

Declaration of Dr. Mary K. Bolin in Support of
Petition for *Inter Partes* Review of
U.S. Patent No. 11,124,027 B2

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

REVVO TECHNOLOGIES, INC.,
Petitioner

v.

TIRE STICKERS LLC,
Patent Owner

IPR2025-00631

U.S. Patent No. 11,124,027 B2
Issue Date: September 21, 2021

Title: Display Assemblies and Methods for Applying the Same to Vulcanized
Rubber Articles

DECLARATION OF DR. MARY K. BOLIN

Declaration of Dr. Mary K. Bolin in Support of
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I, Mary K. Bolin, declare as follows:

1. I am Emeritus Professor at the University of Nebraska, Lincoln Libraries. I have held the following positions: Professor and Catalog and Metadata Librarian, Digital Initiatives and Special Collections Department, University of Nebraska—Lincoln Libraries (2015–2020); Professor and Chair, Discovery and Resource Management and Coordinator of Collection Development, University of Nebraska, Lincoln Libraries (2004–2015); Lecturer, San José State University School of Information: Lecturer (2008–present); Head of the Technical Services Department, University of Idaho Library (1993–2003; promoted to Professor in 1999); Head of the Cataloging Department, University of Idaho Library (1986–1993; promoted to Associate Professor and tenured in 1991); Head of Records Maintenance Section, Cataloging Department, University of Georgia Libraries (1981–1986).

2. Over the course of my work as a librarian, professor, researcher, student research supervisor, and author of numerous scholarly papers and other publications, I have had extensive experience with cataloging records and online library management systems built around Machine-Readable Cataloging (MARC) standards. I also have substantial experience in authenticating printed documents and establishing the date when they were accessible to ordinarily skilled researchers.

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3. Attachment A is my full resume.

4. I have been retained by counsel for Revvo Technologies, Inc. (“Petitioner”) to evaluate, authenticate, and establish the dates of public availability of certain documents in the above-captioned cases. For my time performing this service, I am being paid my usual hourly fee. I have no financial interest in this litigation, or affiliation with Petitioner. My compensation is not dependent upon the outcome of, or my testimony in, this litigation or any other proceeding, including before the U.S. Patent Office.

A. Documents of Interest

5. The documents that are the subject of this declaration are the following:

- **Document 1.** Gent, A. N., & Walter, J. D. (2006). *Pneumatic tire*. Washington, D.C.: US Department of Transportation, National Highway and Transportation Safety Board.
- **Document 2.** “Vulcanization,” Chapter 7, “Vulcanization,” Chapter 7, The Science and Technology of Rubber (Fourth Edition). Elsevier, 2013, pages 337-381.
- **Document 3.** *Know Your Tires with Tire-Track*. Tracking Systems LLC, 2002.
- **Document 4.** *Reduce Your Tire Costs with the Tire-track ID Unit*. Tire Track LLC, n.d.

- **Document 5.** “Fast-drying Cement.”

http://www.patchrubber.com/tire_repair/16450.html

B. Methodology

6. I searched each of these documents in the OCLC database, Google Scholar, and one or more subscription databases such as IEEE Xplore and ACM Digital Library. I also searched the library catalogs of institutions such as the University of Nebraska—Lincoln and other large research libraries. My goal was to find a record in one of these databases that contained a date indicating when the document was available to the public.

7. *Use of MARC Records.* The “Machine Readable Cataloging” standard, also known as “MARC,” is an industry-wide standard method of organizing library catalog information. The Library of Congress first developed MARC in the 1960s. A MARC-compatible library is one that has a catalog consisting of individual MARC records for each of its works. Today, MARC is the primary communication protocol for the transfer and storage of bibliographic metadata in libraries.

8. OCLC is a database of MARC records used by libraries worldwide. When an OCLC-participating institution acquires a work, it creates a MARC record for this work in its computer catalog system, and OCLC automatically supplies the date of creation. The MARC record creation date reflects the date on which (or

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shortly after) the item was first acquired and catalogued. Once the MARC record is created by a cataloger at an OCLC-participating member institution, it is instantaneously available to any OCLC-participating members, and, therefore available to the public.

9. A MARC record comprises several fields, each of which contains specific data about the work. Each field is identified by a standardized, unique, three-digit code corresponding to the type of data that follows. For example, a work's title is recorded in field 245, the primary author of the work is recorded in field 100, an item's International Standard Book Number ("ISBN") is recorded in field 020, an item's Library of Congress call number is recorded in field 050, and the publication date is recorded in field 260 or 264 under the subfield "c." If a work is a periodical, then its publication frequency is recorded in field 310, and the publication dates (*e.g.*, the first and last publication) are recorded in field 362, which is also referred to as the enumeration/chronology field. The library that created the record is recorded in field 040 in subfield "a" with a unique library code. When viewing the MARC record online via OCLC's Worldshare Record Manager database, hovering over this code with the mouse reveals the name of the library. I used this method of "mousing over" the library codes in the OCLC database to identify the originating library for all of the MARC records in this declaration, as

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well as the “display holdings” command to see a list of libraries that own the item. In the MARC records in the OCLC Worldshare Record Manager database, MARC field 040 contains the OCLC symbols of institutions transcribing, creating, and modifying the record.

10. OCLC was created “to establish, maintain and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific, literary and educational knowledge and information.”¹ Among other services, OCLC and its members are responsible for maintaining the WorldCat database (<http://www.worldcat.org/>), which is used by independent and institutional libraries throughout the world. OCLC is the international cooperative to which libraries catalog records and others pay to access MARC records. The MARC records referenced in this declaration, extracted from the OCLC database, were generated in the ordinary course of

¹ Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Incorporated (available at <http://www.oclc.org/en-US/membership/councils.html>).

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business. Further, I personally located and downloaded each of these records associated with the documents on which my declaration focuses.

11. OCLC provides its members online access to MARC records through its OCLC Worldshare Record Manager database. When an OCLC member institution acquires a work, it creates a MARC record for this work in its computer catalog system in the ordinary course of its business. MARC records created at the Library of Congress are batch-loaded into the OCLC database through a subscription to MARC Distribution Services daily or weekly. Once the MARC record is created by a cataloger at an OCLC member institution or is tape-loaded from the Library of Congress, it is then made available to any other OCLC members online, and, therefore, made available to the public.

12. When an OCLC member institution creates a new record, OCLC automatically supplies the date of creation for that record. The MARC record creation date reflects the date on which, or shortly after which, the item was first acquired or cataloged.

13. The date of creation for the MARC record appears in the fixed field (008), characters 00 through 05. Field 005 is a 16 digit field that records the Date characters *yyyymmdd* including 4 for the year, 2 for the month, and 2 for the day. The Date entered on file never changes. These dates are automatically supplied by

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the OCLC system and cannot be changed by the user. When the MARC record is created in OCLC, it is available throughout the world to other libraries and in WorldCat, the public version of OCLC Connexion. Thus, the date of creation of the MARC record by a cataloger at an OCLC member institution reflects when the underlying item is accessible to the public.

14. For each of Documents 1-5, I included a search of OCLC, www.oclc.org, which is a large shared database used by libraries around the world to create and exchange cataloging data, using MARC format, which is a universal communications format for that data.

15. For those documents for which there is a record in OCLC, I determined when the record was created and which libraries own the item. I then visited the website of the library or libraries that own the item, searched their library catalog, and determined when the item was added to the library's collection.

16. I am familiar with many online catalogs, databases, and search engines. In preparing for this declaration, I used authoritative information systems such as the above-mentioned WorldCat (<https://www.worldcat.org>), the online catalog of the Library of Congress (<https://catalog.loc.gov>), shared research databases such as ResearchGate and CiteSeerX, the online catalog of a number of large research libraries such as the University of Nebraska—Lincoln, IEEEExplore, and Google

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Scholar search for records. These records are identified and discussed in this declaration.

C. Document 1

17. The following are my opinions with respect to the authenticity and public availability of Document 1:

1. Authentication of Document 1

18. Document 1, Gent, A. N., & Walter, J. D. (2006). *Pneumatic tire*. Washington, D.C.: US Department of Transportation, National Highway and Transportation Safety Board.

19. There is a MARC record in OCLC for Document 1 with a creation date of October 6, 2008. There is another MARC record in OCLC for Document 1 with a creation date of November 17, 2008.

20. A PDF of Document 1 is available from the NHTSA website, with PDF properties showing a creation date of December 30, 2009.
https://www.nhtsa.gov/sites/nhtsa.gov/files/pneumatictire_hs-810-561.pdf

21. Attachment B is a PDF of the first MARC record for Document 1 from OCLC.

22. Attachment C is a PDF of the second MARC record for Document 1 from OCLC.

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23. Attachment D is a PDF of Document 1 downloaded from NHTSA.
https://www.nhtsa.gov/sites/nhtsa.gov/files/pneumatictire_hs-810-561.pdf

24. Attachment E is a screenshot of the PDF properties of Document 1 downloaded from NHTSA.

2. *Public Availability of Document 1*

25. Based on the fact that a MARC record for Document 1 is found in OCLC with a creation date of October 6 and November 17, 2008, and that a PDF of Document 1 with PDF properties showing a creation date of December 30, 2009, can be downloaded from the NHTSA website, it is my opinion that Document 1 was available in October 2008 and could have been located by a skilled researcher.

D. Document 2

26. The following are my opinions with respect to the authenticity and public availability of Document 2:

3. *Authentication of Document 2*

27. Document 2, “Vulcanization,” Chapter 7, “Vulcanization,” Chapter 7, The Science and Technology of Rubber (Fourth Edition). Elsevier, 2013, pages 337-381.

28. There is a MARC record in OCLC for Document 2 with a creation date of January 28, 2013. There is a MARC record for Document 2 in the library catalog of the Trinity College, Dublin, Library, with a creation date of August 8, 2014.

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29. Attachment F is a PDF of the MARC record for Document 2 from OCLC.

30. Attachment G is a PDF of the MARC record for Document 2 from Trinity, College, Dublin library catalog.

4. Public Availability of Document 2

31. Based on the fact that a MARC records for Document 2 is found in OCLC with a creation date of January 28, 2013, and that a MARC record for Document 2 is found in the library catalog of Trinity College, Dublin, with a creation date of August 8, 2014, it is my opinion that Document 2 was available in January 2013 and could have been located by a skilled researcher.

E. Document 3

32. The following are my opinions with respect to the authenticity and public availability of Document 3:

5. Authentication of Document 3

33. Document 3, *Know Your Tires with Tire-Track*. Tracking Systems LLC, 2002.

34. Document 3 was captured on the web by the Wayback Machine on September 2, 2009. The PDF properties for that capture show a creation date of May 15, 2002.

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35. Attachment H is a PDF of the Document 3 downloaded from the Wayback Machine web capture.
https://web.archive.org/web/20090902154005/http://www.patchrubber.com/training/tire_track.pdf

36. Attachment I is a screenshot of the PDF properties of Document 3 from the Wayback Machine web capture.

6. *Public Availability of Document 3*

37. Based on the fact Document 3 is found on the Wayback Machine with a capture date of September 2, 2009, and PDF creation date of May 15, 2002, it is my opinion that Document 3 was available in May 2002, and no later than September 2009. and could have been located by a skilled researcher.

F. Document 4

38. The following are my opinions with respect to the authenticity and public availability of Document 4:

7. *Authentication of Document 4*

39. Document 4. *Reduce Your Tire Costs with the Tire-track ID Unit*. Tire Track LLC, n.d.

40. Document 4 was captured on the web by the Wayback Machine March 4, 2011. The PDF properties for that capture show a creation date of October 29, 2009.

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41. Attachment J is a PDF of Document 4 downloaded from the Wayback Machine web capture.
https://web.archive.org/web/20110304053609/http://www.tire-track.com:80/PDFs/Tire-Track_Brochure.pdf

42. Attachment K is a screenshot of the PDF properties of Document 4 from the Wayback Machine web capture.

8. Public Availability of Document 4

43. Based on the fact Document 4 is found on the Wayback Machine with a capture date of March 4, 2011, and PDF creation date of October 29, 2009, it is my opinion that Document 4 was available in October 2009 and could have been located by a skilled researcher.

G. Document 5

44. The following are my opinions with respect to the authenticity and public availability of Document 5:

9. Authentication of Document 5

45. Document 5. “Fast-drying Cement.”
http://www.patchrubber.com/tire_repair/16450.html Document 5 was captured on the web by the Wayback Machine November 9, 2013.
https://web.archive.org/web/20131109143040/http://www.patchrubber.com/tire_repair/16450.html

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46. Attachment L is a PDF of the Document 5 downloaded from the Wayback Machine web capture.

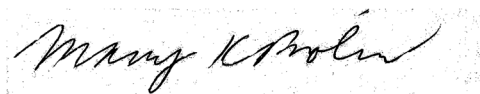
10. Public Availability of Document 5

47. Based on the fact Document 5 is found on the Wayback Machine with a capture date of November 9, 2013, it is my opinion that Document 5 was available in November 2013 and could have been located by a skilled researcher.

* * *

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements are made with the knowledge that willful false statements and the like are punishable by fine, imprisonment, or both, under Section 1001 of Title 18 of the U.S. Code. I state under penalty of perjury under the laws of the United States of America that the foregoing is true and correct.

Executed this 3rd day of February, 2025, in Lincoln, Nebraska.



Mary K. Bolin

Attachment A

Mary K. Bolin, PhD
2433 U Street
Lincoln, Nebraska 68503
mary@marykbolin.com

Mary K. Bolin, PhD

Professor Emeritus
University Libraries
University of Nebraska—Lincoln
mbolin2@unl.edu

Lecturer,
School of Information
San José State University
mary.bolin@sjsu.edu

EDUCATION

PhD, Educational Studies (Educational Leadership and Higher Education), 2007, University of Nebraska

Dissertation: *A Typology and Discourse Analysis of the Status and Appointments of Librarians at Land Grant Universities* (available at digitalcommons.unl.edu)

MA, English, 1999, University of Idaho
Thesis: *Grace: A Contrastive Analysis of a Biblical Semantic Field* (available at digitalcommons.unl.edu)

MSLS, 1981, University of Kentucky

BA, Linguistics, 1976, University of Nebraska—Lincoln

WORK EXPERIENCE

Center for Digital Research in the Humanities. Fellow, 2019- Emeritus, 2020-

University of Nebraska--Lincoln Libraries: Professor and Catalog and Metadata Librarian, Digital Initiatives and Special Collections, 2015-2020. Emeritus, 2020-

University of Nebraska—Lincoln Libraries: Professor and Chair, Discovery and Resource Management, 2004-2015; Coordinator of Collection Development, 2012-2015

University of Idaho Library: Head, Technical Services Department, 1993-2003. Promoted to Professor in 1999

University of Idaho Library: Head, Cataloging Department, 1986-1993. Promoted to Associate Professor and tenured, 1991

University of Georgia Libraries: Head, Records Maintenance Section, Cataloging Department, 1981-1986

Teaching:

San José State University School of Information:

LIBR 281, Metadata. 2009-

LIBR 248, Introduction to Cataloging and Classification. 2013-

LIBR 202, Information Retrieval. 2008-2013

Associate Coordinator, Gateway PhD program, San Jose State University, 2021-2022

American Library Association:

Cataloging for Non-Catalogers, Online Continuing Education Course, 2017-

Intermediate Cataloging for Non-Catalogers, Online Continuing Education Course, 2018-

Lyrasis:

Webinar on BibFrame, taught twice a year, 2020-

Quick and Clean Cataloging, Parts 1, 2, and 3. 2022-

Independent Study in Idaho:

Library Science C415, Technical Services for Small Libraries, 2004-2013

Library Science C416, Library Services to Rural Libraries, 2004-2013

Library Science C422, Use of the School Library, 1999-2013

Library Science C425/525, Organization and Management of Small Libraries,
1988-2013

Library Science C427, Library or Media Center Practicum, 1995-2013

Gateway PhD Program (San Jose State University and Queensland University of Technology).
SJSU supervisor for two PhD students, 2015-

Gateway PhD Program (San Jose State University and Manchester Metropolitan University).
Associate Coordinator, 2021-2022

Consulting

Expert witness for multiple attorneys employed by Wolf, Greenfield & Sacks, P.C.,
Hughes Hubbard & Reed LLP, and other firms. 2017-

Editing

Language and academic editing for [EditSprings](#), a service for international scholars, 2020-

SCHOLARSHIP

Refereed Publications:

(Publications available from digitalcommons.unl.edu)

Pytlík Zillig, Brian, and Mary K. Bolin. (Forthcoming 2024). “Visualization of Semantic Primes in Texts from Early Modern English Drama.” *Journal of the Japanese Association for the Digital Humanities*.

