roughly one-third the amount of MOCA in the suspect area compared to surrounding areas. This difference may have also been picked up by traditional chlorine analysis described in a previous section if care is taken to cut samples for evaluation from both the suspect area and elsewhere in the part. However, depending on how these samples are prepared, the difference in MOCA content may not have been detectable. Evaluation by SEM allows for a visual as well as analytical inspection across an area of a specimen making the anomaly easier to detect. Quantification of true ratio would need to be followed up on with percent chlorine analysis, but identifying a dispersion problem highlights a root cause within the mixing process.

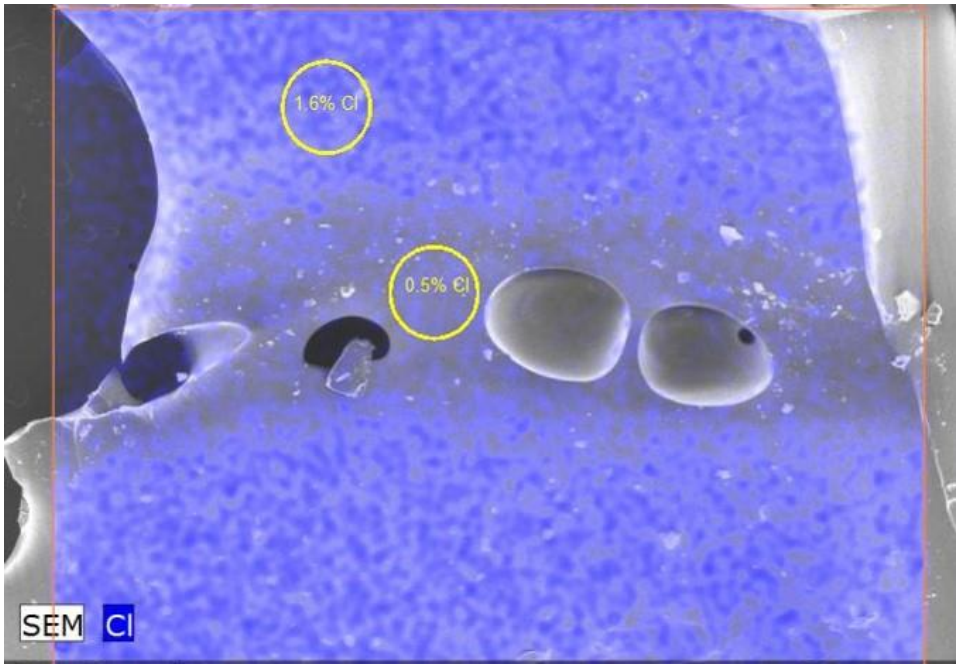

Figure 20: SEM imaging of defect area. Shown is the "swirl" running horizontally through the center and the voids present. Blue indicates Chlorine. Intensity of peaks show roughly 3x the amount of chlorine in surrounding areas compared to defective area

Evaluation of Physical/Dynamic Properties

With many failures it may be difficult to detect a potential root cause before parts are put in the field. Most of the techniques described to this point are valuable investigative tools after the fact, but these tools may be difficult or infeasible to implement as part of process or quality systems due to resource constraints. In addition, there may be no visual indicators on physical parts to alert an operator or inspector of a potential issue.

Let's take the case of a low-free TDI ester / MOCA cast at various stoichiometries from standard 95% down to 87% which would be considered a fairly large deviation from the target. Hardness measurements are often implemented as an easy in-process check, but as seen in Table 2 even as ratio is reduced by almost 10 points, no change in hardness is measured. However, reductions in other properties are noticed almost immediately with changes in ratio, specifically in tensile and tear properties. Data was collected with a standard Instron universal test frame fitted with an extensometer.

LF TDI Ester / MOCA, 100C Mold Temp, Post-cured 16hrs @ 100C				
Stoichiometry	**87**	**90**	**93**	**95**
Tensile Properties (ASTM D-412;speed 20 in/min)				
100% Modulus (psi)	1899	1841	1752	1772
300% Modulus (psi)	5031	4525	3647	3772
Stress at Break (psi)	7176	7205	7369	8148
Strain at Break (%)	339	356	404	409
Trouser Tear (ASTM D-1938;speed 20 in/min)				
Tear Strength (pli)	214	247	328	344
Split Tear (ASTM D-470; speed 20 in/min)				
Tear Strength (pli)	94	145	162	170
Bashore Rebound (ASTM D-2632)				
Rebound (%)	31	33	33	33
Durometer (ASTM D-2240)				
Shore A	96	96	96	96
Compression Set Method B (ASTM D-395)				
%	26	27	28	29

Table 2: Comparison of standard physical properties of LF TDI Ester / MOCA at various ratios

If physical properties do not fall in an expected range, not only is this a possible indicator of a processing concern, this may also result in a part that will not perform as expected. Therefore, utilizing a screening process of physical properties might be a worthwhile exercise to maintain quality and consistency. This equipment is common in the field due to its versatility and is relatively cost effective to install and implement. It could be used in a simple, low-effort manner by spot-checking suspect parts. It could also be implemented more in-depth to capture statistical data on an on-going basis to support quality or continuous improvement objectives. This would require some experimentation on sampling numbers, repeatability and reproducibility (R&R) of the equipment, an understanding of the material systems used, and common variability and sensitivity of these properties in order to define a useful specification for these properties.

