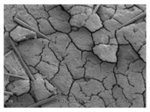

FAILURE ANALYSIS
& PREVENTION

Special points of interest:

- Call for Papers—ANTEC 16
- 2015 ANTEC Wrap Up
- Hayes, Stevenson and Turnquist Receive FAPSIG 2015 Best Paper Award
- FAPSIG Board Meeting Minutes
- Announcements
- FAPSIG Board
- 2015 Dr. Myer Ezrin Best paper

Letter from the Chair — Jennifer Hoffman

Letter from the Chair:

Hello and welcome to the Failure Analysis and Prevention Special Interest Group (FAPSIG) summer newsletter. I am excited to take on a new role as FAPSIG Chair for the next two years where I can oversee the growth and direction of our group. The fact that we have ~1,400 members tells us that we are heading in the right direction! To more effectively connect with our members, I am asking for your feedback regarding our newsletter content and session topics/formats. Are there specific topics you would like FAPSIG to cover at ANTEC 2016? For those who have attended tutorial and/or panel discussions, would you like to see these formats again? Please let us know so we can continue to offer technically relevant and engaging content.

On behalf of the FAPSIG board, thank you for your continued support. We hope you will consider submitting a paper to FAPSIG for ANTEC 2016 and/or joining our board. Our next board meeting will be held during ANTEC 2016 in Indianapolis. We encourage and welcome all members to contribute to our continued success.

Regards,
Jennifer

Jennifer Hoffman, Ph.D.
AirXpanders, Inc.
ANTEC 2016/2017
FAPSIG Chair

Inside this issue:

FAPSIG Newsletter Editor:
Paul Gramann, The Madison Group

ANTEC® 2016

Call for Papers

Failure Analysis and Prevention Special Interest Group

The Failure Analysis and Prevention Special Interest Group (FAPSIG) is soliciting papers for the next ANTEC® conference, which will be held on May 23-25, 2016 in Indianapolis, Indiana.

Many aspects of product and process development, material selection, manufacturing, and end-use/service life testing fall under the umbrella of failure analysis and prevention. Papers can be submitted addressing failure analysis and prevention related to plastic and composite materials, including automotive, consumer products, medical, construction, piping, etc.

Topics for which FAPSIG is soliciting papers include:

- Identifying and demonstrating practical solutions to prevent or mitigate common industrial problems (e.g. adhesion failures, chemical resistance, and environmental stress cracking)
- Case studies on failure prevention in product design and manufacturing
- Case studies illustrating the use of complimentary tools/techniques to determine the root cause of plastic failures
- Use of new methodologies in performing plastic product failure analysis
- Use of non-destructive methodologies (e.g. CT scanning, finite element analysis) to identify and prevent failures in plastic components
- Fracture behavior of polymers and the role of fractography in understanding plastic product failures
- Failure analysis and lifetime prediction of plastic pipe and fittings
- Failure of medical implants, including designed failures (e.g. resorbables)
- Prevention of plastic product failures with use of accelerated aging and/or service lifetime prediction methodology

Paper Submission Deadline: December 8, 2015

Please contact us if you have questions:

Brian Ralston
FAPSIG TPC
E-mail: brian.ralston@campoly.com
Phone: 617-990-4449

Barbara Spain
Events Program Manager
E-mail: bspain@4spe.org
Phone: 203-740-5418

ANTEC 2015 Wrap Up

FAPSIG offered three well-attended sessions, including two joint sessions at ANTEC 2015 in Orlando. We partnered with the Pipes and Fittings SIG to present papers related to Plastic Pipes in Building Construction and the Injection Molding Division where we held an interactive panel discussion on the topic of Understanding and Preventing Failures of Injection Molded Parts. A panel of invited experts answered a variety of questions on the detection, measurement and effect of residual stresses on plastic parts and provided advice on troubleshooting plastics-related failures. Thanks to Vikram Bhargava, Jeff Jansen, Mike Sepe and Suhas Kulkarni for sharing their time and expertise. In addition, congratulations to Michael Hayes (lead author/presenter), Michael Stevenson and Dustin Turnquist with Engineering Systems, Inc. for winning the Dr. Myer Ezrin Best Paper Award for their paper "Failure Analysis of a Glass Filled Phenolic Resin Power Steering Pump Pulley".

FAPSIG would also like to thank the following sponsors for supporting and funding our ANTEC activities: Cambridge Polymer Group, Exponent, Element, Engineering Sciences, The Madison Group, and Plastic Failure Labs. Because of our sponsors we were able to provide refreshments during the panel discussion, sponsor student travel, and continue our annual tradition of handing out $5 Starbucks gift cards to thank attendees for their interest and participation in FAPSIG sessions. If your company is interested in becoming a sponsor for ANTEC 2016, please contact Jeff Jansen (jeff@madisongroup.com).

Overall, the FAPSIG sessions at ANTEC 2015 were a success and we look forward to carrying the positive momentum into ANTEC 2016.

Jennifer Hoffman, ANTEC 2015 FAPSIG Technical Program Chair

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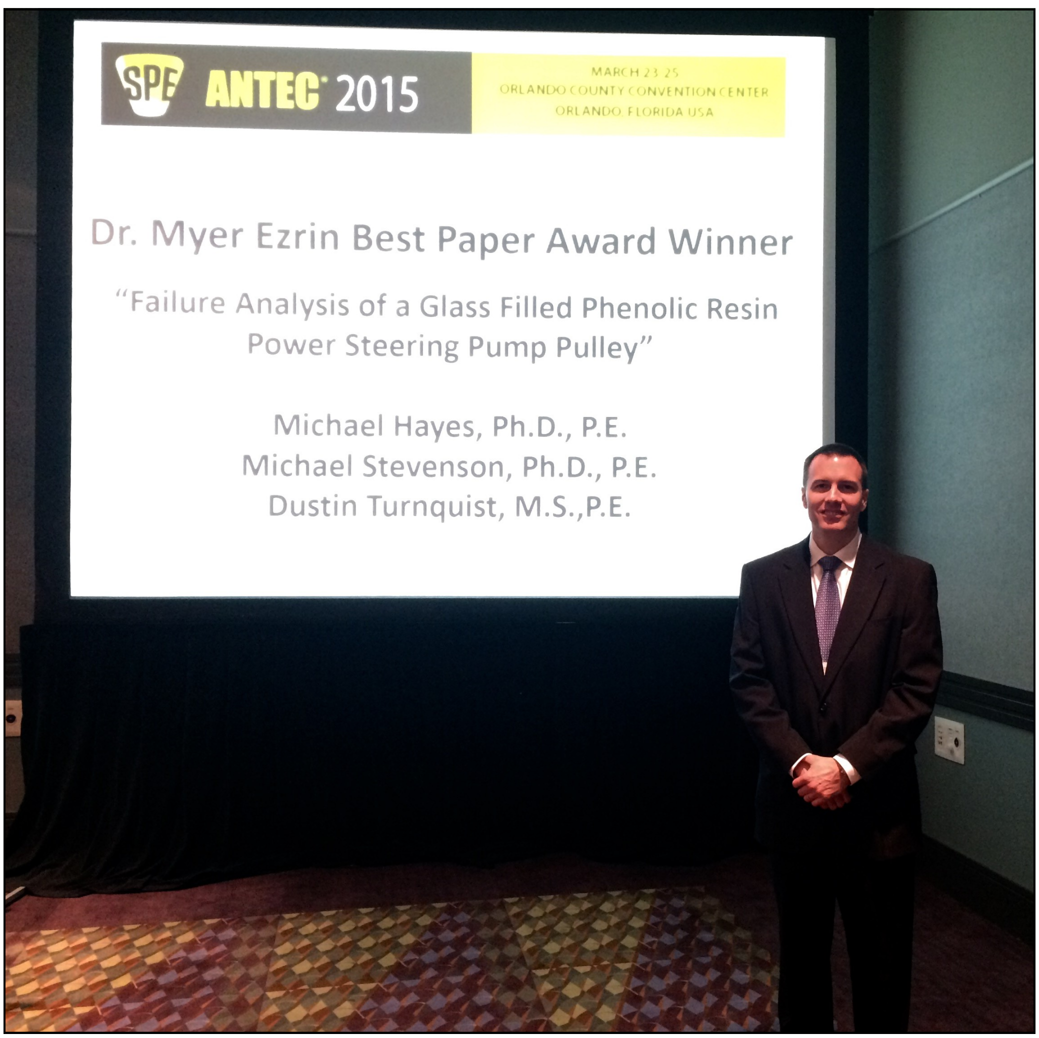
Hayes, Stevenson and Turnquist Receive FAPSIG ANTEC 15 Best Paper Award