Bolin, Mary K. (2022). “Academic Libraries and Writing Centers: Collaborations at US Public Research Universities.” *School of Information Student Research Journal*, 11(2). Retrieved from <https://scholarworks.sjsu.edu/ischoolsrj/vol11/iss2/2>

Bolin, Mary K. (2022). *Refocusing Academic Libraries through Learning and Discourse: The Idea of a Library*. Oxford, UK: Chandos/Elsevier.

Bolin, Mary K. (2022). “Metadata, Catalog Systems, Linked Data, and the Evolving ILS.” In: Sandra Hirsh (Ed.), *Information Services Today: An Introduction*. 3rd ed. New York: Rowman and Littlefield.

Wintermute, Harriet E., and Bolin, Mary K. (2018). "Metadata Generators for Backlog Reduction: Metadata Maker Streamlines Cataloging and Facilitates Transition. *Technical Services Quarterly* 35(2) doi: <https://doi.org/10.1080/07317131.2018.1422879>

Bolin, Mary K. (2018). "Metadata, Catalog Systems, Linked Data, and the Evolving ILS." In: Sandra Hirsh (Ed.), *Information Services Today: An Introduction*. 2nd ed. New York: Rowman and Littlefield.

Bolin Mary K. (2017). *The 21-century Academic Library: Global Patterns of Organization and Discourse*. Oxford: Chandos Publishing. (Chandos Information Professional Series)

Bolin, Mary K. (2017). Linguistics and LIS: A Research Agenda." *SLIS Student Research Journal*, 7:1.
Retrieved from <http://scholarworks.sjsu.edu/slissrj/vol7/iss1/2>

Bolin, Mary K. (2014). "Open Access Web Resources for Library Continuing Education and Training." In S. Hines (Ed.), *Revolutionizing the Development of Library and Information Professionals: Planning for the Future* (pp. 107- 124). Hershey, PA: .
doi:10.4018/978-1-4666-4675-9.ch008.

Bolin, Mary K. (2014). "The Language of Academic Librarianship: The Discourse of Promotion and Tenure." *Advances in Library Administration and Organization* 32.

Bolin, Mary K. "Librarian Status at US Research Universities: Extending the Typology." *Journal of Academic Librarianship* 34:4 (September 2008)

Bolin, Mary K. "A Typology of Librarian Status at Land Grant Universities." *Journal of Academic Librarianship*, 34: 3 (May 2008)220:230.

Bolin, Mary K. "The Library and the Computer Center: Organizational Patterns at Land Grant Universities." *Journal of Academic Librarianship*, 31:1 (2005)

Eckwright, Gail Z. and Mary K. Bolin. "The Hybrid Librarian: The Affinity of Collection Management with Technical Services and the Organizational Benefits of an Individualized Assignment." *Journal of Academic Librarianship*, 27:6 (2001)452:457.

Bolin, Mary K. "Catalog Design, Catalog Maintenance, Catalog Governance," *Library Collections, Acquisitions, and Technical Services*. 24: (2000)53-63.

Bolin, Mary K. "The Collegial Environment and the Functional Organization," *Journal of Library Administration*. 29:2(1999):49-61.

Bolin, Mary K. "Cataloging Environmental Impact Statements and Related Documents," *Resource Sharing and Library Networks*. 14:1(1999): 21-40.

Bolin, Mary K. "Waiting for the Electrician or Someone like Him: Client-Centered Technical Services" Proceedings of the Association of College and Research Libraries National Conference, Nashville, April 1997.

< http://www.ala.org/Content/ContentGroups/ACRL1/Nashville_1997_Papers/Bolin.htm >

Grants:

Electronic Theses and Dissertations. Seed Grant from University of Idaho Office of Research, 2002. Co PI with Gail Z. Eckwright. \$6500.

Interoperability of Metadata for Thematic Research Collections. Grant to the Center for Digital Research in the Humanities from the Institute of Museum and Library Services 2005-2008.

Project Team Member.

http://unlcms.unl.edu/cas/center-for-digital-research-in-the-humanities/projects/pages/iom_files/IOM_Final_Narrative_Report_July_2008.pdf

Other Publications:

Library Philosophy & Practice. Peer-reviewed electronic library science journal. Mary K. Bolin and Gail Z. Eckwright, founders and editors. <http://digitalcommons.unl.edu/libphilprac>

Library Science C415, Technical Services for Small Libraries, through Independent Study in Idaho. 2004.

Library Science C416, Library Services to Rural Libraries, through Independent Study in Idaho. 2004.

Library Science C422, Use of the School Library, through Independent Study in Idaho. Revised 1999.

Library Science C425/525, Organization and Management of Small Libraries through Independent Study in Idaho. Revised 2005.

Library Science C427, Library or Media Center Practicum, Independent Study in Idaho. Revised 1999.

Presentations:

Bolin, Mary K. "BibFrame and the MARC Cataloging Environment: an Introduction." Lyrasis Webinar, June 16, 2020, August 17, 2021.. Recording available <http://lyrasis.adobeconnect.com/paifo9e0dm30/>

Pytlik Zillig, Brian, and Mary K. Bolin. "A Little More than Kin, a Little Less than Kind": the Semantic Field Grace in Early Modern English" Poster Session, Text Encoding Initiative Meeting, Graz, Austria, September 18, 2019

Pytlik Zillig, Brian, and Mary K. Bolin. "Shakespeare and the Enumeration of Semantic Primes." Research Paper Presentation, Text Encoding Initiative Meeting, Tokyo, Japan, September 13, 2018

"Library Philosophy and Practice: Creating and Maintaining an Open-Access E-Journal," Presentation to UNCL meeting (libraries at campuses of the University of Nebraska), Lincoln, Nebraska, March 20, 2008.

Presentation to "Thinking outside the Borders" participants on the open-access electronic journal Library Philosophy and Practice and its role in the international library community. University of Nebraska—Lincoln Libraries, October 24, 2007

Panel discussion on open access electronic journals. GWLA directors' meeting. Linda K. Hall Library, Kansas City, Missouri. April 2007.

"Waiting for the Electrician or Someone Like Him: Client-Centered Technical Services." Association of College and Research Libraries National Conference, Nashville, April 5, 1997.

" 'Some Problems of an Editor': the Idaho Librarian from Manuscript to Published Issue," Joint Annual Conference of the Idaho Library Association and the Washington Library Association, Spokane, Washington, April 6, 1995.

"Automating Idaho's Libraries: a Historical Perspective." Idaho Library Association Annual Conference, Idaho Falls, October 4, 1990.

"Small Library Management." Idaho Library Association Spring Conference, Lewiston, Idaho, May 13, 1989.

"No More 'Good Workers': Excellence and Academic Library Classified Staff." Association of College and Research Libraries 5th Annual Conference, Cincinnati, April 7, 1989.

"Communication to and from Cataloging Departments." Heads of Cataloging Discussion Group, American Library Association Midwinter Meeting, San Antonio, January 1988.

Discussion Leader at the LAMA (Library Administration and Management) Management Exchange. American Library Association Annual Meeting, San Francisco, June 1987.

"Staff Turnover." Heads of Cataloging Discussion Group, American Library Association Midwinter Meeting, Chicago, January 1987.

SELECTED PROFESSIONAL SERVICE

Reviewer. *Resources for College Libraries*. Linguistics bibliography, Spring 2020.

Peer reviewer for ALISE National Conference presentations, Spring 2020.

Peer reviewer for *Journal of Academic Librarianship*, 2012-

Peer reviewer for refereed journal, *Western Nigerian Journal of Medical Sciences* (<http://www.wnjms.org/>), a publication of Ladoke Akintola University of Technology (LAUTECH) Teaching Hospital, 2008-

PhD Reviewer for students from Aligarh Muslim University, India, 2010-

Outside reviewer for numerous library faculty promotion and tenure cases in US universities.

University of Nebraska--Lincoln

Chair, University Libraries Faculty, 2018

Faculty Senate Academic Rights and Responsibilities Committee, 2016- Chair, 2018-19

Faculty Senate – 2004-2008; 2008-2011

Faculty Senate Executive Committee 2004-2008

Academic Planning Committee (APC), 2005-2008; Vice Chair, 2006-2007; Chair, 2007-2008

Aesthetic Review Committee 2006-2007

APC monitor for academic program reviews: Department of Political Science, 2005;
Department of Educational Psychology 2006
Pacific Northwest Library Association:

Editor, *PNLA Quarterly*, December 2002-December 2013

Idaho Library Association:

Editor, *The Idaho Librarian*, September 1990-January 1996

Attachment B

Bibliographic Record - OCLC Number: 260598622

LDR	Record Status	'c' - Corrected or revised
	Type of Record	'a' - Language material
	Bibliographic Level	'm' - Monograph/Item
	Type of Control	' ' - No specified type of control
	Encoding Level	'3' - Abbreviated level
	Descriptive Cataloging Form 'a' - AACR2	
001	260598622	
005	20240202180208.2	
008	Date Entered on File	'081006'
	Type of Date/Publication Status	's' - Single date
	Date1/Beginning Date of Publication	'2006'
	Date2/Ending Date of Publication	' '
	Place of Publication, Production, or Execution Code	'dcu' - District of Columbia
	Illustrations	'ad '
	Target Audience	' ' - Unknown or unspecified
	Form of Item	'q' - Direct electronic
	Nature of Contents Code	'b '
	Government Publication	'f' - Federal/national
	Conference Publication	'0' - Not a conference publication
	Festschrift	'0' - Not a festschrift
	Index	'1' - Index present
	Literary Form	'0' - Not fiction
	Biography	' ' - No biographical material
	Language Code	'eng' - English
	Modified Record	' ' - Record is not modified
	Cataloging Source Code	'd' - Other
007	Category of Resource	'c' - Electronic Resource
	Specific Material Designation (c)	'o' - Optical disc
	Color (c)	'c' - Multicolored
	Dimensions (c)	'g' - 4 3/4 in. or 12 cm.
	Sound (c)	' ' - No attempt to code
	Image Bit Depth (c)	' '
	File Formats (c)	' ' - No attempt to code
	Quality Assurance Target(s) (c)	' ' - No attempt to code
	Antecedent/Source (c)	' ' - No attempt to code
	Level of Compression (c)	' ' - No attempt to code
	Reformatting Quality (c)	' ' - No attempt to code
040	AKR \$b eng \$c AKR \$d OCLCQ \$d OCLCA \$d OCLCQ \$d OCLCF \$d OCLCQ \$d OCLCO \$d OCLCQ \$d OCLCL	
050	4 TL270 \$b .P54 2006	
090	\$b	
049	LDLL	

245 0 4 The pneumatic tire / \$c edited by A.N. Gent and J.D. Walter.
 300 [Washington, D.C.] : \$b National Highway Traffic Safety Administration ; \$c [2006]
 300 1 CD-ROM ; \$c 4 3/4 in.
 336 text \$b txt \$2 rdacontent
 337 computer \$b c \$2 rdamedia
 516 Text document (vi, 701 p. : ill. (some col.), charts) in PDF format.
 500 Title from title screen.
 500 "Washington, D.C., 2005, DOT Contract DTNH22-02-P-07210"--Disc label
 538 System requirements: Windows operating system, Adobe Acrobat Reader.
 500 "February 2006."
 505 0 Ch. 1: An overview of tire technology / by B.E. Lindemuth -- Ch. 2: Mechanical properties of rubber /
 by A.N. Gent -- Ch. 3: Tire cords and cord-to-rubber bonding / by E.T. McDonel -- Ch. 4: Mechanics o
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 overy and re-use / by A.I. Isayev and J.S. Oh.
 504 Includes bibliographical references and index.
 650 0 Tires.
 650 6 Pneus.
 650 7 Tires. \$2 fast \$0 (OCoLC)fst01151458
 655 0 CD-ROMs.
 700 1 Gent, Alan N.
 700 1 Walter, Joseph D.
 710 1 United States. \$b National Highway Traffic Safety Administration.
 710 2 University of Akron.
 758 \$i has work: \$a The pneumatic tire (Text) \$1 <https://id.oclc.org/worldcat/entity/E39PCFPr44DvVQcjHyW4vrVhBP> \$4 <https://id.oclc.org/worldcat/ontology/hasWork>

Attachment C

Bibliographic Record - OCLC Number: 315848630

LDR	Record Status	'c' - Corrected or revised
	Type of Record	'a' - Language material
	Bibliographic Level	'm' - Monograph/Item
	Type of Control	' ' - No specified type of control
	Encoding Level	'M' - Added from a batch process
	Descriptive Cataloging Form	'i' - ISBD punctuation included
001	315848630	
005	20240127100239.6	
008	Date Entered on File	'080717'
	Type of Date/Publication Status	's' - Single date
	Date1/Beginning Date of Publication	'2006'
	Date2/Ending Date of Publication	' '
	Place of Publication, Production, or Execution Code	'xx' - No place, unknown, or undetermined
	Illustrations	' '
	Target Audience	' ' - Unknown or unspecified
	Form of Item	'q' - Direct electronic
	Nature of Contents Code	' '
	Government Publication	' ' - Not a government publication
	Conference Publication	'0' - Not a conference publication
	Festschrift	'0' - Not a festschrift
	Index	'0' - No index
	Literary Form	'0' - Not fiction
	Biography	' ' - No biographical material
	Language Code	'eng' - English
	Modified Record	' ' - Record is not modified
	Cataloging Source Code	'd' - Other
007	Category of Resource	'c' - Electronic Resource
	Specific Material Designation (c)	'o' - Optical disc
	Color (c)	'u' - Unknown
	Dimensions (c)	'u' - Unknown
	Sound (c)	'u' - Unknown
	Image Bit Depth (c)	'___'
	File Formats (c)	'u' - Unknown
	Quality Assurance Target(s) (c)	'u' - Unknown
	Antecedent/Source (c)	'u' - Unknown
	Level of Compression (c)	'u' - Unknown
	Reformatting Quality (c)	'u' - Unknown
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245	0 0 Pneumatic tire \$h [Elektronische Ressource] / \$c ed. by A.N. Gent.	
260	[S.l.] : \$b National Highway Traffic Safety Administration, \$c [ca. 2006]	

300 1 CD-ROM. ; \$c 12 cm
336 Text \$b txt \$2 rdacontent/ger
337 Computermedien \$b c \$2 rdamedia/ger
700 1 Gent, A. N. \$4 edt
758 The pneumatic tire (Text) \$1 <https://id.oclc.org/worldcat/entity/E39PCFPr44DvVQcjHyW4vrVhBP>
\$4 <https://id.oclc.org/worldcat/ontology/hasWork>

Attachment D



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of Transportation
**National Highway
Traffic Safety
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DOT HS 810 561

February 2006

The Pneumatic Tire

This publication is distributed by the U.S. Department of Transportation, National Highway Traffic Safety Administration, in the interest of information exchange. The opinions, findings and conclusions expressed in this publication are those of the author(s) and not necessarily those of the Department of Transportation or the National Highway Traffic Safety Administration. The United States Government assumes no liability for its content or use thereof. If trade or manufacturer's names or products are mentioned, it is because they are considered essential to the object of the publication and should not be construed as an endorsement. The United States Government does not endorse products or manufacturers.

Preface

For many years, tire engineers relied on the monograph, “*Mechanics of Pneumatic Tires*”, edited by S. K. Clark, for detailed information about the principles of tire design and use. Published originally by the National Bureau of Standards, U.S. Department of Commerce in 1971, and in a later (1981) edition by the National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation, it has long been out of print. No textbook or monograph of comparable range and depth has appeared since. While many chapters of the two editions contain authoritative reviews that are still relevant today, they were prepared in an era when bias ply and belted-bias tires were in widespread use in the U.S. and thus they did not deal in a comprehensive way with more recent tire technology, notably the radial constructions now adopted nearly universally. In 2002, therefore, Dr. H.K. Brewer and Dr. R. Owings of NHTSA proposed that NHTSA should sponsor and publish electronically a new book on passenger car tires, under our editorship, to meet the needs of a new generation of tire scientists, engineers, designers and users. The present text is the outcome.