Rather than testing general properties, another approach is to implement testing that evaluates a specific performance criteria that needs to be met by the part. One such example is cyclic applications where low hysteretic loss is critical and standard physical properties are not the driving factor in end performance. In these cases Dynamic Mechanical Analysis (DMA) can be used to determine properties such as tan delta and storage/loss moduli which are indicators of dynamic performance of a part.

- Tan delta is indicative of the energy dissipation potential of a material. Good dynamic materials have a low tan delta.
- Storage and loss modulus relate to a materials ability to retain energy vs energy that is lost. It can also be indicative of how a parts behavior changes as it heats up in use. Typically a stable modulus vs temperature is favorable.

These properties can be sensitive to processing variables like ratio, as shown in Figure 21.

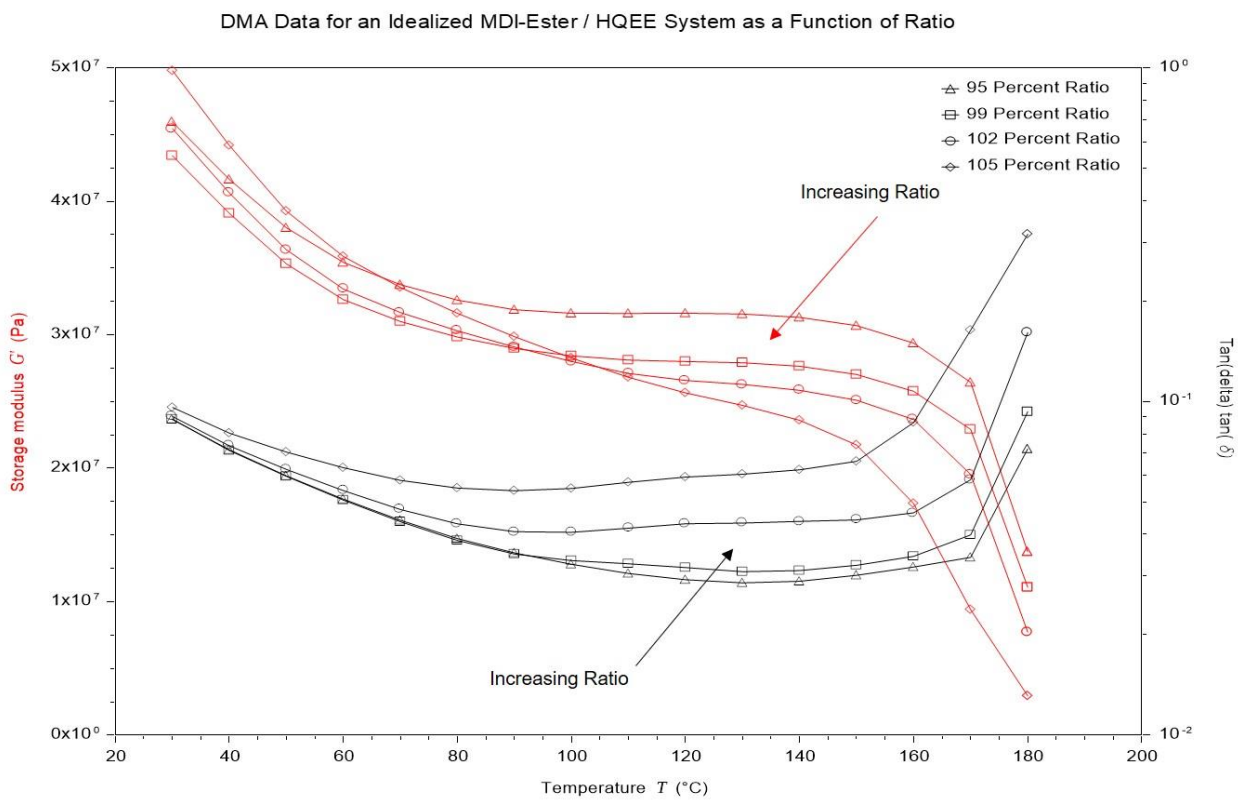

Figure 21: Example of DMA behavior changing as a result of ratio

In one case involving a dynamic application, several failed parts were tested on an Ares G2 rheometer for dynamic properties and compared against known good parts that passed field testing. Once a clear difference was observed in the results of this testing (Figure 22), a processing design of experiments (DOE) was performed to evaluate ratio

and post-curing conditions. This allowed the manufacturer to determine the processing limits that results in parts that meet the performance criteria.