Congratulations to Michael Hayes (lead author/presenter), Michael Stevenson and Dustin Turnquist with Engineering Systems, Inc., for winning the FAPSIG Dr. Myer Ezrin Best Paper Award for their paper "Failure Analysis of a Glass Filled Phenolic Resin Power Steering Pump Pulley." There were excellent papers/presentations given during the FAPSIG sessions. This paper stood out for its content and quality. The abstract of the paper is given below. The full paper is shown at the end of this newsletter.

Abstract — FAPSIG ANTEC 2015 Best Paper:

A root cause failure analysis was performed on a glass filled phenolic resin power steering pump pulley that was implicated in an automobile accident. A thorough investigation including vehicle inspection, macroscopic and microscopic examination, stress analysis, and exemplar testing was performed to test two competing hypotheses postulated to explain the failure. The first hypothesized cause of failure was the impact of the pulley with other under-the-hood components during a rear end impact. The second hypothesized cause was fracture due to fatigue, which was the result of various defects. This paper details the various investigative steps and identifies the ultimate root cause.



Michael Hayes accepting the 2015 ANTEC FAPSIG Dr. Myer Ezrin Best Paper Award

FAPSIG Receives Bronze Sponsorship for Student Activites

SPE
FAILURE ANALYSIS & PREVENTION

The Failure Analysis and Prevention Special Interest Group donated $750 to the SPE Student Travel Fund for graduate and undergraduate students to attend the Society of Plastics Engineers Annual Technical Conference (ANTEC) in Orlando from March 23-25. FAPSIG Chair Jennifer Hoffman received the bronze certification from Len Czuba, the SPE Student Activities Fund Raising Chair

The FAPSIG has funded this extremely important program for several years. It allows for tomorrow's engineers to participate in the industry's premier technical conference. At the same time it allows students to network with possible employers at the many events that take place during the week of ANTEC.

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FAPSIG Meeting Minutes, March 25, 2015

Attendees:

Anand Shah – Chair
Brian Ralston – Best Paper Award
Jennifer Hoffman – Technical Program Chair (TPC)
Dale Edwards – Past Chair
Paul Gramann - Newsletter
Javier Cruz – Education
Todd Menna – Secretary
Jeffrey Jansen – Sponsorships
Don Duvall – Memberships
Antoine Rios – Activities
Sue Mantell – Webmaster
Kathy Schacht – SPE Liaison

Others

Jose Perez (Element)
Rob Farina (Exponent)
3 unidentified foreign graduate students

Absent

Mike Hayes – Social Networking
Steve MacLean - Treasurer

Board (Shah):

Minutes approved from 2014 meeting, no changes requested.
Anand Shah to vacate Chair position become Past Chair, Jennifer Hoffman to take position as Chair for 2015-2017.
Jennifer Hoffman to vacate TPC position, Brian Ralston to take position as TPC for 2015-2017.
Brian Ralston to vacate Best Paper Award position, Rob Farina to take position for 2015-2017.
Todd Menna to vacate Secretary position, take on "TPC in Training" role for 2015-2017.
Jose Perez to take Secretary position for 2015-2017.
New informal Board position – Newsletter Reviewer, to be handled by Jennifer Hoffman.
All other Board positions to remain the same through 2015 calendar year.
Discussion regarding question of whether FAPSIG wanted to become a full Division within SPE. Duvall and Schacht reviewed general criteria for Divisions. Decision made to stay SIG until long term goals are determined, but to slowly work towards meeting qualification in the event the decision to convert is made in the future. Schacht will assist, as necessary.

Finance (Ralston):

Ralston handled Finance due to absence of MacLean.
As of 12/31/2014, balance was $9,084
Sponsorship contributions and ANTEC 2015 gift card and best paper expenses led to balance of $12,734 as of 4/25/14. This amount does not include the Best Paper Award or Student Travel expenses incurred for ANTEC 2015.
Discussion of what to do with surplus funds. We are acquiring more money than we are spending. Options discussed: annual reception, increase scholarship level, student travel stipend, TOPCON.

Travel funds would include a solicitation of projects and award funds to travel and present work at ANTEC. Rios to begin building the program, Shaw and Mantell to assist. $1,000 – 2,000 budget approved. Board members to review proposal by email.

$500 Student Travel sponsorship increased to $750; all in favor, motion passed.

TPC Update (Hoffman):

13 papers submitted, 1 rejection, 1 withdrawal, 2 shifted to other SIGs

Begin soliciting papers ASAP

Work with other to create joint sessions and/or make sure papers are presented in the correct SIG.

Ralston to contact Composites SIG to attempt to have a joint session at 2016 ANTEC.

Newsletter (Gramann/Shaw):

Of roughly 1,400 FAPSIG members, the current content may not be relevant to all members. Gramann to send email blast to entire FAPSIG asking for new newsletter content.

Hoffman to become reviewer of Newsletter after creation by Gramann and prior to delivery/publication to FAPSIG members.

Best Paper Award (Menna/Ralston):

Menna handled Best Paper Award due to conflict with Ralston being nominated.

Award Winner: Hayes, M.D, Stevenson, M.E., Turnquist, D.A. "Failure Analysis of a Glass Filled Phenolic Resin Power Steering Pump Pulley"

Scoring and Judging Criteria

Nominees judged on paper and presentation, with paper being worth 2/3 of final score and presentation being worth 1/3 of final score.

Three judges used for 2015 papers.

Nominees were not notified ahead of time that they were a nominee, nor were the nominees announced in the meeting due to presentations and award not yet presented.

Judging criteria approved via email in 2014 didn't work as planned. Too many conflicts with nominees being coworkers or previously reviewed papers by the judges. Need to update criteria as to how judges are selected and whether nominees should be notified ahead of time.