Professor Clark agreed to serve as chair of an Editorial Board, composed of leading executives in the tire industry (listed on following page), which gave advice on the choice of authors and subjects and provided detailed reviews of the manuscripts. We are greatly indebted to Professor Clark and the other members of the Editorial Board for their expert guidance and constructive criticisms during the long process of preparing and revising the book. In particular, we would like to acknowledge the careful and thorough reviews provided by Dr. D. R. Dryden and his colleagues at Cooper Tire & Rubber Company. Nevertheless, final decisions about wording and content have been our responsibility.

The chapter authors are recognized authorities in tire science and technology. They have prepared scholarly and up-to-date reviews of the various aspects of passenger car tire design, construction and use, and included test questions in many instances, so that the book can be used for self-study or as a teaching text by engineers and others entering the tire industry.

Conversion of chapter manuscripts, prepared in different typesstyles and formats, into a consistent and attractive book manuscript was carried out by Ms. M. Caprez-Overholt. We are indebted to her and her colleague, Mr. Don Smith, of *Rubber World* for their skillful assistance.

Alan N. Gent and Joseph D. Walter

The University of Akron

August 2005

Revvo's Exhibit 1057

Revvo v. Tire Stickers

IPR2025-00631 - Page 033

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Chapter 1

An overview of tire technology

by B. E. Lindenmuth

1. Introductory comments

Tires ... round, black and expensive! That is the impression of most consumers who often consider them a low-tech commodity and make purchasing decisions based solely on price. Those with an opportunity to tour a tire production facility are surprised to learn that there are 20 or more components, with 15 or more rubber compounds, assembled in a typical radial passenger car tire and marvel at the massive amount of machinery and processing involved to achieve the finished product. Tires are highly engineered structural composites whose performance can be designed to meet the vehicle manufacturers' ride, handling, and traction criteria, plus the quality and performance expectations of the customer. The tires of a mid-sized car roll about 800 revolutions for every mile. Hence, in 50,000 miles, every tire component experiences more than 40 million loading-unloading cycles, an impressive endurance requirement.

Historically, pneumatic tires began in Great Britain during the late 1800s as an upgrade from solid rubber tires. They had small cross-sections and high pressures, principally for bicycle applications. Larger "balloon" tires were introduced in the early 1920's with applications in the mushrooming motor vehicle industry. Tubeless tires were introduced with improvements in rim design in the early 1950s. Belted bias tires (see Section 2.2, Figure 1.1) became popular in the late 1960s. Radial tires, first introduced in Europe, became popular in the USA starting in the early 1970s and now dominate the passenger tire market.

This chapter serves as an introduction and overview of radial passenger tire construction, performance, and testing typical of today's product.

2. Tire basics

2.1 Function

Vehicle to road interface

The primary function of passenger car tires is to provide the interface between the vehicle and the highway. The rubber contact area for all four tires for a typical mid-size car is less than that of an 8½ x 11 inch sheet of paper; each tire has a footprint area of about the size of an average man's hand. Yet we expect those small patches of rubber to guide us safely in a rain storm, or to allow us to turn fast at an exit ramp, or to negotiate potholes without damage.

Supports vehicle load

Vehicle load causes tires to deflect until the average contact area pressure is balanced by the tires' internal air pressure. Assuming a typical passenger tire is inflated to 35 psi, then a 350 lb load would need an average of 10 square inches of contact area to support the load. Larger loads require more contact area (more deflection) or higher tire pressures. A larger contact area usually requires a larger tire. Fortunately, industry standards exist for these requirements (see Section 2.3).

Road surface friction

The ability of vehicles to start, stop and turn corners results from friction between the highway and the tires. Tire tread designs are needed to deal with the complex effects of weather conditions: dry, wet, snow-covered and icy surfaces. Slick racing tires or bald tires may have good traction on dry surfaces, but may be undrivable in wet, rainy conditions due to hydroplaning. Tire tread designs enable water to escape from the tire-road contact area (the tire footprint) to minimize hydroplaning, while providing a reasonable balance between the sometimes conflicting requirements of good dry traction, low wear and low noise.

Absorbs road irregularities

This attribute is a key benefit of the pneumatic tire. In effect, tires act as a spring and damper system to absorb impacts and road surface irregularities under a wide variety of operating conditions.

2.2 Tire types

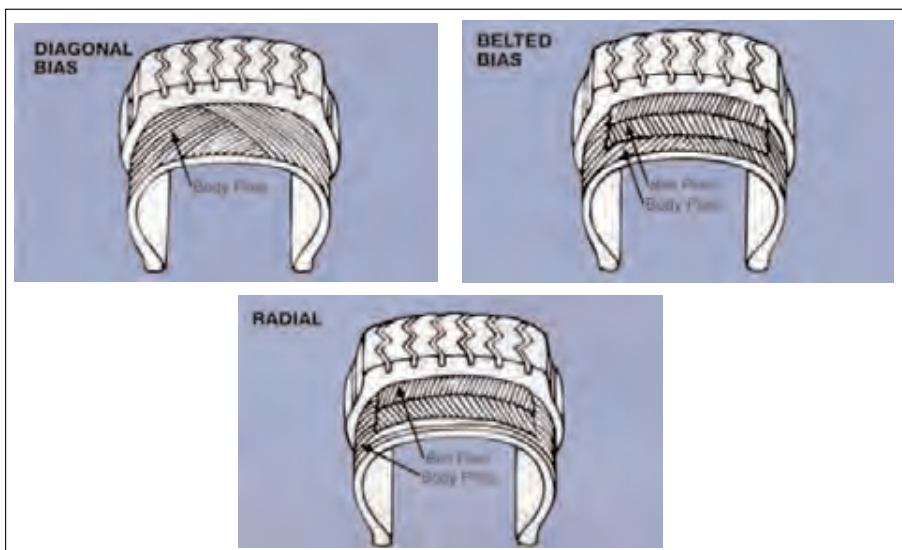
Diagonal (bias) tires

Still used today in some applications for trucks, trailers and farm implements, as well as in emerging markets, bias tires have body ply cords that are laid at angles substantially less than 90° to the tread centerline, extending from bead to bead (see Figure 1.1).

Advantages: Simple construction and ease of manufacture.

Disadvantages: As the tire deflects, shear occurs between body plies which generates heat. Tread motion also results in poor wear characteristics.

Figure 1.1: Tire types



Belted bias tires

Belted bias tires, as the name implies, are bias tires with belts (also known as breaker plies) added in the tread region. Belts restrict expansion of the body carcass in the circum-

ferential direction, strengthening and stabilizing the tread region (see Figure 1.1).

Advantages: Improved wear and handling due to added stiffness in the tread area.

Disadvantages: Body ply shear during deflection generates heat; higher material and manufacturing cost.

Radial tires

Radial tires have body ply cords that are laid radially from bead to bead, nominally at 90° to the centerline of the tread. Two or more belts are laid diagonally in the tread region to add strength and stability. Variations of this tire construction are used in modern passenger vehicle tire (see Figure 1.1).

Advantages: Radial body cords deflect more easily under load, thus they generate less heat, give lower rolling resistance and better high-speed performance. Increased tread stiffness from the belt significantly improves wear and handling.

Disadvantages: Complex construction increases material and manufacturing costs.

2.3 Industry standards

Sizing/dimensions

USA tire manufacturers participate voluntarily in an organization known as TRA, The Tire and Rim Association, Inc. It establishes and promulgates engineering standards for tires, rims, and allied parts (tubes, valves, etc.) Participation and adherence to these standards assures interchangeability of component parts among different tire manufacturers. “P-metric” sizing was introduced as radial tire usage began to expand in North America in the early 1970s. Size nomenclature can be described as follows (see Figure 1.2). For a P205/70R15 tire, the “P” indicates that it is for a “passenger” car (“T”, temporary; “LT”, light truck). (Note: European tire sizes typically do not utilize the P, T or LT symbols). The “205” is the nominal section width of the inflated, unloaded tire in millimeters. The “70” is the aspect ratio, or “series”. It gives the tire section height as a percentage of the section width. Lower aspect ratio tires, e.g., 45, 50, 55 series tires, are primarily used in high performance applications but are becoming more popular in conjunction with large rim diameters for styling enhancements in larger vehicles. “R” identifies radial construction (“D” for diagonal or bias tires, “B” for belted bias construction). “15” is the rim diameter in inches. Other USA sizing designation systems have been used but will not be explained here, due to the prevalence of “P-metric sizing”.

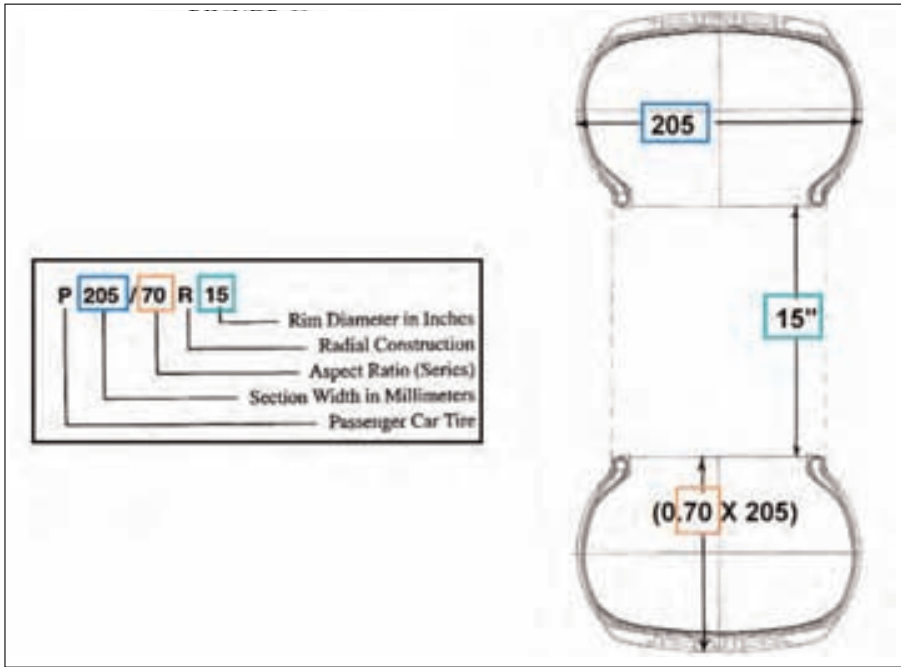
Load capacity

Tables of tire load ratings and load carrying capacity have been established by TRA. Their purpose is to maintain a rational basis for choosing tire size, load and inflation. Details will be covered in Chapter 5. TRA also coordinates its standards with other international organizations such as ETRTO (European Tyre & Rim Technical Organization) and JATMA (Japanese Automobile Tire Manufacturing Association). Note that ETRTO and JATMA sizes can have different load-carrying capacities than like-sized P-metric tires.

Load index and speed ratings (service description)

Most tires typically have a service description added following the size, e.g., P225/60R15 90H. The “90” refers to a load index that is related to its load carrying capacity, and may be used for interchangeability purposes. The “H” refers to the tire’s speed rating, a code initiated in Europe and adopted by TRA. See Chapter 17 for details.

Figure 1.2: Size nomenclature



U.S. Government Regulations: DOT 109/110/139.

Since 1968, the U.S. Government's Department of Transportation (DOT) has had regulations for passenger tires, including testing and labeling, DOT 109, and tire selection for vehicle manufacturers, DOT 110. DOT 109 covers indoor test requirements, plus standards for tire labeling and serial number. The indoor tests include drum testing for high speed and endurance plus road hazard (plunger) and bead-unseat tests. The current regulations, DOT 139 and modified DOT 110, were changed in 2003 as a result of the TREAD Act of 2000. Details of the testing requirements are covered later in Chapter 16.

Uniform Tire Quality Grading (UTQG) was implemented by the U.S. Federal Government in 1979. It includes treadwear, traction and temperature grades that are applied to all passenger tires, with the exception of deep traction (i.e., winter/snow) tires and temporary spares. All grades are determined by tire manufacturers and are displayed (molded) on the tire sidewall, as well as tire labels at retail outlets.

The treadwear grade is based on actual wear test results. Tires are run for 7,200 miles on a 400 mile highway loop that originates in San Angelo, TX. The wear grade is determined by comparing the wear rate of the candidate tire to that of an industry-standard tire.

The traction grade is based on locked-wheel braking results on wet asphalt and wet concrete skid pads, also at San Angelo, TX. Again, the results are compared with those of an industry-standard control tire.

Temperature grades are based on speed capabilities from indoor drum tests similar to those described in DOT 109 and 139. Test specifics and grading procedures are covered in Chapter 17.

3. Tire components

3.1 Rubber compounds

Purpose

Beyond the visible tread and sidewall compounds, there are more than a dozen specially formulated compounds that are used in the interior of the tire. They will be discussed in Section 3.3: Tire components.

Basic ingredients

Polymers are the backbone of rubber compounds. They consist of natural or synthetic rubber. Properties of rubber and rubber compounds are described in more detail in chapter 2.

Fillers reinforce rubber compounds. The most common filler is carbon black although other materials, such as silica, are used to give the compound unique properties.

Softeners: Petroleum oils, pine tar, resins and waxes are all softeners that are used in compounds principally as processing aids and to improve tack or stickiness of unvulcanized compounds.

Antidegradents: Waxes, antioxidants, and antiozonants are added to rubber compounds to help protect tires against deterioration by ozone, oxygen and heat .

Curatives: During vulcanization or curing, the polymer chains become linked, transforming the viscous compounds into strong, elastic materials. Sulfur along with accelerators and activators help achieve the desired properties.

Material design property balance

Considering the many polymers, carbon blacks, silicas, oils, waxes and curatives, plus specialty materials such as colorants, adhesion promoters, and hardeners, the variety of compounds available seems endless. A typical car tire uses about 60 raw materials. However, the tire compounder quickly learns that adjusting one of the properties often affects other performance areas. The best tread compound for dry traction and handling might be lacking in wet/snow traction, chip/tear resistance, or fuel economy. Thus, compounds must be “engineered” or “balanced” to meet performance criteria for both the original equipment (OE) vehicle manufacturer and the aftermarket customer. . Adding to the complexity, the chosen compound must be cost-competitive and processable in manufacturing plants.

3.2 Reinforcement materials

Purpose

A tire’s reinforcing materials — tire cord and bead wire — are the predominant load carrying members of the cord-rubber composite. They provide strength and stability to the sidewall and tread as well as contain the air pressure.

Type and common usage

Nylon type 6 and 6,6 tire cords are synthetic long chain polymers produced by continuous polymerization/spinning or melt spinning. The most common usage in radial passenger tires is as cap, or overlay ply, or belt edge cap strip material, with some limited applications as body plies.

Advantages: Good heat resistance and strength; less sensitive to moisture.

Disadvantages: Heat set occurs during cooling (flatspotting); long term service growth.

Polyester tire cords are also synthetic, long chain polymers produced by continuous

polymerization/spinning or melt spinning. The most common usage is in radial body plies with some limited applications as belt plies.

Advantages: High strength with low shrinkage and low service growth; low heat set; low cost.

Disadvantages: Not as heat resistant as nylon or rayon.

Rayon is a body ply cord or belt reinforcement made from cellulose produced by wet spinning. It is often used in Europe and in some run-flat tires as body ply material.

Advantages: Stable dimensions; heat resistant; good handling characteristics.

Disadvantages: Expensive; more sensitive to moisture; environmental manufacturing issues.

Aramid is a synthetic, high tenacity organic fiber produced by solvent spinning. It is 2 to 3 times stronger than polyester and nylon. It can be used for belt or stabilizer ply material as a light weight alternative to steel cord.

Advantages: Very high strength and stiffness; heat resistant.

Disadvantages: Cost; processing constraints (difficult to cut).

Steel cord is carbon steel wire coated with brass that has been drawn, plated, twisted and wound into multiple-filament bundles. It is the principal belt ply material used in radial passenger tires.

Advantages: High belt strength and belt stiffness improves wear and handling.

Disadvantages: Requires special processing (see figure 1.16); more sensitive to moisture.

Bead wire is carbon steel wire coated with bronze that has been produced by drawing and plating. Filaments are wound into two hoops, one on each side of the tire, in various configurations that serve to anchor the inflated tire to the rim.