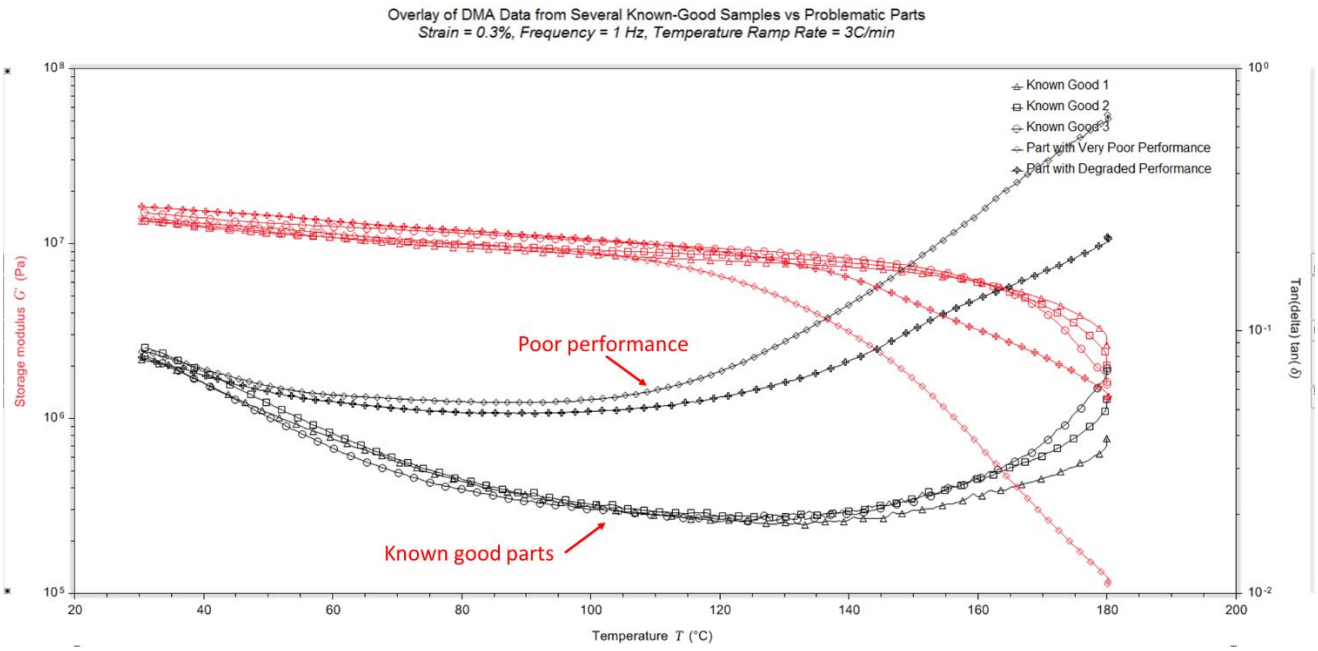

Figure 22: DMA data of known good samples compared to failed parts

Having this specification defined, even when not checked on an ongoing basis, provides a reference on questionable or returned parts. It also clarifies communication between processors and end-users which helps prevent disagreements as a result of underdefined acceptance criteria.

Finite Element Analysis (FEA)

There are cases where no matter what material is chosen for an application or how that material is processed, the part does not meet lifetime requirements. Many design engineers are familiar with working with metals but may fail to take into consideration the rubbery behavior of polyurethane when designing PU parts. This can result in design flaws that are likely to end in failure. Ideally, design problems are caught as early in the product life-cycle as possible. Some design tools exist to help predict and model how parts will behave in the field. One of these tools is Finite Element Analysis (FEA) which can be used either as a predictive tool or to evaluate failed parts at the prototype phase to model a part and characterize how it will behave.

FEA derives from a mathematical method of solving differential equations by breaking a system down into smaller, simpler parts (called elements) and applying boundary value problem solving techniques to determine the inputs and outputs of each element. This method has been incorporated into computerized engineering and design

software commonly used to predict how a part will react to forces, torques, constraints, and boundary conditions. The resulting model allows the analyst to quantify information such as deflections, reaction forces, stresses, and strains, all of which is useful in evaluating a design. While the capabilities of FEA far exceed this, being able to simply predict stresses and strains of a urethane part is a valuable design tool to highlight areas of concern that might contribute to a failure.