Todd Menna, FAPSIG Secretary

PLASTIC FAILURE LABS

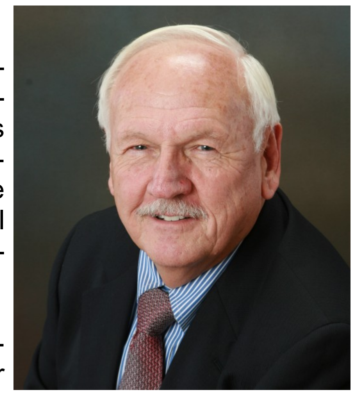
www.plasticfailure.com

Announcements

Element New Berlin is Pleased to Welcome Robert Pieper.

Robert Pieper, Ph.D., has recently joined the polymer engineering team at Element Materials Technology New Berlin as a Polymer Chemist. Rob is a coatings and polymer chemist with extensive experience in coatings design, formulation and testing, polymer design, material selection, structure-property relationships, thermal and mechanical properties/testing methods and polymer processing. His most recent position was with NETZSCH Instruments where he served in an Applications Scientist/Sales Support role assisting customers with their equipment and performing failure analysis project work. Rob obtained his Ph.D. in Coatings and Polymer Materials from North Dakota State University and his B.S. in Chemistry from the University of Wisconsin. Rob can be reached directly at (262) 901-0541 or robert.pieper@element.com.

NSL Analytical Builds NE Region Staff to Help Area Manufacturers Resolve Testing Issues



March 2015 (Cleveland, OH) --- NSL Analytical Services, Inc. announces the appointment of Jim Martin as Business Development Leader in the Northeast States. Mr. Martin brings more than 39 years of industry experience in business development, sales and marketing in testing and instrumentation. His knowledge and experience in Spectrometry, Materials Testing, and Physical Quantification brings a wealth of knowledge and experience to this position. He is an active member and contributor to technical groups, published numerous articles, and has been recognized for his activities in support of ASM International, Society Of Plastics Engineers and others.

“It is really great to have Jim join our team to support our customers and answer questions about testing and how NSL can support them in meeting testing needs of their products,” said Larry Somrack, President. “Jim’s experience, degree in engineering, MBA, and knowledge of customers in the Northeast is a real asset for NSL.”

His responsibilities include assisting NSL's customers and representatives with business and technical issues. He is charged with helping customers in Massachusetts, New Hampshire, Maine, Rhode Island and Connecticut meet requirements and resolve issues with NSL’s broad range of thorough, accurate, timely objective materials analysis, testing, characterization and consulting services.

Mr. Martin will offer the full suite of analytical testing NSL offers for industrial, commercial and research organizations…continuing NSL’s quality policy of *Trust, Technology, and Turnaround*. NSL clients can be found in many industries ranging from Aerospace and Medical Devices; to Plastics and Automotive; to Electronics and Metals Forming; to Heat Treating and Energy; Nuclear and Organic Polymers; Food and Pharmaceuticals; and Ceramics and Optics. For more information, visit http://www.nslanalytical.com.

Direct Contact Information: Jim Martin--Business Development-East Coast
Phone: (781) 956-8521 Email:jmartin@nslanalytical.com

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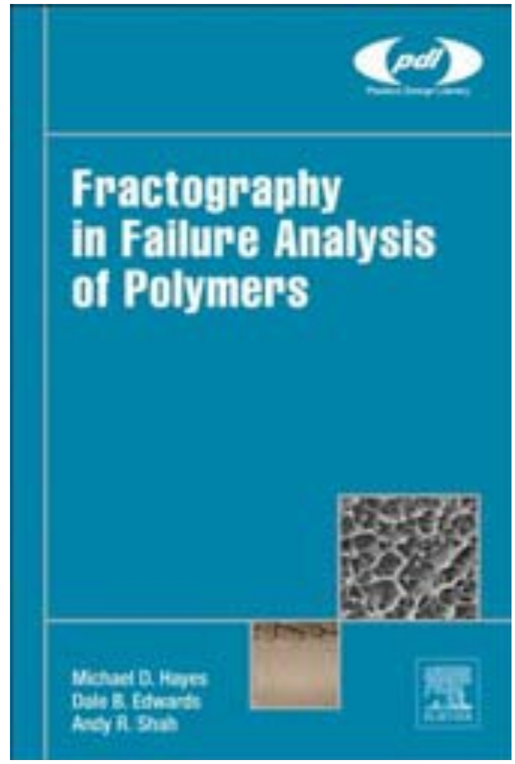
Fractography in Failure Analysis of Polymers



AURORA, IL – May 29, 2015. ESI is pleased to announce that "Fractography in Failure Analysis of Polymers," a technical reference authored by ESI consultants Michael Hayes, Ph.D., P.E., Andy Shah, P.E., M.B.A., and Dale Edwards, P.E. is now available for purchase through Amazon, and on the Elsevier website. This reference, part of Elsevier's Plastics Design Library Handbooks series, fills an important need for a standard text to use in the fractographic examination of plastics – one that includes both reference images and context for its application in failure investigations.

In the book, the authors introduce the science of fractography, a review of fractographic tools and techniques, and important information about the practical application of fractography in the failure analysis of plastic components. A key element of this book is its incorporation of case studies to help readers understand the practical application of the covered concepts in real-life situations – including different polymer types, applications, and failure modes. The authors also highlight common mistakes made when interpreting fractographic features, and distinguish between the behavior and failure modes of plastics and those found in metals and ceramics.

Together, the authors have decades of combined, hands-on experience in complex, multidisciplinary investigations involving a range of materials and applications, including consumer products, packaging, medical devices, piping, and plumbing/construction materials.

3-Day Course on Analysis/Prevention of Plastic Part Failure to be Given at UW-Milwaukee

The University of Wisconsin—Milwaukee School of Continuing Education will be holding its Annual 3-day course entitled, **"Plastic Part Failure: Analysis, Design & Prevention"** taught by The Madison Group engineers Antoine Rios, Erik Foltz, Javier Cruz, and Jeffrey Jansen. The course will cover a broad range of topics essential to understanding and preventing plastic failure. Allows attendees to receive continuing education units/credits. Get introduced to the strategies behind analysis, design and prevention with course material that includes:

- Essential knowledge of why plastic components fail
- The five factors affecting plastic part performance
- The process of conducting a failure investigation
- Ductile-to-brittle transitions and their role in plastic component failure
- Methods for understanding how and why a product has failed
- Approaches to more quickly respond to and resolve plastic component failure
- Methods and techniques to avoid future failures

Receive 2.0 CEU and 20PHs

For more information contact:
Murali Vedula at UW-Milwaukee
mvedula@uwm.edu, p:414-227-3121

October 12 — 14, 2015

AirXpanders Expected to Receive FDA Approval for Medical Device

AirXpanders, Inc. based in Palo Alto, CA was recently listed on the Australian Stock Exchange as AXP. AirXpanders has TGA approval in Australia, CE Mark in Europe and is expecting to receive FDA approval at the end of this year for sale in the US. AirXpanders manufactures a breast tissue expander device that is used in the first stage of breast reconstruction following a mastectomy. The device is essentially a flexible balloon that is inflated to the final breast shape over the course of a few months with carbon dioxide gas. Compressed gas is stored in a reservoir inside of the device. Gas is released when a magnetically actuated valve opens using a hand-held dose controller. The device is differentiated from current technology in that the expansion is patient-controlled, needle-free and expansion takes ~1/3 of the time as traditional saline expanders.