3.3 Radial tire components (see Figure 1.3)

Innerliner

The innerliner is a thin, specially formulated compound placed on the inner surface of tubeless tires to improve air retention by lowering permeation outwards through the tire.

Body ply skim

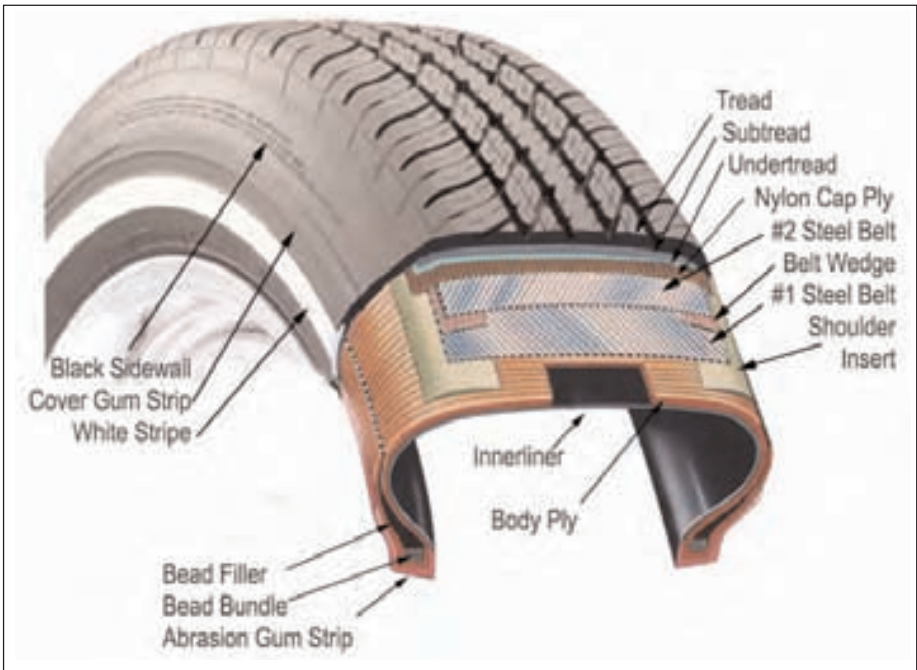
Body ply skim is the rubber coating that encapsulates the radial ply reinforcing cords. The skim is calendered onto the body ply cords in thin sheets, cut to width, and spliced end-to-end into a roll.

Body plies

Body plies of cord and rubber skim wrap around the bead wire bundle, pass radially across the tire and wrap around the bead bundle on the opposite side. They provide the strength to contain the air pressure and provide for sidewall impact resistance. The tire example shown has one body ply. In larger sizes, two body plies are typically used.

Bead bundles

Individual bronze plated bead wires are rubber coated and then wound into a bundle of specified diameter and configuration prior to tire assembly. The bead bundles serve to anchor the inflated tire to the wheel rim.

Figure 1.3: Components of a radial tire*Abrasion gum strip*

Abrasion gum strips provide a layer of rubber between the body plies and the wheel rim for resistance against chafing. The airtight seal between the tire and rim must be maintained under all operating conditions. This component is also known as a gum chafer or gum toe guard.

Bead filler

Bead filler (also known as the apex) is applied on top of the bead bundles to fill the void between the inner body plies and the turned-up body ply ends on the outside. Varying the bead filler height and hardness affects tire ride and handling characteristics.

Sidewall

Tire sidewall rubber serves to protect the body plies from abrasion, impact and flex fatigue. The sidewalls also carry decorative treatments, sometimes including white or colored stripes or letters. The rubber compound is formulated to resist cracking due to environmental hazards such as ozone, oxygen, UV radiation and heat.

Sidewall reinforcements (not shown in figure 1.3)

Some tires feature lower sidewall reinforcements to improve handling or stability. These items are known as chippers, flippers or a floating reinforcement. Also, many run-flat constructions feature full sidewall thick rubber or other reinforcements to help support the load when the inflation pressure is low or zero.

Stabilizer ply skim (belt skim)

Belt skim is the rubber coating for the brass plated steel cords. The skim is calendered or extruded onto the steel cord in sheets, which are cut to width on an angle and then spliced into continuous rolls for tire assembly. Belt skim is primarily formulated to resist fatigue and tear.

Stabilizer plies (belts)

Two steel belts are applied at opposite angles to one another on top of the body plies, under the tread area. They restrict expansion of the body ply cords, stabilize the tread area and provide impact resistance. Varying the belt widths and belt angles affects vehicle ride and handling characteristics. Alternate belt constructions with materials other than steel, with three or more belts, or with woven materials have also been utilized.

Belt wedges

Small strips of belt skim or other fatigue resistant compounds are sometimes placed between the belts near the edge of the top (number 2) belt. The purpose is to reduce the interply shear at the belt edge as the tire rolls and deflects.

Shoulder inserts

Shoulder inserts are small, sometimes contoured strips of rubber placed on the body ply, under the belt ends. They help maintain a smooth belt contour and insulate the body plies from the belt edges.

Tread

The tread must provide the necessary grip or traction for driving, braking and cornering, and the tread compound is specially formulated to provide a balance between wear, traction, handling and rolling resistance.

A pattern is molded into the tread during vulcanization or curing. It is designed to provide uniform wear, to channel water out of the footprint, and to minimize pattern noise on a variety of road surfaces.

Both the tread compound and the tread design must perform effectively in a multitude of driving conditions, including wet, dry or snow covered surfaces, while also meeting customer expectations for acceptable wear resistance, low noise, and good ride quality. For driving in severe winter conditions, snow tires with increased tread depth and specially formulated tread compounds are recommended.

Subtread

The subtread, if used, is typically a lower hysteresis, cooler-running compound extruded under the tread compound to improve rolling resistance in order to meet the OE vehicle manufacturers' goals for fuel economy. It also can be used to fine-tune ride quality, noise, and handling.

Undertread

The undertread is a thin layer of rubber placed under the extruded tread/subtread package to boost adhesion of the tread to the stabilizer plies during tire assembly and to cover the ends of the cut belts.

Nylon cap plies/cap strips

Higher speed rated tires may feature a full-width nylon cap ply or plies, sometimes called an overlay, wrapped circumferentially on top of the stabilizer plies (belts) to further restrict expansion from centrifugal forces during high speed operation. Nylon cap strips are used in some constructions but cover only the belt edges.

*3.4 Radial tire design process (see flowchart figure 1.4)**Identify goals/requirements*

Before the tire engineer begins the design process, he must assemble a list of product goals, including customer performance expectations, manufacturing requirements, internal company performance standards and regulatory requirements. Targets or specifications for each of the tests discussed in Section 4 are typically identified. Performance targets reflect sales and marketing needs or OE vehicle manufacturers' requirements. Certain standards (e.g., government) are mandatory. Manufacturing plants usually have processing procedures that may restrict certain material and construction choices.

Tread pattern design

Figure 1.5 illustrates most of the tread pattern features used by design engineers. The number of ribs and groove spacing affect the way water is eliminated to avoid hydroplaning (refer to section 3.1). See thru, percent void, shoulder slot size and orientation can all affect traction, handling and water exit paths. The number of pitches and pitch sequence as well as the placement of tie-bars and sipes can affect traction, noise, wear, and the tendency to wear non-uniformly. Figure 1.6 illustrates a noise treatment using different pitch lengths around the tire circumference to limit tone generation as the tire rotates. Additionally, tread designs need to be acceptable aesthetically and to match the customer's perception of product performance.

Mold contour features

Mold section width and outside diameter have an obvious impact on the dimensions of the vulcanized tire. But mold profile items like tread, center and shoulder radii and skid depth can also significantly affect tire performance. Vastly different footprint shapes are possible, as shown in figure 1.7, and can influence vehicle ride and handling, tire wear and traction.

Construction selection

Body ply denier, cord style, EPD (Ends Per Decimeter) or EPI (Ends Per Inc), and number of plies affect body strength and are chosen based on manufacturing, engineering, and design criteria. Likewise steel cord construction (style) and EPD both affect belt strength and are chosen typically based on tire size and application. Belt widths and belt crown angle (see figure 1.8) also influence tire performance. Different crown angles change the belt package stiffness, laterally and longitudinally, which can affect cornering ability and ride. Belt widths can also be varied. If a high speed rating is required, the addition of nylon cap strips at the belt edges or full-width nylon cap plies may be added. The bead and sidewall areas can also contribute to subtle performance enhancements. The bead filler volume and height, as well as the location of the end of the turned-up body ply (see figure 1.8) all impact sidewall stiffness.

Figure 1.4: Tire design flow chart

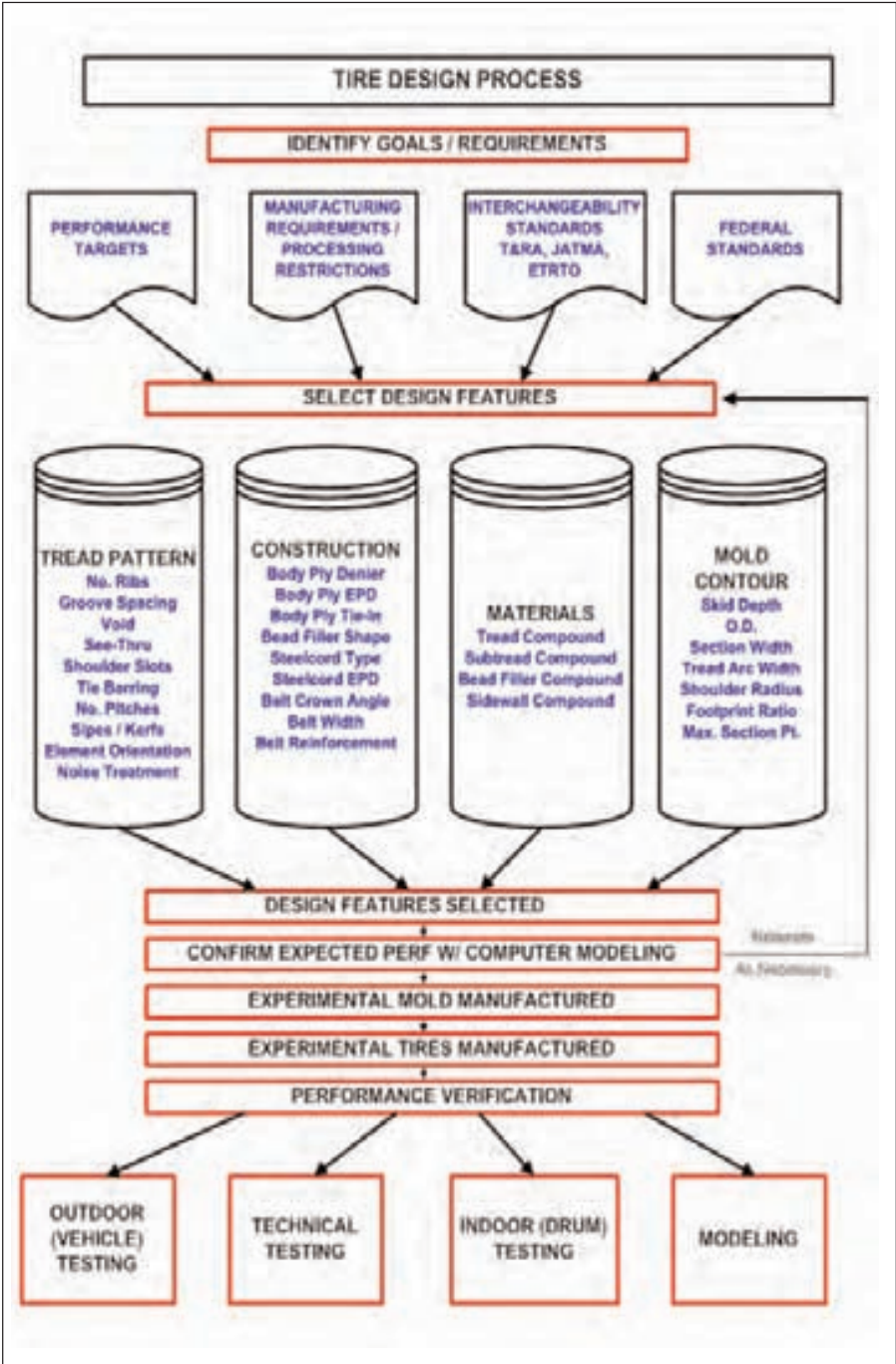


Figure 1.5: Tread pattern design

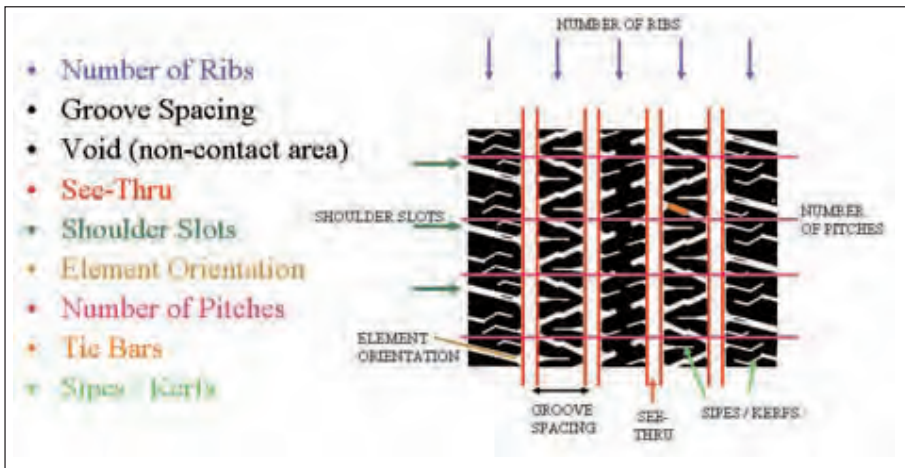
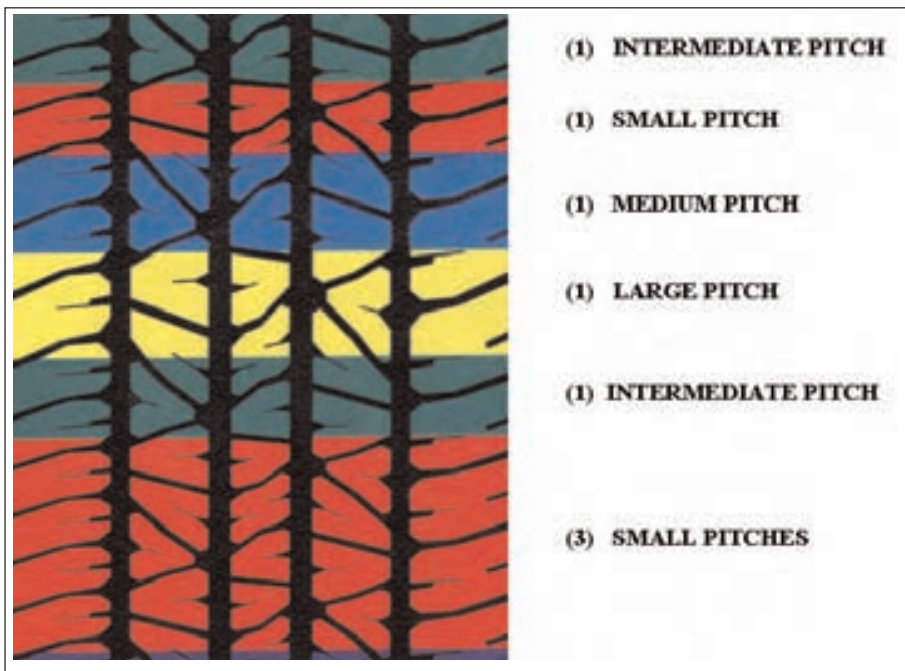