Full details of Finite Element Analysis is an in-depth topic, but a quick outline of the steps involved is as follows:

- A 2D or 3D model of the part is created and imported.
- The part is broken down into smaller elements through a process called “meshing”
- Boundary conditions and constraints are added (fixed displacement, symmetry, degrees of freedom) and loads/forces/pressures/displacements are applied
- A material characterization is applied to define the behavior of the material. This often can be one of the more challenging aspects of analysis on elastomeric parts due to its viscoelastic behavior.
- Analysis is performed through the software and results are made available to review. This includes visuals of the part deformations or changes as well as engineering info such as stresses, strains, and displacement values

FEA Case 1 – Shear Spring

In a case where a customer attempted to drop a urethane solution into a historically rubber shear spring application, it was originally thought that matching the hardness would be enough to keep performance similar while adding the normal benefits of urethane materials. Unfortunately, cracks were observed during the testing phase. FEA was employed as part of the failure analysis as material-related root causes were being ruled out, and results showed two high risk areas. First, a stress riser or stress concentrator, which is a feature in a part such as a sharp bend or corner that causes increases in localized stresses, was observed. Stresses were highest in this area which corresponded to the areas where cracks were appearing (Figure 23). It also predicted that the material was subject to 75% strain, which is exceedingly high for a urethane part. Given that this application is cyclic, repeated deflections to 75% strain would lead to quick fatigue failures in almost any urethane part regardless of the urethane chosen. This is further exacerbated by the presence of stress concentrations inherent in the design.

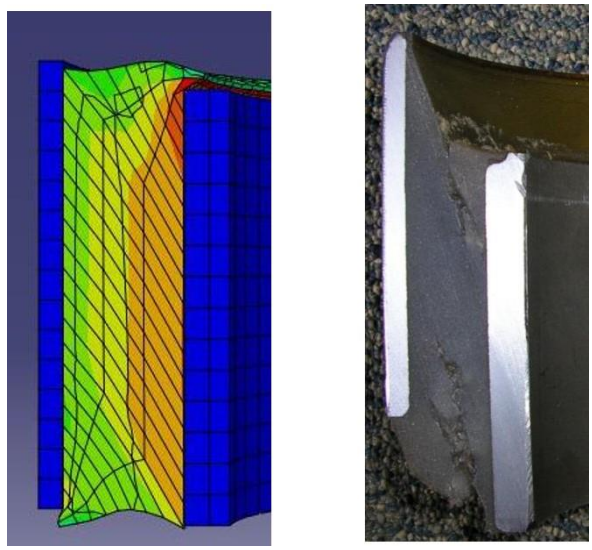

Figure 23: FEA results showing high stress areas during compression (left), image of cracks in field part after testing appearing in the same area (right)

These results illustrate that no matter what material solution was chosen, failures were likely and lifetime targets for the part were unlikely to be met. Through iterations of some design changes and re-running FEA it becomes possible to balance lowering strains while simultaneously keeping spring rate constant to ensure the part performs as intended. Cracking would still be possible and likely in high stress areas. However, a stress relief area, which is a modification of the geometry designed to reduce strains and stresses by allowing the material more room to bulge or deflect, was also incorporated into the design (Figure 24).

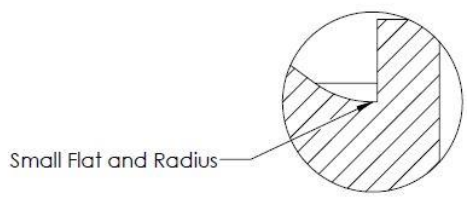

Figure 24: Stress relief area incorporated to reduce localized stress and strains

Various iterations included radii of different magnitudes, notches, chamfers, and bends, ultimately choosing a design that kept strains in a reasonable range. Prototyping without FEA would have required multiple molds and time to trial additional designs, but utilizing predictive FEA techniques design can be optimized before tooling is requisitioned.

Conclusion

Given how challenging the design and processing of polyurethane parts can be, understanding the tools available to identify why a part is failing is essential to successfully and consistently manufacturing parts that meet the requirements of the end applications. Utilizing these tools throughout the product-life cycle allows for optimized designs, consistent processing, and confidence in identifying true root causes when failures occur. All methods and instrumentation will require some level of capital investment and training. Choosing tools that add enough value to manufacturing and quality control processes for the cost and complexity involved will be dependent on the needs of an individual processor. Some methods will not be feasible for all users to implement due to resource constraints but these can be outsourced when appropriate to take advantage of their utility. Others provide a great deal of return value for relatively low cost and user-friendly instrumentation. These have the potential to add to a processor's toolbox to raise the bar of productivity and consistent quality.