SPE Failure Analysis and Prevention SIG Board Members

Jennifer L. Hoffman, Ph.D.
Chair
AirXpanders, Inc.
1047 Elwell Ct.
Palo Alto, CA 94303
P: 650-390-9015
jhoffman@airxpanders.com

Andy R. Shah
Past Chair
Engineering Systems, Inc.
3851 Exchange Avenue
Aurora, IL 60504
Work Phone: (630) 851-4566
arshah@esi-il.com

Steve MacLean, Ph.D.
Treasurer
Exponent, Inc.
17000 Science Drive, Suite 200
Bowie, MD 20715
Work Phone: (585) 387-0327
smaclean@exponent.com

Brian Ralston, Ph.D.
TPC
Cambridge Polymer Group
56 Roland St., Suite 310
Boston, MA 02129

Todd J. Menna, Ph.D.
TPC in Training
Element Materials Technology
3200 South 166th Street
New Berlin, WI 53151
todd.menna@element.com

Jose Perez
Secretary
Element Materials Technology
3200 South 166th Street
New Berlin, WI 53151
Jose.perez@element.com

Paul J. Gramann, Ph.D.
Newsletter Editor
The Madison Group
2615 Research Park Dr.
Madison, WI 53711-4951
Work Phone: (608) 231-1907
paul@madisongroup.com

Javier Cruz, Ph.D.
Education Comm. Chair
The Madison Group
2615 Research Park Dr
Madison, WI 53711-4951
Work Phone: (608) 231-1907
javier@madisongroup.com

Jeffrey A. Jansen
Sponsorship Chair
Engineering Manager
The Madison Group
2615 Research Park Dr
Madison, WI 53711-4951
Work Phone: (608) 231-1907
jeff@madisongroup.com

Michael Hayes, Ph.D.
LinkedIn Chair
Engineering Systems Inc
6190 Regency Parkway
Norcross, GA 30071
Work Phone: (678) 990-3280
mdhayes@esi-atl.com

Prof. Susan Mantell
Website Coordinator
University of Minnesota
ME 11A
Minneapolis, MN 55455
Ph: 612-625-1324
smantell@umn.edu

Antoine Rios, Ph.D.
Activities Chair
The Madison Group
2615 Research Park Dr
Madison, WI 53711-4951
Work Phone: (608) 231-1907
antoine@madisongroup.com

Robert Farina , Ph.D.
Best Paper Chair
Exponent
17000 Science Dr.
Bowie, MD 20715
Work Phone: (301) 291-2524
rfarina@exponent.com

Donald E Duvall, Ph.D.
Membership Comm. Chair
Engineering Systems Inc
3851 Exchange Ave
Aurora, IL 60504
Work Phone: (630) 851-4566
deduvall@esi-il.com

Myer Ezrin, Ph.D.
Director
43 Morgan Ridge
Longmeadow, MA 01106
mezrin80@comcast.net

Dale B Edwards
Director
Engineering Systems, Inc.
3851 Exchange Avenue
Aurora, IL 60504
Work Phone: (630) 851-4566
dbedwards@esi-il.com

FAILURE ANALYSIS OF A GLASS FILLED PHENOLIC RESIN POWER STEERING PUMP PULLEY

Michael D. Hayes, Ph.D., P.E.
Michael E. Stevenson, Ph.D., P.E.
Dustin A. Turnquist, M.S., P.E.

Engineering Systems Inc., Atlanta, GA

Abstract

A root cause failure analysis was performed on a glass filled phenolic resin power steering pump pulley that was implicated in an automobile accident. A thorough investigation including vehicle inspection, macroscopic and microscopic examination, stress analysis, and exemplar testing was performed to test two competing hypotheses postulated to explain the failure. The first hypothesized cause of failure was the impact of the pulley with other under-the-hood components during a rear end impact. The second hypothesized cause was fracture due to fatigue, which was the result of various defects. This paper details the various investigative steps and identifies the ultimate root cause.

Background

The authors have investigated the fracture of a power steering pump pulley associated with a fatal accident involving an automobile. The pulley, shown in Figure 1 is made of a mineral and glass fiber filled phenolic thermoset resin ("Bakelite"). The pulley is mounted onto a triangular steel plate with a center boss that is then mounted onto the shaft of the power steering pump (Figure 2). Conflicting witness reports suggest that either a failure caused the vehicle to come to an abrupt stop or the vehicle was stopped with the engine idling. In either scenario, the vehicle was stationary on the highway when it was struck from behind by an oncoming vehicle that was traveling at or near the posted speed limit. The cause of the pulley failure was disputed in subsequent litigation. One of the investigators argued that the fracture of the pulley induced a sudden loss of power thereby causing the engine to cease running and precipitating the accident. However, an accident reconstruction expert opined that the engine was idling at the time of impact. This analysis was based on a review of the engine control module (ECM) data.

The authors performed a comprehensive root cause failure analysis, beginning with a visual examination of the subject and exemplar vehicles, as well as macroscopic and microscopic inspection of the pulley. Based on the information gleaned from these inspections, a most likely cause of failure was hypothesized. To test this hypothesis, several additional steps were taken, including Charpy impact testing; literature review; dimensional analysis of the under-the-hood components; stress analysis; static load testing of exemplar pulleys; impact testing of exemplar pulleys to replicate the proposed cause of failure; and mechanical testing of various exemplar components. The details of these steps are provided in this paper. The second hypothesis, discussed in further detail next, was also evaluated using this data.

Visual Examination

Examination of the subject parts revealed several significant findings:

- A macroscopic fracture pattern suggestive of bending loads, e.g. an angled fracture surface.
- Witness marks along the circumference of the pulley's outer flange that spans multiple pieces, as shown in Figure 1, suggesting contact of the pulley with another object.
- Damage to the V-belt (not shown)
- Damage to the radiator fan shroud (not shown)
- Witness marks on the coolant overflow tank (not shown)
- Fracture of both the driver's side and passenger's side engine mounts (not shown)
- The transmission mounts were intact.
- Other various damage in the engine compartment

The damage pattern suggests that the pulley came into contact with the coolant overflow tank and/or the radiator fan shroud during the incident. Damage to the engine mounts confirms that the engine could have displaced forward to cause the contact, and this motion was possibly associated with the vehicle coming to an abrupt stop after impact due to substantial damage resulting from the rear-end collision. The continuous witness marks across multiple pieces of the pulley also suggest that the pulley was rotating during the impact.

This observation contradicts the allegation that the pulley failure occurred prior to the impact.

Microscopy

Next, the subject pulley was examined in greater detail using a stereomicroscope (Figure 3) and a Scanning Electron Microscope (SEM). Little to no fractographic detail in the phenolic resin matrix was discernible. This is not unusual for highly filled resin. The fracture surfaces of individual fibers were also studied. The fracture surface of the glass fibers demonstrated classical mist, mirror, and hackle features indicative of brittle fracture, as shown in Figure 4. No evidence of features that can be attributed to fatigue, environmental stress cracking, or chemical attack was observed.