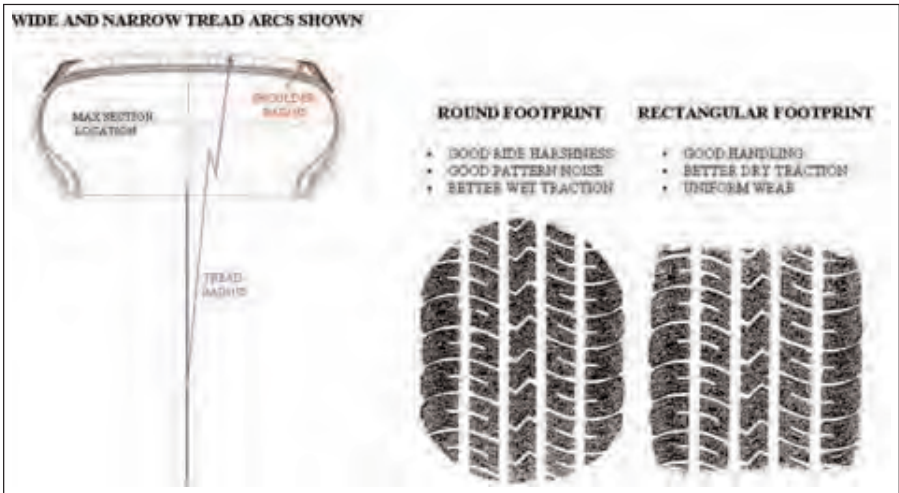
Figure 1.6: Noise treatment



Materials selection

Tread compounds are chosen to meet handling and traction requirements for wet, dry and snow (if necessary), but must have suitable wear potential and resistance to gravel chips and tearing. Subtread compounds and thickness are often determined by the rolling

Figure 1.7: Mold contour effects

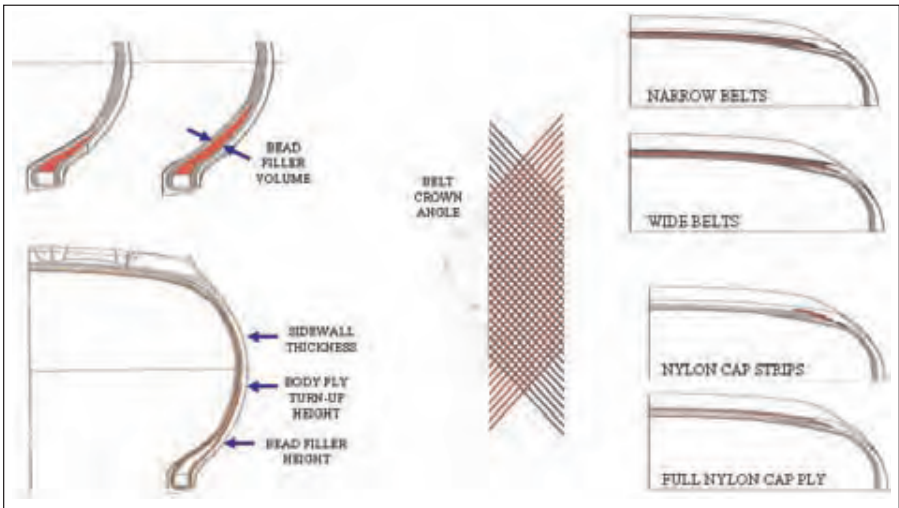


resistance requirement imposed by the OE vehicle manufacturer. Bead filler compounds are chosen for controlling lower sidewall stiffness, based on ride and handling expectations. Sidewall compounds are chosen to resist environmental effects (weathering) and damage from impacts and abrasion, but they also affect the rolling resistance.

Design/construction performance balance

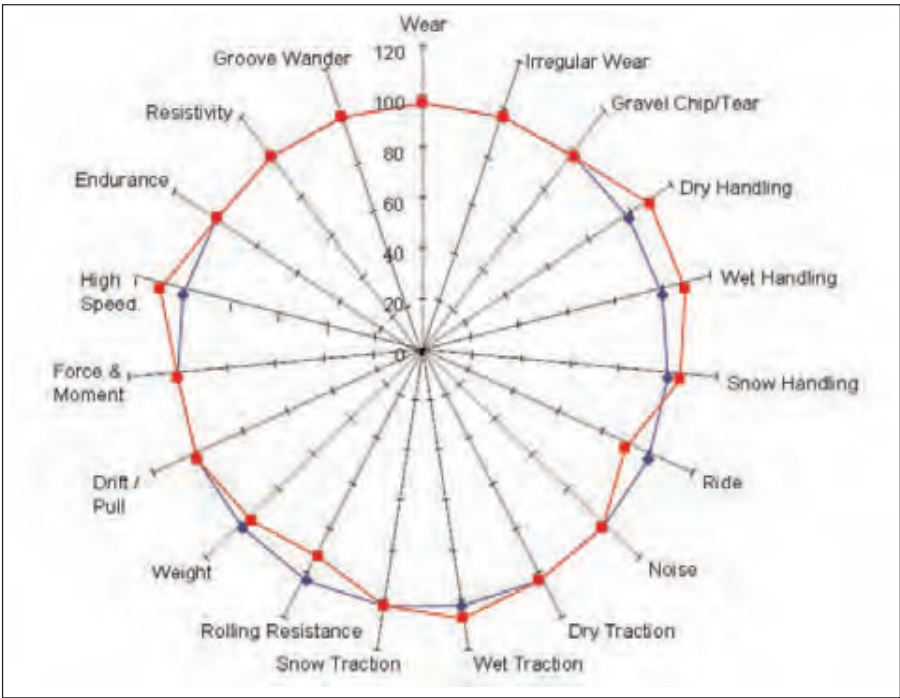
While specific performance parameters follow in Section 4, many environments and performance categories must be satisfied. Beginning with size, load capacity, speed rating, body and belt materials, compounds, tread designs and construction variations, how do we choose? Obviously, industry-wide guidelines exist (TRA, DOT, ETRTO, etc.),

Figure 1.8: Construction variables



and guidelines and standards have been developed by individual tire manufacturers as well. They serve as a starting point. In addition to experience, tire engineers use computer models and performance maps to help guide their selections and predict if performance targets will be met. Using an iterative process of design, construction and material choices, the engineer can reach a balance of compromises for each application. Figure 1.9 illustrates the impact of just one component change, wider belts, on selected tire performance parameters. In this so-called “spider diagram” a higher rating (outside the circle) indicates improved performance. Handling and wet traction are improved but ride, rolling resistance and weight have suffered. If the customer desires the handling improvements but is unwilling to accept the loss in ride quality and higher rolling resistance, the tire engineer must look at other factors to balance the overall performance. This dilemma is what drives new tire technology in design, materials and construction.

Figure 1.9: Effect of increased belt width



4. Tire performance criteria

4.1 Outdoor (vehicle) tests

Wear rate

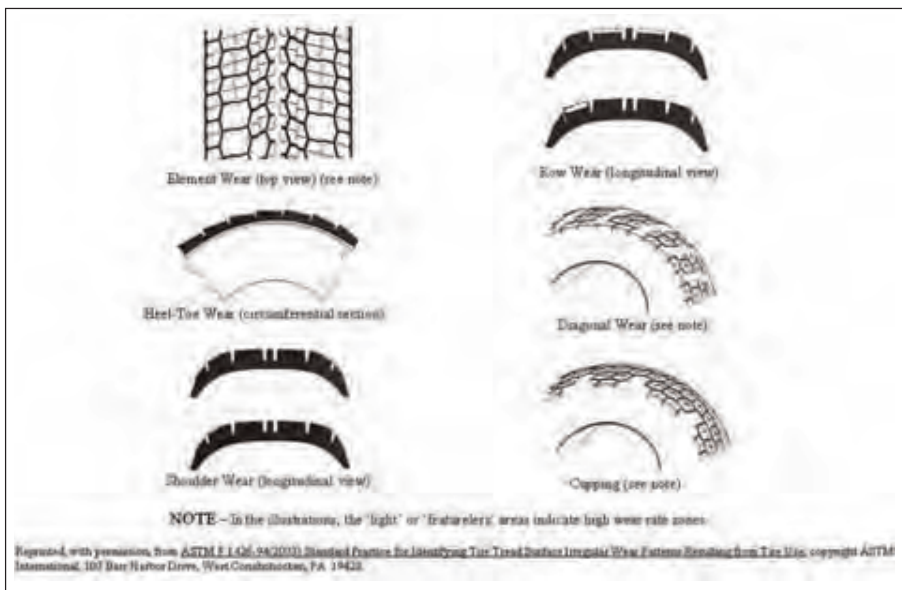
Traditionally with an outdoor test, sets of tires are driven at prescribed speeds on a known course to evaluate wear rate, usually measured in miles of travel per thousandth of an inch of tread depth loss (i.e., miles per mil) or as tread loss per mileage increment (i.e., mils/1000 mi). Control of vehicle alignment, loads, and acceleration/deceleration rates are all critical to obtaining repeatable results. Comparison tests are usually conducted using

vehicle convoys to negate environmental factors, differences in road surfaces, or other variables.

Irregular wear

Abnormal wear features, such as heel and toe, cupping, or shoulder wear (see figure 1.10) can significantly shorten the service life or mileage potential of tires. While tread design and tire construction are influential, many external factors such as vehicle mis-alignment, vehicle suspension geometry and driving factors such as high speed cornering, rapid acceleration or braking and underinflation of tires play significant roles in promoting irregular wear patterns. Consumers who regularly check tire inflation pressure and maintain a schedule for rotating tire positions and checking vehicle alignment will maximize tire mileage.

Figure 1.10: Types of irregular wear



Gravel chip/tear

Some tread compounds and tire designs can be sensitive to chipping and tearing of tread elements during off-road or gravel road applications. Many outdoor wear and durability tests include a small percentage of gravel roads to assure that this performance is acceptable.

Handling: dry, wet and snow

Handling is a result of tire/vehicle interactions in response to various driver inputs. Handling tests are used by tire engineers and OE vehicle engineers as part of their approval process. Tires are evaluated for their response, stability, recovery linearity, on-center-feel, brake in turning, and other characteristics. Tests range from lane change maneuvers to maximum cornering capability. Also, closed course test tracks with a variety of curves can be used to compare lap times with experimental tire constructions.

Most test facilities can run the same test in both wet and dry conditions. Snow tests are conducted at special facilities where the snow can be groomed and compacted to make a consistent surface.

Ride comfort

A vehicle's perceived ride comfort, whether "sporty" or "plush," can be significantly influenced by tires. Engineers' evaluations go far beyond expectations of shake-free and vibration-free ride on smooth highways. Tires are evaluated for impact harshness over highway joints and railroad tracks, and for damping and bounce memory after road disturbances. They are also graded for plushness (road isolation), nibble (steering wheel oscillations), shake, vibration and other vehicle-specific features. Most tire manufacturers have test facilities with dedicated lanes specifically designed for consistent evaluation of tire and vehicle combinations by professional ride evaluators. Ride is one of the compromises encountered in designing tires. For instance, wider belts may improve vehicle handling but can contribute to increased ride impact harshness.

Noise

Significant time and effort goes into designing tire tread patterns and constructions to minimize noise. Patterns have tread elements of varying pitch lengths to prevent tires from generating identifiable tones. Multiple pitch lengths, typically 3 to 7 (see Figure 1.6), are assembled in a computer-generated pattern around the tire circumference to dispel any constant frequency noise as the tire rotates. Professional tire evaluators, using prepared test areas, are able to sense not only airborne pattern noise but also structure-borne noise as well. Structure-borne tire noise is transmitted through the tire carcass, the wheel and suspension, sometimes aggravating resonances in a vehicle component. Evaluators rate coarse road noise transmitted through the tire from textured highway surfaces. They listen for growl, a low frequency noise noticed during low speed braking, and sizzle, a hissing sound on ultra-smooth surfaces. These and other noise conditions add to the tire engineers design dilemma. Increasing tread thickness and softening the bead filler reduces coarse road noise but increases rolling resistance and affects ride and handling.

Rain groove wander

Many states, particularly California, grind longitudinal grooves into concrete highways to minimize hydroplaning during rain storms in high traffic areas. If the grooves on the highway line up with tire tread design grooves, side-to-side vehicle motions can occur, making drivers uncomfortable. Tire engineers must change tread pattern groove spacing or reduce the number of ribs in smaller tires to minimize this phenomenon.

Drift/pull

A vehicle with drift/pull has a tendency to pull right or left while driving on a straight, flat, level highway with minimal wind. Tires can contribute to this condition but vehicle alignments and suspension geometry are also key factors. Drivers find the constant steering correction annoying.

Endurance

Outdoor testing for tire endurance usually involves loading a vehicle to the maximum specified load and inflation, or more, and driving on a closed road course at a specified

schedule of speeds. With a three shift per day operation, and measurement/inspection/maintenance delays, it takes approximately 45 working days to accumulate 40,000 mi. Each tire company has its own proprietary test protocol.

4.2 Indoor (drum tests)

High speed

Indoor laboratory tests are typically run on 1.708 m (67.23") diameter drums (300 rev/mile) that have been an industry standard for decades. Ambient temperatures of 38°C (100°F) are typical. Most industry high speed tire tests utilize the SAE J1561 standard which calls for 80% of the maximum load and speed increases of 10 km/hr in 10 minute increments until the specified speed is achieved, or tire failure occurs. Tests start at speeds four steps below the desired speed rating. Inflation pressure varies by tire type and speed rating, e.g., 260 kPa (38 psi) for a standard load passenger "S" rated tire. This reduced load is an adjustment to give an equivalent tire deflection on the drum's curved surface to that expected on a flat highway surface. DOT 109 and 139 and UTQG temperature grade tests require speed increases at 30 minute intervals, for tires inflated to 220 kPa (32 psi) and carrying 85% of maximum load. (See Chapter 17).

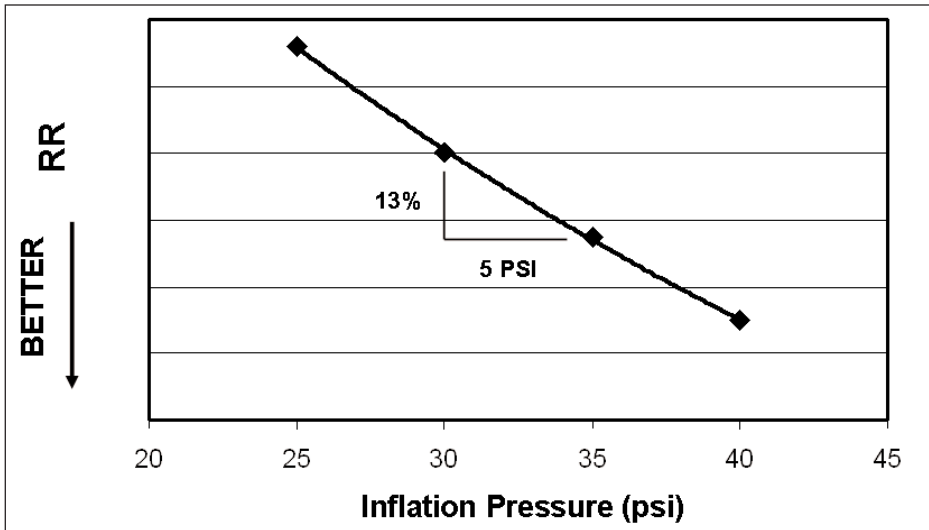
Endurance

In high speed testing, load is constant and speed is varied. In most indoor drum endurance tests, the speed is constant and load is varied. Tests similar to DOT 109 and the new DOT 139 are as follows. The ambient temperature remains at 38°C. Pressure for a P-metric standard load passenger radial is 180 kPa (26 psi) with a constant speed of 80 km/hr (50 mi/hr) for DOT 109 type tests. New DOT 139 regulations require 120 km/hr (75 mi/hr) testing, becoming mandatory in June 2007. The test load begins at 85% of maximum load for 4 hours and then becomes 90% for 6 hours and finally 100% for 24 hours. Tires completing the initial 34 hour test must also complete an additional new DOT 139 low pressure step at 140 kPa (20 psi) for an additional 90 minutes at the 100% load condition. (See Chapter 17).

Rolling resistance

The force necessary to overcome hysteretic losses in a rolling tire is known as rolling resistance. This parameter became important to USA vehicle manufacturers with implementation of C.A.F.E. (Corporate Average Fuel Economy) standards for new cars. It is measured by placing load cells in the wheel spindle and measuring the rolling resistance force in the horizontal (longitudinal) direction. It requires precise instrumentation, calibration, speed control and equipment alignment for repeatable results. Rolling resistance is usually expressed as a coefficient: resistance force per 1000 units of load. OE passenger car tires designed for fuel efficiency may have coefficients in the range 0.007 to 0.010 when fully inflated and evaluates at thermal equilibrium (see chap. 12). The test load, speed and inflation pressure vary according to the vehicle manufacturers' requirements. Rolling resistance is significantly influenced by inflation pressure, as illustrated in Figure 1.11. Since tire rolling resistance can consume up to 25% of the energy required to drive at highway speeds, it is economically wise to keep tires inflated properly.