However, another party argued that the hackled portion of the fracture surface on some of the glass fibers was actually a second crack origin growing from the opposite side of the glass fiber, and they attributed this two-sided crack propagation to fatigue. This interpretation is flawed for two reasons. First, such a phenomenon would require loading individual fibers in reversed bending, which is unlikely given the geometry and loading. Second, the appearance of the alleged second origin can be explained as follows. During tensile loading of a fiber within a composite, tensile and shear stresses (and strengths) compete. Typically, the crack initiates and grows perpendicular to the long axis of the fiber, but in some cases, shear dominates and the crack grows on an angle, i.e. normal to the direction of shear stresses. This is illustrated in Figure 5. The result can be a hackle zone that is not planar with the origin, but rather angled [8].

To further illustrate this principle, the authors performed an impact test following ASTM D6110-10 (Charpy impact) [18] on an un-notched coupon of material cut from the flat disk web section of an exemplar pulley. Fracture surfaces on representative glass fibers are shown in Figures 7 and 8. Comparing these images to those from the subject pulley (Figure 4) confirms that the fibers in the subject pulley fractured in a manner consistent with classical brittle fracture due to overload. Thus, this particular physical evidence does not rule out the possibility of impact failure.

Admittedly, though, the absence of any striations also does not rule out the possibility of fatigue failure, as glass fibers do not generally exhibit the classic fatigue crack growth behavior common to other materials. Highly filled resins in fatigue typically fracture in a brittle manner without a striation pattern [12]. Additionally, Quinn states "nearly all glasses are not susceptible to classic fatigue crack growth, by which iterative cyclic loading to a crack causes damage nucleation, accumulation, and stepwise growth with periodic spaced striations on the fracture surface" [3]. Consequently, the evidence provided by the fiberglass fracture surfaces can be considered neutral: it can neither confirm nor rule out both fatigue and impact as plausible failure modes. Further proving the point, one investigator in this matter performed fatigue testing of coupons cut from exemplar pulleys and was unable to identify any evidence of fatigue.

Hypotheses

Based on examination of the physical evidence, the most likely hypothesis for failure was impact with one of the other components in the ensuing events immediately after a rear-end collision. (This scenario would require failure of the engine mount to allow the engine and pulley to move forward and make contact with another component.) However, the other party in the matter argued that the most likely cause of failure was fatigue resulting from improper material selection, defective design, and a material defect (specifically, the distribution of glass fiber diameter was said to be too broad) – despite the lack of physical evidence. The first two arguments are addressed herein. The third argument is not addressed, as no evidence was presented to link fiber distribution with the failure mode.

Material Selection

On the issue of material selection, it was argued that phenolic resin is too brittle and notch sensitive for this application or design. However, the use of phenolics for such applications is widespread. In fact, phenolic resin parts have been used in automotive applications since at least the 1930's, primarily in electrical parts and other non-structural components [10]. With improvements in manufacturing methods and a greater understanding of the performance of fiber reinforced composite materials in the 1950's and 1960's, phenolics began to be introduced more widely throughout the automobile. The first phenolic poly-V power steering pulley was released in 1985 [13,15]. By 2000, the use of phenolics for power steering pulleys continued and the general the use of phenolic pulleys in vehicles was growing [4]. The development of phenolic pulleys for air conditioner (A/C) compressors [11] and idler pulleys [1] occurred in the early 2000s. Other automotive applications of phenolics include the impeller and pump housing for the coolant pump, the tensioning pulleys and toothed pulleys for the coolant pump, generator/alternator, air conditioner, and the toothed belt drive controlling the camshaft [6]. Phenolics are also used for aircraft pulleys[1].

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[1] For example, Ralmark Company manufactures phenolic pulleys, which are designed to Military Specification MIL-DTL-7034 (www.ralmark.com).

The advantages of phenolics for this and the other under the hood automotive applications are detailed in References [2,5,11,12,13], and they are in fact considered the "preferred materials for such systems" [12]. To the point about impact performance and notch sensitivity, Fitts and Bessette [5] addressed concerns about impact toughness, concluding that "…the impact resistance of phenolics can be remarkably similar to that of some reinforced thermoplastics…Experience has shown that structures molded of phenolic materials can have good impact resistance if appropriate design principles are used…a significant improvement in impact resistance is possible with short fiber reinforcement while still maintaining the other attractive attributes of phenolics."

Hence, the argument of defect by improper material choice is unfounded.

Defective Design Argument

The opposing party also argued that the choice of a triangular mounting plate was inappropriate as it generated a significant stress concentration and therefore represented a design defect. The location of the crack origin at or near the apex of the plate was used to support this hypothesis. However, the initiation of fracture at this location is also consistent with impact (see exemplar test results below) and therefore inconclusive. In addition, the stresses during normal operation were determined to be negligible through finite element analysis (FEA), as discussed next.

Stress Analysis

To understand the stresses experience by the pulley in each hypothetical scenario, i.e. impact and normal operation, a series of stress analyses were performed using the Finite Element Method. The 3D geometry of a pulley was constructed in ABAQUS 6.12 software (Figure 8) and then meshed using 3D continuum type elements. Basic, linear elastic material properties from the material data sheet were assumed. The triangular mounting plate was modeled as perfectly rigid, a reasonable assumption since the modulus of elasticity of steel (200 GPa) is 16 times greater than the phenolic resin. The plate was constrained against all motion (assumed to be fixed). In order to model the effect of preload, the steel mounting bolts were also modeled and given a preload estimated to be just over 13.3 kN (3000 lbs) using the "Maney Formula" [3].

Load was applied using a continuous (and rigid) surface that provides multi-point (distributed) contact to simulate impact with the overflow tank. This surface spanned across the height of the pulley and provided, at a minimum, two points of contact. Belt tension was added by modeling the belt simply as a thin shell. The geometry of the belt, i.e. the angles of the belt at the points where 1) it comes into contact with the pulley ("leading edge") and 2) it loses contact with the pulley ("trailing edge"), were determined using geometry reconstructed from a laser scan of an exemplar vehicle's engine compartment.

In accordance with the ECM data, i.e. assuming the vehicle to be idling at the time of impact (no pulley acceleration), a tension load was applied to the upper belt end in Figure 8. The bottom end was constrained against axial motion to provide an opposing force and maintain static equilibrium. In order to establish the operating tension on the serpentine V-belt, belt tensions were measured on an exemplar vehicle before and after replacement of its belt during regular maintenance.

Various simulations were performed to consider the effect of bolt preload, belt tension, and impact loading at various configurations. For the purposes of this analysis and due to uncertainty in the loading rate during an impact, a static analysis was performed. The following observations were made:

- The effect of preload is negligible. The tensile stresses are very small (20% of the reported tensile strength and 10% of the flexural strength). The only sizeable stresses are compressive and therefore not likely to initiate cracking.[2] Furthermore, the peak compressive stress is 54% of the compressive strength.
- Belt tension during idling also has little effect.
- Comparing the edge loading results to the flexural strength of the material suggests an ultimate load capacity of approximately 2050 N (460 lbs) with this force distributed along a portion of the pulley's flange.
- The stress distribution around the bolt holes is consistent with the crack patterns documented above, predicting the initiation of both circumferential and radial cracking at both holes (Figure 9).

To test the theory that the pulley failed due to fatigue under normal use (2nd hypothesis), an additional analysis was performed. The peak stresses during normal operation would presumably occur during rotational acceleration of the pulley. Accordingly, this case was modeled by first removing the rigid surface and belt (and its boundary conditions and load) shown in Figure 8. Next, a distributed load (traction) was applied to the pulley/belt contact surface in order to simulate the moment experienced by the pulley during acceleration. A moment value assumed by the other party was applied, as the actual value was unknown. The resulting maximum

[2] Crack initiation in materials occurs in response to a principal tensile stress, i.e. on a plane normal to the maximum principal tensile stress [16].

principal stress was again insignificant relative to the material strength (< 4%).

Exemplar Testing

Static Bend Testing

A static bend test of exemplar pulleys was developed to characterize the fracture behavior of the power steering pulley under transverse loading and to validate the FEA. The setup is shown in Figure 10. The pulleys were bolted to the triangular mounting plate using the three bolts spaced 120° apart, just as in the actual application. The mounting plate was then affixed to a rigid mount on the bottom of the load frame. Load was applied through an aluminum rod mounted on the upper, moveable platen of a universal test frame. Tests were performed for the load applied at various positions (i.e. rotations) along the circumference of the outer flange. Tests were run with the three mounting bolts hand tightened only or torqued to the specified torque of 21.4 N-m (189 in-lbs.). Load was applied at a quasi-static rate of 1 inch/min.

The load to induce cracking varied between 2470 N (555 lbs) and 2740 N (617 lbs) for four exemplars. A sample tested following the method above with the loads rotated 30° from the nearest mounting holes is shown in Figure 11. The crack pattern is characterized by "radial" cracks on both sides of the hole located between the loading points (labeled 1 in Figure 11), a circumferential/transverse crack along the apex of the triangular mounting plate (opposite side) (2), and a 45° angle crack that emanates off the transverse crack and grows outward to the flange, where it then turns to propagate circumferentially (3). All of these features are consistent with the subject pulley (Figure 12). A single radial crack is found to be associated with each of the other two holes, as well.

Impact Testing

Next, a dynamic bend test of exemplar pulleys was developed to characterize the fracture behavior of the power steering pulley under transverse impact loading. The setup is shown in Figure 13 and Figure 14. This test effectively simulates the failure mode proposed by the authors albeit in a more controlled manner. For example, it assumes only fore/aft relative motion of the engine/pulley and overflow tank and neglects the possibility of contact with other components.

The pulleys were mounted to a fixed steel frame using rubber-mounted bearings. Three pulleys were configured such that the angle of belt wrap on the pulley to be impacted was consistent with the angle of wrap measured on an exemplar vehicle (slightly more than 90° of engagement, as determined from the laser scan). The serpentine belt was tensioned to the exemplar vehicle value using an idler pulley affixed to an adjustable slide. One pulley (lower left of Figure 13) was driven using an electric motor. The serpentine belt then drove the other pulleys. The velocity of the electric motor was controlled using an AMETEK speed controller and verified using a EXTECH model 461891 digital contact tachometer.

A pneumatic actuator was attached to an adjustable frame (Figure 13). Exemplar coolant overflow tanks were sectioned, and a small test coupon was excised from the corners. These tank coupons were then adhesively bonded to the end of the actuator. The frame position could be adjusted to control the region of the tank test coupon that came into contact with the test pulley as well as the depth of penetration of the ram/tank test coupon through the contact plane with the test pulley. Again, the mounting bolt preload was varied. Through trial and error, it was determined that a cylinder load of approximately 1780 N (400 lbs) was required to fracture or significantly crack the pulley. This value, although lower, is consistent with the data from the static bend tests and stress analysis, considering dynamic effects such as impact factor and the strain-rate dependence of the polymer's strength.

The fracture patterns on the tested pulleys and witness marks on the coolant tank test coupons were examined. Again, the crack pattern was very similar to the subject and static tested pulleys (Figure 15). Furthermore, witness marks similar to those on the subject overflow tank were found on the exemplar overflow tank samples (not shown).

Mount Testing

As discussed previously, contact of the pulley with other engine components requires significant deformation and, possibly, fractures of both the engine mounts and transmission mounts. To characterize the mechanical response of exemplar mounts under shear loading, a static shear test was developed. A test in progress is shown in Figure 16. For each test, the new and unused sample was mounted to two metal angles. Each angle was connected to the frame or moveable platen of the load frame via threaded rod and adapters. A Tinius Olsen LoCap 30k universal test frame was utilized to apply a load at a quasi-static rate of 1 inch/min until the sample fractured or deformation of the fixturing became excessive.

Both types of mounts were found to exhibit considerable ductility due to their primarily rubber construction, but the engine mount was found to fail at a smaller displacement (8.1 cm, as opposed to 11.1 cm for the transmission mount). This result is consistent with the observation that the transmission mounts had not failed.

Conclusions

Early in the investigation of the accident associated with the pulley fracture, two competing hypotheses were proposed: 1) fatigue failure due to defect and 2) overstress failure due to the rear end impact.

The failure analysis conducted by the authors found no physical evidence to support fatigue. No macroscopic evidence suggested a fatigue failure, and the microscopic evidence was found to be inconclusive. In addition, the arguments about material and design defect were unfounded and unproven. In fact, a review of the literature indicates widespread use of glass filled phenolic resin for automotive under-the-hood applications. Stress analysis also demonstrated low stresses during normal operation negating the design defect argument.

On the other hand, the evidence supporting the impact hypothesis was numerous. First, the ECM data indicated the engine was idling at the time of impact. Second, witness marks on the pulley itself suggested it contacted another object during the fracture event. The continuity of the witness marks across the various fragments of the pulley suggests the pulley was rotating at the time of the incident. Third, fracture of the engine mounts confirm that the engine (and the attached power steering pump pulley) did displace during the incident, thereby allowing contact of the various components under the hood. This motion and contact is further evidenced by damage to those other components and witness marks on the nearest component, the coolant overflow tank. Finally, a thorough analytical and experimental investigation based on basic engineering and mechanics principles clearly demonstrated that the crack pattern on the subject pulley was consistent with bending failure due to impact. In fact, the authors' impact testing nearly replicated the exact crack pattern on the pulley, as well as the witness marks on the overflow tank samples.

This case study illustrates the use of the scientific method in performing a root cause failure analysis [14,17]. The authors 1) collected data through visual and microscopic examinations; 2) analyzed that data through fractographic interpretations and basic engineering analyses; 3) developed hypotheses; 4) tested those hypotheses through exemplar testing, stress analysis, and additional microscopy; and 5) selected a final hypothesis: failure by impact.

As a side note, the allegation of multiple fatigue crack origins on the glass fibers and their interpretation as evidence of fatigue is a perfect example of the so-called "red herring", that is, a piece of irrelevant evidence or an argument that draws attention away from the original argument [7]. This is a common pitfall to be avoided at all cost in forensic investigations. The authors recommend a multi-disciplinary approach based in fundamental engineering principles and the scientific method with a strict peer review process at every step to catch errors in both analysis and fractographic interpretation.