Figure 1.11: Rolling resistance vs. inflation



4.3 Technical tests

Weight

OE vehicle manufacturers often specify tire weight targets as part of their requirements for meeting C.A.F.E. goals.

Force and moment properties

A tire's cornering capability comes from the forces generated when a tire's direction of motion is different from its heading direction, causing a slip angle. Measurement equipment and interpretation of results are complex and dealt with in detail in Chapter 8. In the most general case, three forces and three moments are resolved in the tire contact patch or at the wheel axle.

Resistivity

Moving vehicles can generate static electricity which is aggravated by low temperature and humidity. While rubber is usually thought to be an insulator, it is partially conductive, and tire compounds influence the rate of static discharge. Test fixtures in humidity and temperature-controlled laboratories are used to measure tire resistivity.

Uniformity

Due to material and assembly variations that occur during manufacturing and curing, small deviations in tire cross section circumferentially can result in measurable spring rate or dimensional changes, for example, an out-of-round condition. Tire Uniformity Grading machines are used to measure the variations that occur around the circumference of the tire. Inflated tires are loaded against an instrumented rotating drum. The radial and lateral force variations measured are compared to acceptance standards for smooth, vibration-free ride.

Flat spotting

Some tires, when parked, can develop a temporary “set” in the rubber compounds and reinforcement cords, referred to as a “flat spot”. To test for this condition, tires are warmed up or exercised at high speed, measured for uniformity and then loaded statically against a flat plate for a prescribed time (usually days). Tires are then retested for uniformity, exercised and the recovery time observed for the flat spot to disappear.

Traction: dry, wet and snow

Specially equipped instrumented trailers with computer-controlled braking capability are towed over known skid pad surfaces. Brakes are applied gradually to cause wheel lock-up and peak and slide friction forces are recorded. Wet traction is conducted on the same surfaces with water being metered to the front of the tire as a way of controlling water depth. Snow traction is determined using special trucks for measuring driving traction at constant slip over groomed, compacted snow surfaces.

Air permeation

Innerliner compounds are formulated to minimize permeation of air through the tire carcass. The permeation rate depends on the compound properties and gauge (thickness) as well as the temperature and inflation pressure. Long term tests, taking months, require regulated temperatures and leak-free tire mounting and test plumbing. Typical passenger car tires lose approximately 1 psi per month due to air permeation.

*4.4 Industry/government standards**Dimensions*

Tires, mounted and inflated on an appropriate wheel, are scanned by a laser profiler. Section width, diameter and size factor (sum of diameter and section) must be within T/RA guidelines.

High speed

DOT 139 requires testing conditions as described in Section 4.2. Tires must complete the 160 km/hr (100 mi/hr) step without failure to be in compliance.

Endurance

DOT 139 requires completion of all three steps at 120 km/hr (75 mi/hr) as described in Section 4.2. All tires must complete the endurance portion, plus a 90-minute low inflation pressure step, without failure to be in compliance.

Bead unseat

DOT 139 requires that tires retain air pressure and beads remain seated on the wheel in a test where an anvil is pressed against the tire sidewall. Wheel, tire inflation and anvil location are specified by rim diameter and tire type. Potential revisions to this test are under study.

Road hazard (plunger)

DOT 139 requires that tires withstand a slow-moving plunger placed in the center area of the tread and forced into the tire. The plunger travel at the peak load is recorded, reached when either the tire ruptures or the plunger bottoms-out against the rim, and the peak

energy is calculated. Minimum energy requirements without tire rupture occurring must be met at multiple locations around the tire circumference to be in compliance. Research continues to determine if new or revised test procedures are needed to accommodate new, lower aspect ratio tire sizes.

Uniform tire quality grades

As a USA Federal requirement, Uniform Tire Quality Grades must be established and displayed within six months of start of production for new tire lines. Grading categories are covered in Section 2.3.

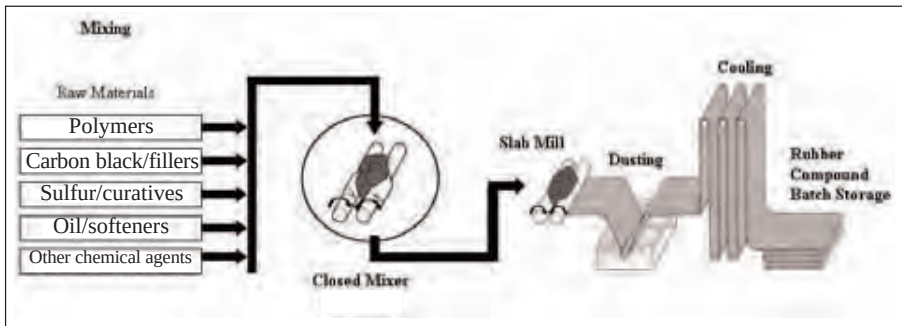
5. Tire manufacturing

5.1 Compound preparation (see Figure 1.12)

Raw materials

Approved vendors supply the basic ingredients including polymers, fillers (carbon black and/or silica), softeners and antidegradants. Lab tests are run to sample, code and release the materials for use in production.

Figure 1.12: Tire manufacturing - Rubber compound preparation



Mixing

The appropriate blend of polymers, fillers, oils and pigments for a specific compound formula are combined in a closed mixer in batches of 180 kg (400 lbs) to 500 kg (1100 lbs). Batch temperatures are closely controlled, as are mixing power, cycle time and rotor speed, in accordance with the compound specification. Each batch is flattened into slabs or extruded and cut into pellets (not shown in figure 1.12) for storage and later blending with other batches or materials.

Blend/feed mills

Large, closely spaced, water-cooled rollers squeeze and knead a bank of compounds to blend mixed batches and to warm up compounds prior to extrusion or calendering.

5.2 Component preparation

Calendering

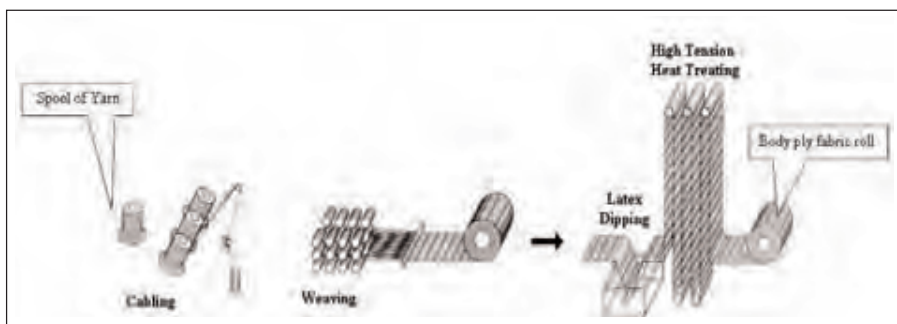
Similar in appearance to rubber blending and feeding mills, calenders press rubber compounds between two or more rotating rolls to form thin, flat sheets of rubber to specified gauges. Control systems can regulate the sheet thickness to within 0.001". The

sheets are used in tire assembly for inner-liner, gum strips, or belt wedges, or in preparing body ply or stabilizer ply material.

Body plies

In textile reinforcements of nylon, polyester, rayon, aramid, etc., individual filaments are twisted and cabled together to form cords. The cords are woven, with pick cords to maintain spacing, into a wide sheet of fabric prior to dipping in a latex adhesive to enhance bonding to rubber, followed by a high-tension heat treatment (see Figure 1.13). Body ply fabric is prepared in rolls approximately 57 inches wide by 3,000 yards long having the appropriate denier (cord style) and EPD (ends per decimeter). The fabric is then passed through a four-roll calender (see Figure 1.14) where a thin sheet of rubber (body ply skim) is pressed onto both sides and squeezed between the cords of the fabric. The calendered fabric is wound into 350-yard rolls, with a polypropylene liner inserted to keep the fabric from sticking to itself, and then sent to a stock-cutting process.

Figure 1.13: Textile cord manufacturing process



Body ply stock cutting and splicing (see figure 1.14)

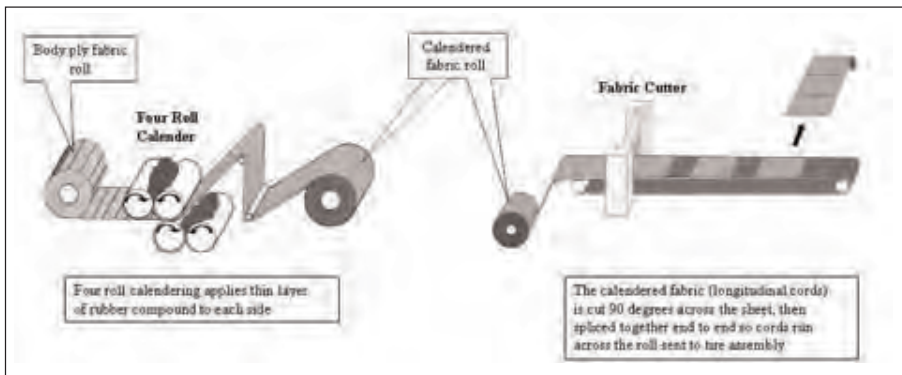
The individual cords are aligned longitudinally in the calendered roll but they need to go across, not around, the radial tire carcass. Therefore the calendered fabric is cut into pieces, rotated 90° and spliced back together, so that cords go across the roll. The result is a continuous roll of body ply material at a specified width for the appropriate tire size and construction.

Stabilizer ply (belt) calendering (see figure 1.15)

Unlike woven body ply material, steel cord, already brass plated and twisted, is purchased from vendors as individual cords wound onto spools. To make a sheet of belt material, hundreds of spools are located in a low humidity, temperature controlled creel room. The cords from the spools pass through rolling guides to give the appropriate EPD (Ends Per Decimeter) and move directly into a four-roll calender that presses a thin sheet of belt skim rubber onto and between the individual cords. The calendered steel-cord sheet is then wound between polypropylene liners for later processing. [Another processing arrangement extrudes rubber onto the steel cord and forms smaller sheets.]

Stabilizer ply (belt) cutting and splicing (see figure 1.15)

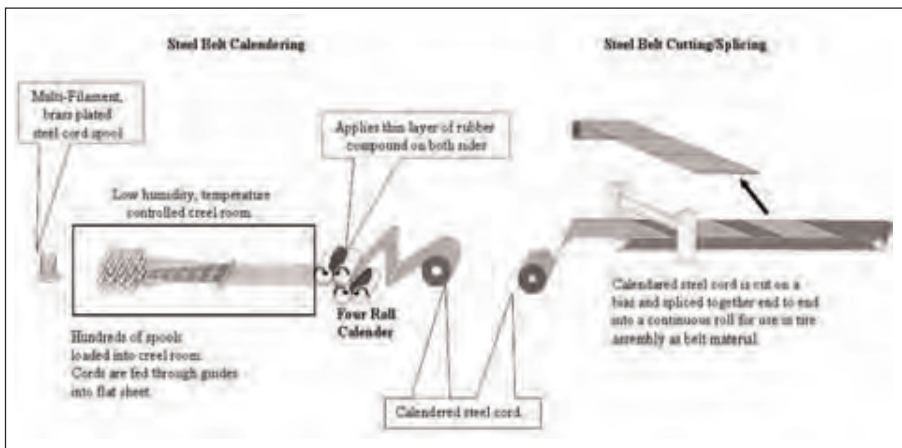
The steel cords run longitudinally in the calendered roll. For use as stabilizer ply, the steel

Figure 1.14: Tire manufacturing - body ply preparation

cord sheet is cut, rotated, and spliced together again to form a continuous strip of a specified width, with the cords at a specified angle. Since the number 1 and number 2 belts have different widths and opposite angles, they must be prepared accordingly.

Nylon cap ply calendaring

Like body ply material, nylon cap ply fabric is purchased in large rolls and cap skim is applied via a calender. Unlike body ply, it is not necessary to cut, rotate, and splice since the cords are intended to be longitudinal in the tire. The calendered sheet is slit into the required width per specification.

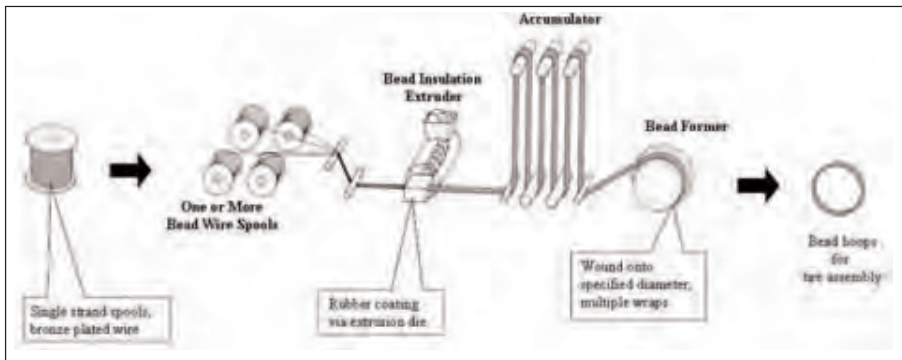
Figure 1.15: Tire manufacturing - steel stabilizer ply preparation

Bead bundle preparation (see figure 1.16)

Bead wire is bronze plated. Single-strand wire is purchased on spools and coated with rubber using an extrusion die. Depending on the bead configuration used, single strands (programmed shape) or multiple strands (box style) are wound onto a chuck to the specified diameter and shape. Sometimes the bead bundle is wrapped with rubber-coated fabric to facilitate tire assembly. Specified bead filler material can be pre-assembled onto

the bundle for tire building efficiency. Some tire manufacturers use a cable bead that features a solid core with several bead wires cabled around it. This requires a different manufacturing process than that shown in figure 1.16.

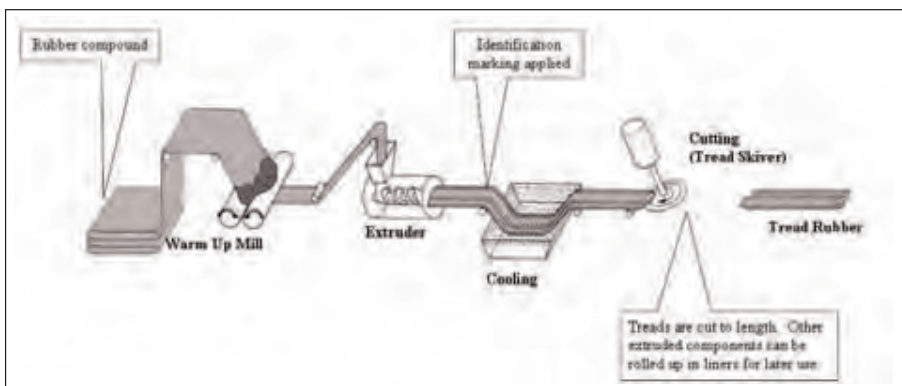
Figure 1.16: Tire manufacturing - bead bundle preparation



Extrusion (see figure 1.17)

Rubber components (e.g. treads and sidewalls) are shaped by forcing rubber through a die opening of appropriate shape. The rubber compound is carried to the die through a feeder tube or barrel containing an auger-like screw. Up to four barrels may feed a single die, allowing co-extrusion of different compounds into a single component, e.g. tread and sub-tread with sidewall wings. Die shape, compound properties, and extrusion speed control the dimensions and shape of the extrudate. Extruded pieces are marked with color coded stripes and lettering for identification and quality control purposes.