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Figure 1. Subject power steering pump pulley. Witness marks indicated.

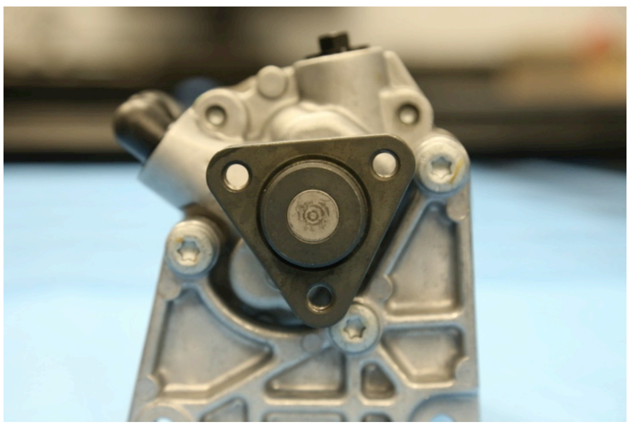

Figure 2. Power steering pump with triangular mounting plate (pulley not installed).

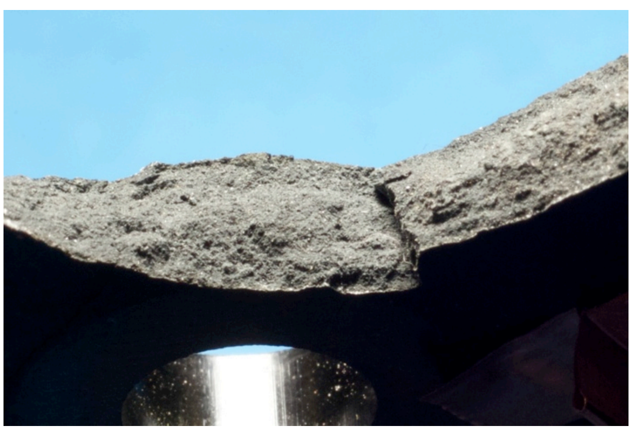

Figure 3. Fracture surface of subject pulley near the likely origin.

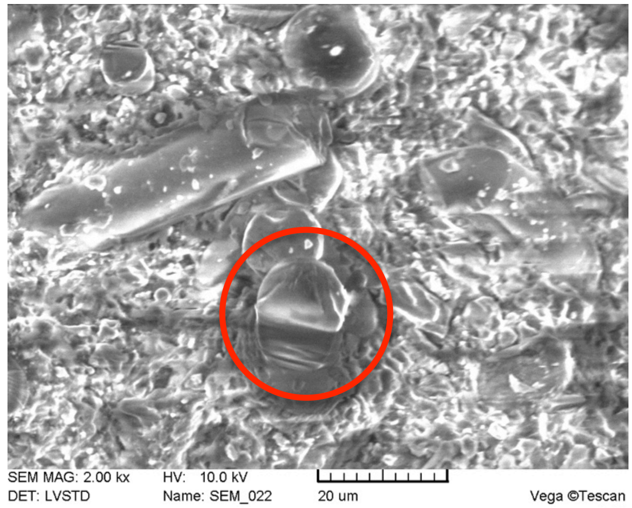

Figure 4. SEM micrograph of the subject pulley fracture surface showing representative fiber fractures.

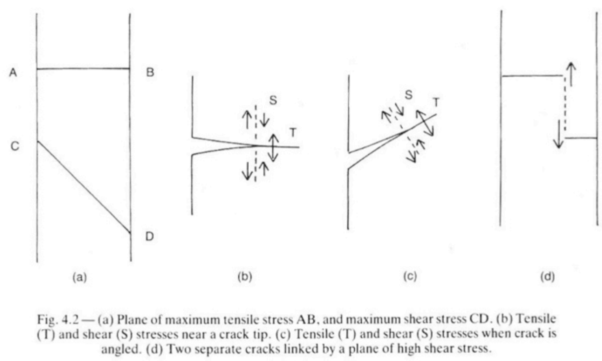

Figure 5. Courtesy Hearle et al. [9]

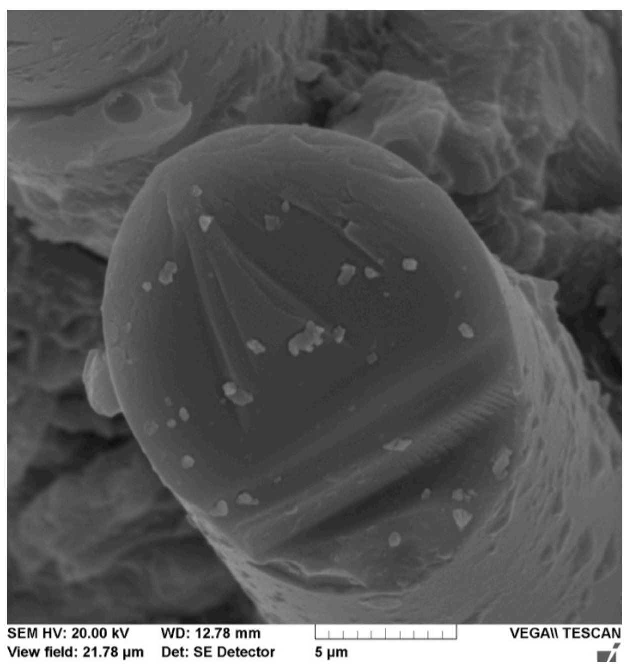

Figure 6. Typical fiber fracture from Charpy impact specimens from an exemplar pulley.

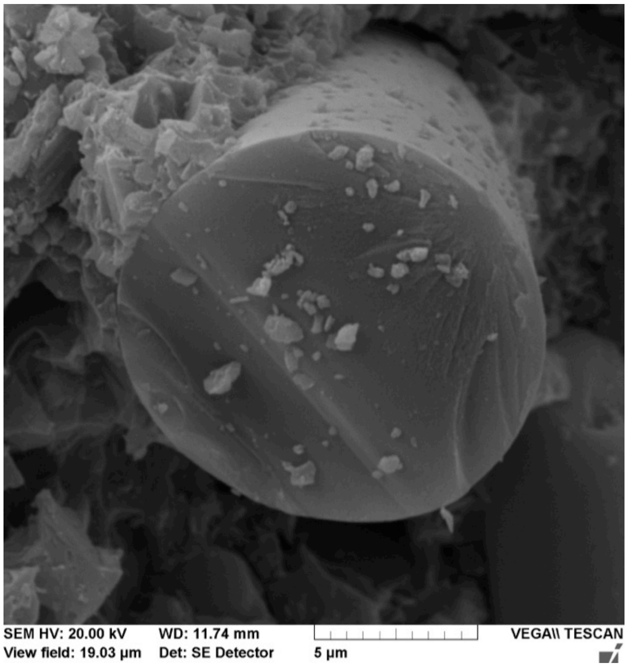

Figure 7. Typical fiber fracture from Charpy impact specimens from an exemplar pulley.

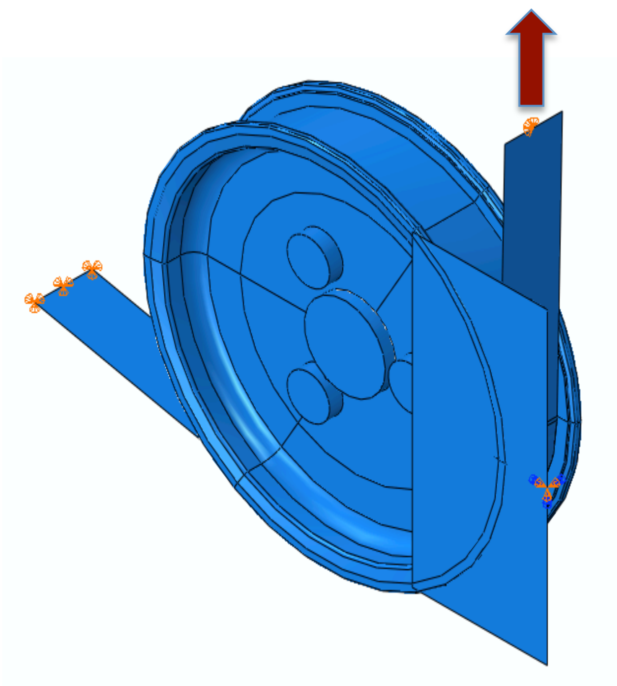

Figure 8. Finite element model. Belt load indicated. The impacted body (overflow tank) is represented as a rigid surface that contacts the pulley along a portion of the outer flange.

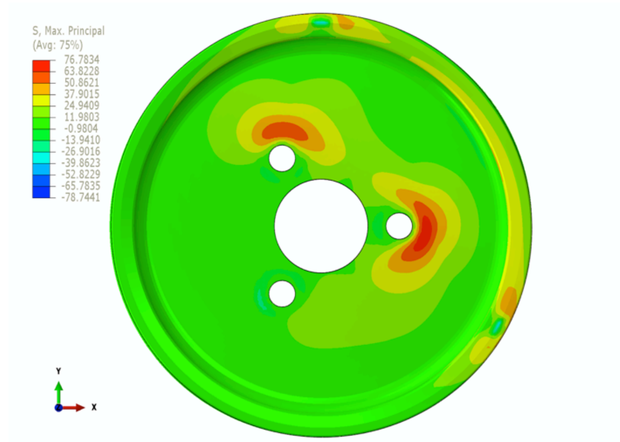

Figure 9. Maximum principal stress distribution for edge loading with the pulley rotated such that the contact points are 30° away from the bolt holes.

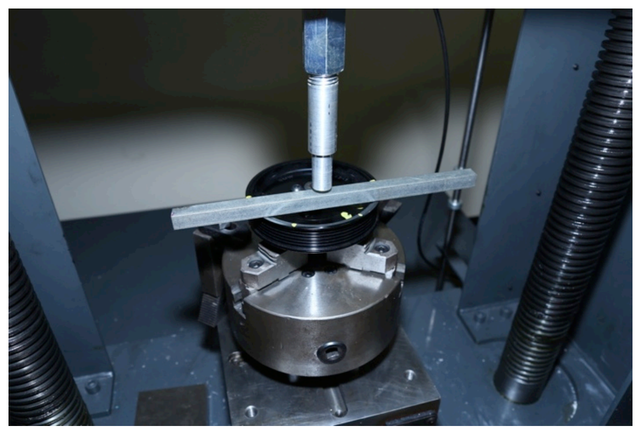

Figure 10. Static two-point bend test setup.

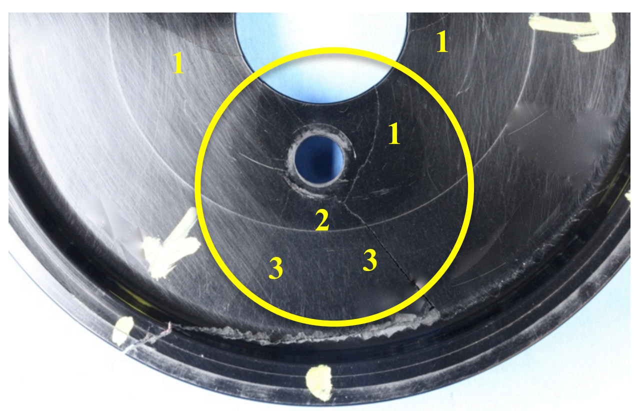

Figure 11. Close-up of exemplar pulley loaded under two-point loading.

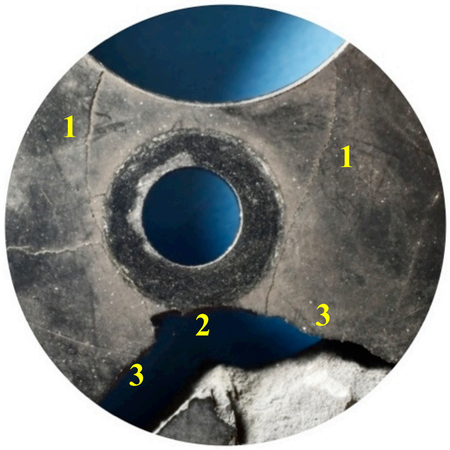

Figure 12. Close-up of cracking on outboard face of subject pulley.

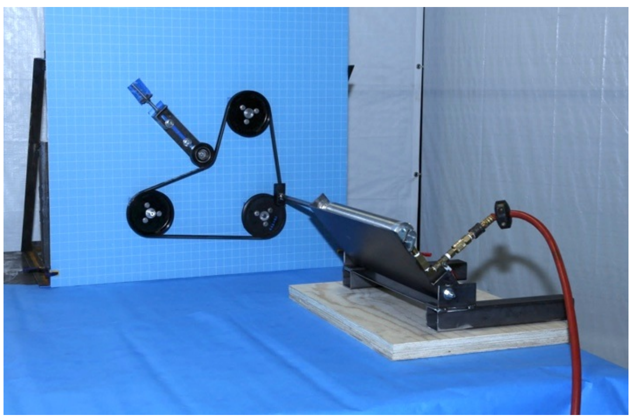

Figure 13. Overview of the dynamic impact test setup.

Figure 14. Close-up of the coolant expansion tank test coupon bonded to the end of the actuator pushrod.

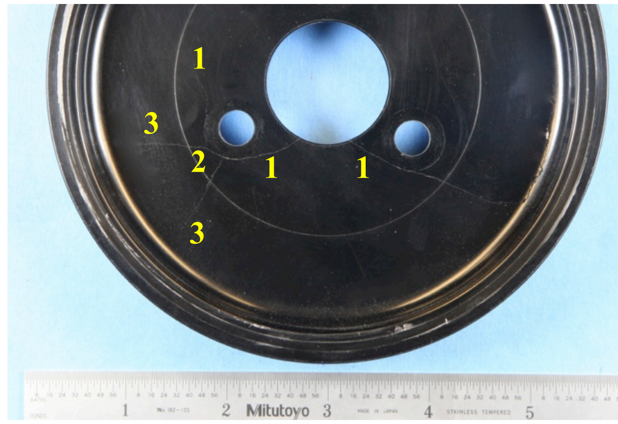

Figure 15. Crack pattern on an exemplar pulley resulting from dynamic impact.

Figure 16. Transmission mount during shear test.