Figure 1.17: Tire manufacturing - extrusion process



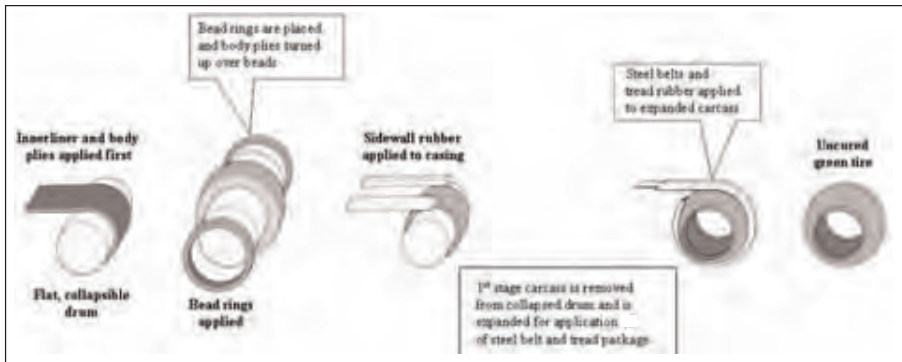
5.3 Tire assembly (see figure 1.18)

Carcass (body ply)

Radial tires are often built in two stages. In the first stage, the body carcass is assembled on a rotating, collapsible drum that is slightly larger than the bead diameter. The innerliner and body plies are applied first and rolled down over the edges of the drum. Then the beads and bead filler are set in place and the body ply(s) are turned-up over the

beads and rolled or stitched to adhere to the body ply lying flat on the drum. Strips of sidewall compound are then placed on top of the turned-up ply on both edges. The drum is then collapsed so the completed body carcass can be removed and taken to the second stage machine.

Figure 1.18: Tire manufacturing - radial tire assembly



Belt and tread assembly

The belts and tread are assembled on another rotating drum, to a diameter that is close to that of the final tire as possible, while allowing for clearance when the tire is inserted in the mold for curing. If required by the specified speed rating, full width nylon cap ply(s) or cap strips are wound over the belts before the extruded tread/subtread/undertread package is applied.

Green tire assembly

The second-stage equipment takes the first-stage body carcass and expands it into the larger belt-and-tread assembly. The finished “green” (i.e., uncured) tire is then rotated against tread area stitching wheels to adhere all of the components uniformly to the body carcass. The “green” tire is then stored on a rack for transfer to the curing room.

Several tire manufacturers and equipment vendors have devised automated tire assembly equipment that combines several assembly steps or links them into a continuous process. Substantial productivity gains are gained with high volume production. However, loss of production flexibility and the impact of equipment breakdowns or maintenance stoppages may create scheduling challenges.

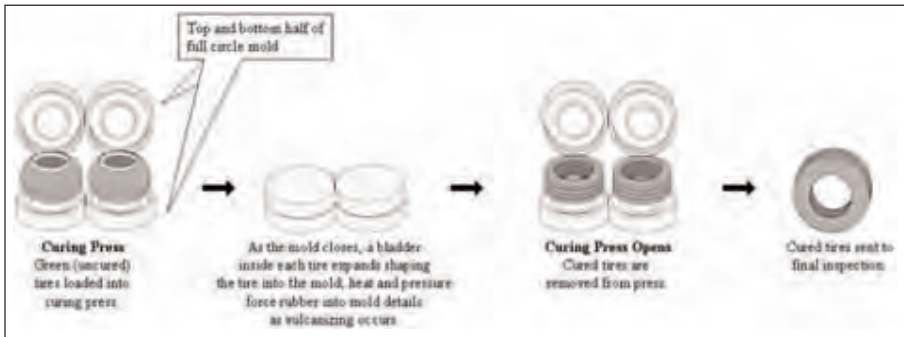
5.4 Curing (see figure 1.19)

Curing press

While there are different types available, most curing presses are massive devices (3.6 m wide x 2.8 m deep x 4 m high, weighing 20,450 kg). They hold two tire molds that resemble two open clamshells side-by-side. They have water, air, vacuum and steam lines attached, plus conveyors, and have automatic loading devices for placing the green tires over curing bladders in the center of each mold.

Full circle/segmented molds

There are two types of tire mold; full circle and segmented. Historically, full circle molds were developed for bias tires. The mold is divided into two circular pieces that join around

Figure 1.19: Tire manufacturing - curing (vulcanizing) process

the diameter of the tire, most often in the middle of the center rib. The two mold halves are attached to the top and bottom of the curing press and the green tire is inserted between them. As the press closes, bringing the two halves together, the green tire is expanded by inflating an internal rubber bladder that forces the outside of the green tire to conform to the inner surface of the mold. After curing is completed, the mold parts separate and the tire is removed. Note that the tread must deform to some degree as the mold opens, which can be more difficult for some tire profiles, compounds, and tread designs.

Segmented molds are more complicated but are preferred for certain radial tires. This is because the green tire diameter can more closely approach the mold diameter, minimizing expansion of the belt. The tread region of the mold typically consists of 8 or 9 radially-divided pieces or segments that come together as the mold closes. They must fit together precisely, both radially and with the top and bottom sidewall plates, when the mold is completely closed. The advantage of segmented molds is that less expansion is required of the green tire to fill the mold and the segments pull directly away from the tire after curing. This is an important feature in manufacturing low-profile tires and tires that use some tread compounds designed for low rolling resistance.

Curing (vulcanization)

As the mold closes, a bladder inside the tire expands and presses the green tire against the mold. The high bladder pressure (several hundred psi) forces the uncured rubber into every detail of the inner surface of the mold. Super-heated steam or hot water is then circulated within the bladder and around the mold for about 12 to 15 minutes. This rise in temperature causes a chemical reaction (curing, or vulcanization) to occur in the rubber compounds whereby the long polymer molecules become crosslinked together by sulfur or other curatives. The rubber compounds are transformed in this way into strong, elastic materials in the finished, cured tire. Curing times, temperatures and pressure are computer-controlled to give full cure of the chosen rubber compounds.

5.5 Final inspection

Vent trimming

To prevent air from being trapped in the tread pattern, tiny vents are drilled through the mold in the corners of tread elements. In a complex tread design, there can be thousands of such vents. Uncured rubber flows into the vent holes and is cured there, giving the final tread a “hairy” appearance. The rubber threads are trimmed off in a final inspection by

sharp knives held flat against the rotating tire.

Visual inspection

All tires are inspected visually for any imperfections (e.g., plugged vents or trapped air) before being transferred to a warehouse. If a minor imperfection cannot be buffed away or repaired, the tire is scrapped.

Uniformity grading

Most passenger tires are screened for uniformity (Section 4.3) against limits established by the OE vehicle manufacturer and/or the tire manufacturer. The test includes laser or probe inspection of the sidewalls and tread.

White stripe or white letter grinding

White or colored pigment compounds are sometimes applied to the sidewall. During building and curing they are covered with a protective thin film of a non-staining black compound. After curing, the raised sidewall is rotated against fine grinding wheels to expose a crisp, attractive stripe or letter. This process is often done in combination with uniformity grading.

5.6 Quality control testing

Production release

All tire manufacturing facilities run production qualification tests to assure compliance with performance requirements. Industry and government standards must be met, as well as any technical and indoor tests required by the customer as described in Section 4. While some of the tests are both time consuming and destructive, they must be completed successfully before volume production can begin.

Statistical sampling

Once in production, QA (Quality Assurance) protocols utilize statistical process control and sampling methods to assure that production tires remain in compliance with their original quality and performance standards.

6. Consumer care

6.1 Maintain proper inflation

By law, every vehicle sold in the United States has a placard that identifies the tire size(s) and the inflation pressures recommended for front, rear, and spare tires by the OE vehicle manufacturer. Beginning in the 2006 model year, the placard is to be located on the driver's door B-pillar. The location on older vehicles varies, sometimes being on the driver's door, the trunk lid, a door pillar or the glove box. In addition, the maximum load and inflation information is stamped on the sidewall of every tire, usually in the bead area just above the rim.

Tire pressures should be checked regularly. Radial passenger tires can be underinflated by 12 psi or more and still look normal. As explained in Section 4.3, air permeates through tires slowly, so that they typically lose about 1 psi per month, and even more in hot climates. Moreover, a small puncture from an imbedded nail or screw can cause a tire to be significantly underinflated. Underinflation contributes to rapid and uneven tread wear, a loss in fuel economy, poor vehicle handling and excessive heat buildup which may lead

to tire failure. It is recommended that tire pressures be checked at least monthly and before long trips or when additional passengers and luggage are carried. Pressures should be checked when the tires are cold, i.e., when the vehicle has not been driven for several hours, and using an accurate gauge. It should be noted that every 10°F drop in ambient temperature results in about one psi drop in tire inflation pressure. It is also recommended that tire valve assemblies be replaced when a new tire is installed.

6.2 Avoid overload

The vehicle tire loading information placard also specifies GVWR (Gross Vehicle Weight Rating) plus front and rear GAWR (Gross Axle Weight Rating). Exceeding these loads affects vehicle handling, steering and braking but also has an impact on tire life. Overloading increases the deflection and flexing of tires, which can generate excessive amounts of heat within the tire and may lead to failure. See Chapter 15 for more detail.

6.3 Regular rotation/alignment checks

Uniform tire wear prolongs the useful life or mileage potential of tires. Rotating tires between positions on the vehicle on a regular schedule minimizes uneven wear. Tires should be rotated every 6,000 to 8,000 miles, or sooner if signs of uneven wear appear. For new tires, the first rotation is the most important as the tread elements are most flexible at full depth. Rotation patterns vary, and some tires with asymmetric tread designs are uni-directional (see Direction of Rotation Arrows on Upper Sidewall). Consult the vehicle owner's manual or local tire dealer for specific recommendations.

Wheel mis-alignment, can cause uneven tire wear. While it is often considered to be an issue only with the front, steering wheels, alignment of an independent rear suspension is also important. Computerized alignment equipment can check all positions, including the rear to front relationship (i.e., thrust angle). Maintaining proper wheel alignment, regular rotation of tires, and proper inflation pressures will maximize tire service life.

Acknowledgement

The writer would like to thank Dan Saurer, Division Vice-President, Consumer Tire Development, Bridgestone/Firestone North American Tire, LLC, for providing the resources and support to assemble the material contained in this chapter.

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Chapter 2

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by A. N. Gent

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Chapter 2

Mechanical Properties of Rubber

by A. N. Gent

1. Elasticity and visco-elasticity

1.1 Rubbery, crystalline and glassy states

Rubber is a fascinating material, with unique properties that make it an essential component of a pneumatic tire: it is soft, elastic, resistant to cutting and scraping, with a high coefficient of friction and low permeability to gases. We consider here what molecular features give rise to this remarkable combination of properties and how they affect tire performance.

All rubbery materials consist of long chain-like polymer molecules. The original elastomeric material (raw rubber) is basically a highly-viscous liquid but it can show elasticity because the long molecules are held together, at least temporarily, by being intertwined and entangled. The basic reaction in rubber processing is the joining of long molecules together by a few chemical bonds (crosslinks) to form a loose three-dimensional permanent molecular network. The shape becomes fixed and the material is transformed from a high-viscosity liquid into an elastic solid.

This joining reaction is often termed “curing”, because the material is no longer a viscous sticky liquid, or “vulcanization” because it is usually carried out with reagents that introduce sulfur crosslinks between the molecules.

The cure curve for a representative practical rubber compound (compound C in Table 2.1), is shown in figure 2.1. A sample of the prepared mix of elastomer, filler, curatives and protective agents is placed in an Oscillating Die Rheometer (ODR) or Moving Die Rheometer (MDR) where the thin rubber layer is sandwiched between the heated stationary wall of the test chamber and a rigid cylindrical die. The die is made to execute small amplitude and low frequency oscillatory rotations, subjecting the rubber layer to oscillatory shear strains. The torque required to maintain the motion is monitored continuously. As the rubber compound becomes increasingly crosslinked and changes from a viscous liquid to a rubbery solid, the torque amplitude increases, reflecting the increasing torsional stiffness of the sample. A practical measure of a characteristic cure time is the time at which the torque reaches 90% of its maximum value, denoted t_{90} . For the mix formulation used here, t_{90} is about 10 min at 160°C. We now describe the elasticity of *unfilled* rubber vulcanizates before turning to the behavior of practical compounds (see Table 2.1) that contain large amounts of particulate filler. It should be noted in passing that the presence of filler can affect the rate of cure significantly by influencing the chemistry of crosslinking. For example, carbon black tends to increase the rate of cure by a factor of up to 3, and reduces t_{90} correspondingly.

The molecular segments in raw rubber and the molecular strands between crosslinks in cured rubber are in rapid thermal motion at normal temperatures. On deforming the molecular network, the strands take up new average positions that are less probable than their original ones. Changes in bond energies or conformational energies are relatively

**Table 2.1: Some representative tire compounds
(amounts given in parts by weight per 100 parts of elastomer).**

	A Passenger tire tread	B Sidewall	C Steel belt compound
<u>Elastomers</u>			
Natural rubber	-	50	100
Styrene-butadiene copolymer (25/75)	75	-	-
Cis-polybutadiene	25	50	-
<u>Fillers</u>			
Fine carbon black (e.g., N220)	75	-	-
Medium carbon black (e.g., N330)	-	-	60
Coarse carbon black (e.g., N660)	-	50	-
<u>Vulcanization agents</u>			
Zinc oxide	3	3	10
Stearic acid	3	1	1.2
Sulfur	1.55	2	5.5
Vulcanization accelerator (sulfenamide type)	1.9	1	0.5
Secondary accelerator (guanidine)	0.25		
<u>Processing aid</u>			
Processing oil	10	10	-
<u>Protective additives</u>			
Antioxidant/antiozonant	1.5	3.5	1
<u>Resin and adhesion promoter</u>			
Resin components	-	-	8
Adhesion promoter (e.g. cobalt naphthenate)	-	-	2

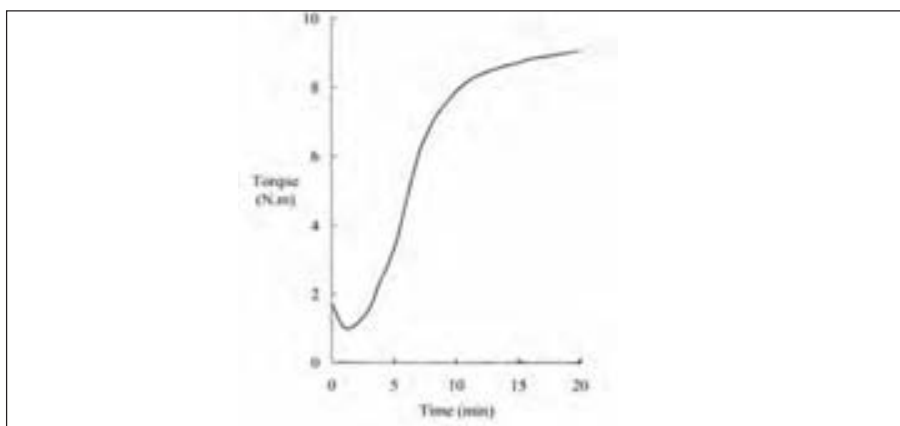
Vulcanized for 10-15 minutes in a tire mold at a temperature of 170-175°C

small - only the *entropy* of the network is reduced. Thus, rubber is an entropic spring - it returns to the undeformed state only because that is the most probable one. As a result, the stiffness of rubber *increases* with temperature T because the contribution ΔS of entropy to the free energy of deformation is given by the product: $-T\Delta S$. This characteristic feature of rubber is in marked contrast to the behavior of springy crystalline materials, like metals, where the stiffness decreases with rising temperature because, on deforming metals, the atoms are forced out of an ordered state into a more random arrangement, with lower bond energies and higher entropy.

An approximate statistical calculation gives the tensile modulus E (Young's modulus) of elasticity for an unfilled rubber vulcanizate under small tensile strains as

$$E = 3NkT \quad (1.1)$$

where N is the number of molecular strands comprising the network, k is Boltzmann's constant and T is absolute temperature. A typical value for N is about $1.5 \times 10^{26}/\text{m}^3$. Thus a typical value for E is about 2 MPa, i.e., about four orders of magnitude smaller than for metals, reflecting the ease with which the shapes of long flexible molecules can be rearranged.

Figure 2.1: Cure curve for compound C at 160°C

The average network strand consists of about 100 repeat units (mers) of a particular chemical group, typically with a molecular weight of around 60. Some repeat units in rubbery materials commonly used in tires are:

- C₄H₆- : cis-1,4 polybutadiene
- C₅H₈- : natural rubber (cis-1,4-polyisoprene)
- CH₂C₃H₆- : butyl rubber
- (-CH₂-C₇H₁₂-)_n-(-C₄H₆-)_m : SBR (a copolymer of styrene, n units, and butadiene, m units)

But why are only relatively few polymers rubbery? There are two main reasons why a polymeric solid might not exhibit rubberlike elasticity. When the long molecules are highly regular and able to pack closely together, they tend to arrange themselves in this way under the weak van der Waals attractive forces that are present in all materials – they spontaneously *crystallize*. For example the commercial plastic – polyethylene – is as much as 60% crystalline at room temperature and shows little elasticity. Instead, it behaves as a typical crystalline solid. Initially rather stiff, after the material is deformed by a few percent the crystallites begin to yield and the deformation then becomes ductile and plastic, rather than elastic.

The other reason why polymeric materials may fail to show rubbery behavior is that the chemical repeat units are relatively heavy and bulky, so that thermal energy at normal temperatures is not sufficient for molecular segments to move freely. Polymers in this state are termed *glassy solids*. Typical examples are polystyrene and polymethylmethacrylate that are glasslike at temperatures below about 100°C.

On raising the temperature, crystals melt and immobile molecules acquire more energy, so that both crystalline and glassy polymers become rubbery at sufficiently high temperatures, for example, above 150°C for polyethylene and above 100°C for polystyrene and polymethylmethacrylate. And all rubbery polymers turn into glassy solids at a characteristic low temperature, even if they have not spontaneously crystallized as they are cooled down. The transition temperature (glass temperature, T_g) is one of the most important characteristics of a polymer and, as shown later, it controls the mechanical behavior at temperatures far above the actual glass temperature. Values of T_g for selected rubbery polymers are given in Table 2.2.

Table 2.2: Glass temperatures T_g ($^{\circ}\text{C}$) for some common elastomers.

Elastomer	T_g
Polydimethylsiloxane (silicone rubber)	-125
Cis-1,4-polybutadiene	-100
Cis-1,4 polyisoprene (natural rubber)	-72
Poly(isobutylene-co-isoprene) (butyl rubber)	-70
Poly(styrene-co-butadiene) 25/75 (SBR, emulsion)	-60
Poly(ethylene-co-propylene) 56/44 (EPR)	-55
Plus ca 5% diene comonomer, (EPDM)	-55
Polychloroprene (Neoprene)	-50
Poly(butadiene-co-acrylonitrile) 85/15 to 65/35 (Nitrile rubber)	-40 to -10
Poly(styrene-co-butadiene) 50/50 (High-styrene SBR)	-25

The other important physical feature of a rubbery solid is the average length of the molecular strands comprising the network, generally denoted by the molecular weight M_c . The original molecules have molecular weights in the range 100,000 to 500,000, not higher than this because very high molecular weight materials are difficult to extrude and shape. After crosslinking, the molecular weight M_c of the network strands ranges from about 5,000 to 20,000 molecular weight units. Although this number may, in principle, be varied widely by introducing more or fewer crosslinks, in practice if M_c is small then the material is stiff and brittle and if M_c is large then some of the original long molecules are not tied into the network completely, and contribute little or nothing to stiffness and strength. Nevertheless, the practical range of crosslinking and hence of elastic modulus E is from about 1 MPa to about 3 MPa, a greater range (a factor of 3) than for any other structural solid. And by adding particulate fillers, the modulus can be raised still further without serious loss in strength - indeed, often with a pronounced gain in strength, termed reinforcement (see later).

1.2 Elastic behavior

The elastic modulus of a rubber compound is often characterized by its resistance to indentation by a blunt indenter. The amount of indentation is indicated on a non-linear scale, from 0 to 100 International Rubber Hardness Degrees (IRHD), corresponding to values of modulus E ranging from zero to infinity. Values of IRHD and E covering the practical range of rubber modulus are given in Table 2.3. Outside this range the materials are either extremely soft and weak or hard and relatively inflexible.

Rubber can often be treated as virtually incompressible in bulk because the modulus of bulk compression is quite high, about 2 GPa, comparable to that of liquids such as water, and much higher than the tensile modulus E , typically about 2 to 5 MPa. Consequently, the elastic shear modulus G is approximately equal to $E/3$, and Poisson's ratio is close to one-half, about 0.499. [Definitions of the various elastic coefficients are shown in figure 2.2.]

Table 2.3: Relation between International Rubber Hardness Degrees (IRHD) and elastic (Young) modulus E.

IRHD	E(MPa)
30	1.0
35	1.2
40	1.5
45	1.9
50	2.3
55	2.9
60	3.6
65	4.5
70	5.5
75	7.5
80	9.5
85	15

Note that when a solid rubber block is “compressed”, its volume does not decrease significantly unless the pressures are extremely high. Instead, the block compresses vertically and expands laterally - the volume remains virtually unchanged. Compression of a block bonded between two plates is sketched in figure 2.3. Due to the restraint on lateral expansion, the effective modulus E_e can be quite high.

Rubber molecules move freely because the intermolecular forces are low. The expansion in volume on heating is correspondingly high, similar to that for simple liquids. The linear thermal expansion coefficient α for unfilled rubber compounds ranges from about 1.5 to $2 \times 10^{-4}/^\circ\text{C}$. Due to the low thermal expansion coefficients of filler particles, values of α for typical filled compounds are somewhat lower, 1.2 to $1.5 \times 10^{-4}/^\circ\text{C}$, but still far higher than for metals, about 50 times greater. Thus, when a rubber article is removed from the metal mold in which it has been shaped and crosslinked at a high temperature (typically about 160°C) and then allowed to cool down to ambient temperature, it shrinks in linear dimensions by about 2%.

1.2.1 Elastic behavior at large strains

Because rubber is highly extensible, small-strain elasticity theory using moduli E and G is inadequate to describe the response to large strains. Instead, a useful measure of response is the mechanical energy W stored in unit volume by a deformation. A simple relation for W for an initially-isotropic, incompressible elastic solid is:

$$W = (E/6) J_1 \quad (1.2)$$

where J_1 describes the deformation in terms of stretch ratios $\lambda_1, \lambda_2, \lambda_3$ in the principal directions, see figure 2.4:

$$J_1 = (\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3) \quad (1.3)$$

(Note: $\lambda_1 = 1 + e_1$, etc., where e_1 is the strain in the 1 direction.) Because rubber is virtually incompressible, the product $\lambda_1 \lambda_2 \lambda_3 = 1$. Equation 1.2 is termed the neo-Hookean constitutive law because it reduces to Hookean (linear) elasticity, figure 2.2, in the limiting case of small strains and gives reasonably accurate predictions at moderately large strains.

Figure 2.2: Elastic coefficients (moduli) for small strains

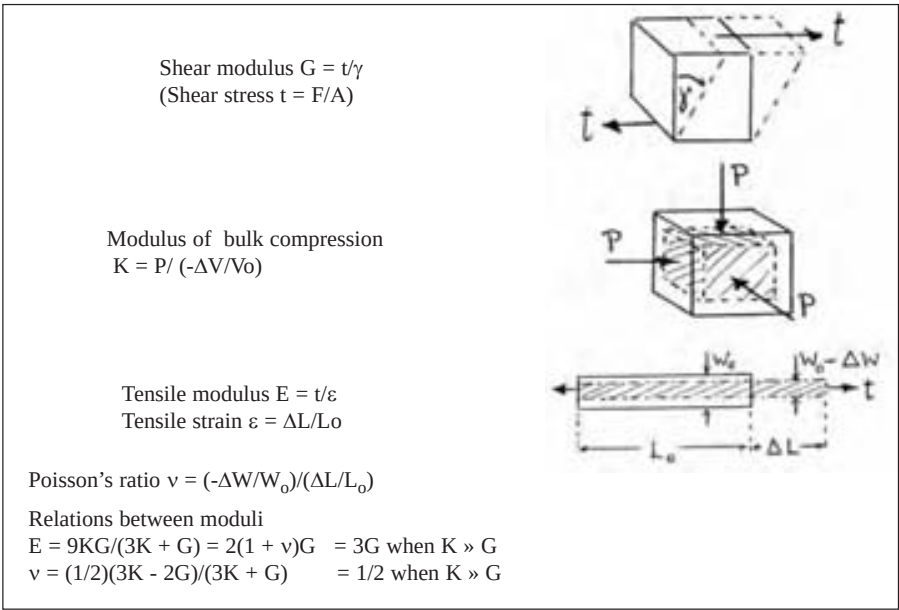


Figure 2.3: Compression of a bonded rubber block

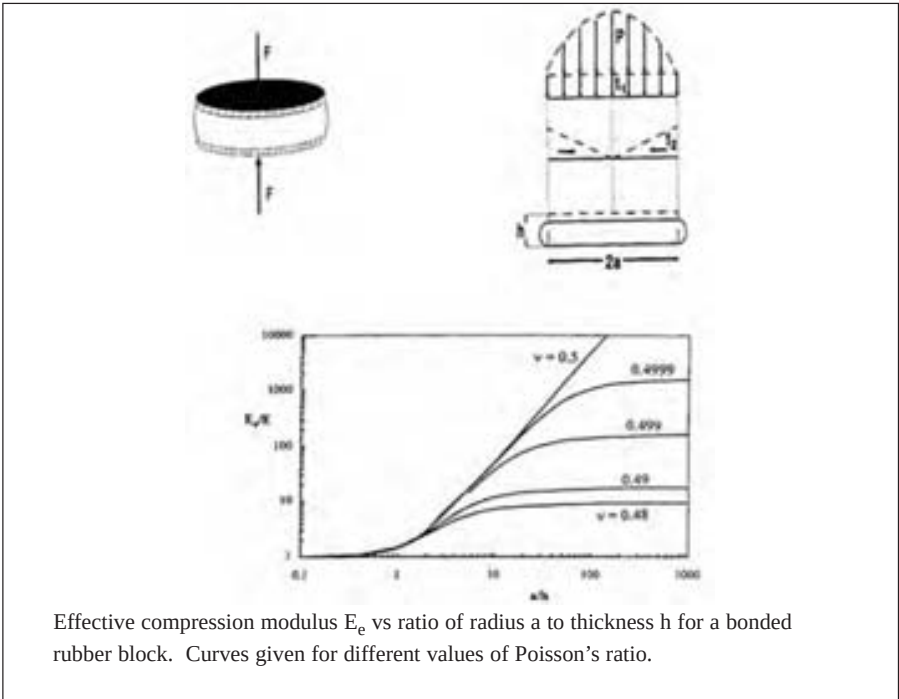
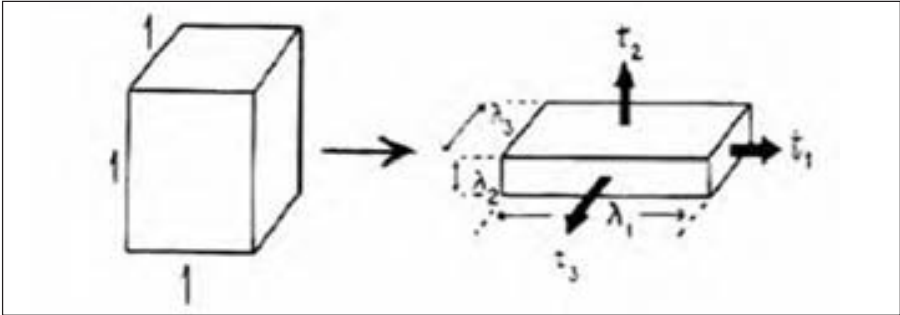
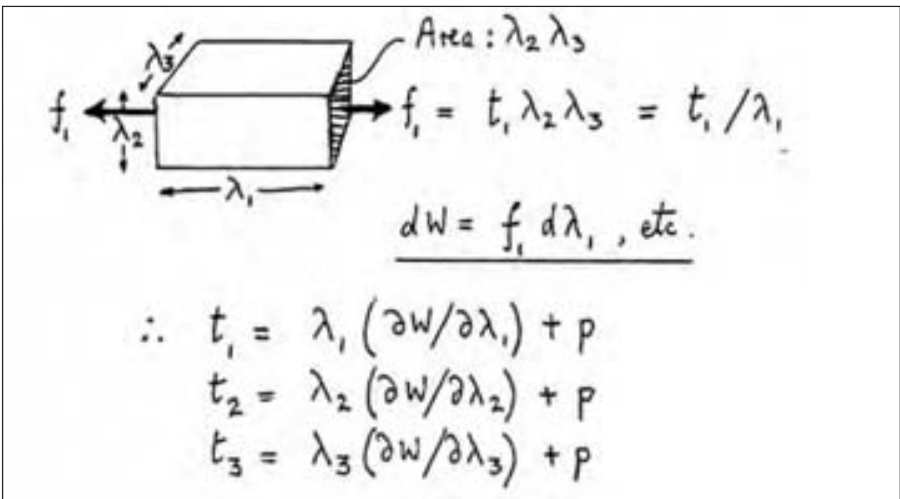


Figure 2.4: Stretch ratios λ and stresses t Figure 2.5: Relations between strain energy W and stresses t 

Using the simplifying assumption that deformations are accompanied by no change in volume, stress-strain relations can be deduced from W by considering a hypothetical change in extension $\delta\lambda_1$ causing a corresponding change δW in W (figure 2.5):

$$\delta W = (\lambda_2 \lambda_3) t_1 \delta\lambda_1 \quad (1.4)$$

Thus,

$$t_1 = \lambda_1 (dW/d\lambda_1) + P \quad (1.5)$$

where P is an undefined pressure that must be included because, for incompressible materials, a hydrostatic pressure can do no work. The appropriate value to assign to P is determined by establishing a base-line for stress in any particular case. In simple tension, for example, the side stresses t_2 and t_3 are zero and P is therefore given by $[t_1 - \lambda_1(dW/d\lambda_1)]$.

The stress t_1 is the force acting in direction 1 on a unit of cross-sectional area, where the area is measured in the deformed state. It has unfortunately become common practice in the rubber industry to use the word *stress* to denote the force σ acting on a unit of undeformed cross-sectional area, because this is a more easily measured quantity. To

distinguish between the two usages, σ is sometimes termed *engineering stress*. For an incompressible material, like most rubbery solids, the imposition of a stretch ratio λ leads to a contraction in cross-sectional area by a factor $1/\lambda$ and thus there is a simple relation between the two measures of stress (see figure 2.5):

$$\sigma = t/\lambda \quad (1.6)$$

In rubber technology, the term “modulus” is often used to describe the tensile force per unit of unstrained cross-sectional area at a stipulated tensile strain. For example, M_{100} denotes the stress σ when $e = 100\%$. Values for M_{100} , M_{200} , M_{300} , etc., are often reported also - they give an indication of the shape of the stress-strain curve, see figure 2.6.

The stress-strain relation in simple extension is obtained from Equation 1.5 as:

$$t = (E/3) (\lambda_1^2 - 1/\lambda_1) \quad (1.7)$$

This is the large-deformation equivalent of the result: $t = Ee$, applicable at small strains. Experimental stress-strain relations for soft rubber compounds are found to be in reasonable agreement with equation 1.7 up to moderately large extensions, about 300%.

Note that stress-strain relations for rubber are usually *non-linear*, figures 2.7 - 2.9. Equation 1.7, for example, predicts that the tensile stress-strain relation, after the expected linear region at small strains, will be concave with respect to the strain axis, as is observed. At higher strains a pronounced stiffening occurs as the molecular strands approach the fully-stretched state, figure 2.8. Thus, non-linearity does not indicate that internal yielding or fracture has occurred. Instead, it follows directly from a consideration of the elastic behavior of a network of long molecular chains, each of which is linearly-elastic over a wide range of extension but because they are randomly arranged in space, the combined effect is usually non-linear.

There is one outstanding exception to the general non-linear character of rubberlike elasticity, however, and that is a simple shear deformation. Using equation 1.5 the calculated stress-strain relation in simple shear is *linear*, and rubber compounds are found to be approximately linear in shear up to moderately large strains, 100% or more, with a slope (shear elastic modulus G) of $E/3$.

Many constitutive laws have been proposed to model the elastic behavior of rubber more accurately than the simple neo-Hookean form for W given in Equation 1.2, for example by taking into account the stiffening observed at high strains, Figures 2.6 and 2.8. This feature is not predicted by Equation 1.2. It can be modeled by introducing a maximum possible value J_m for the deformation term J_1 . Thus one modified version of Equation 1.2 is the logarithmic form:

$$W = - (EJ_m/6) \ln (1 - J_1/J_m) \quad (1.8)$$

which reduces to equation 1.2 when the deformations are small compared to J_m , but gives increasingly large values for W and thus for stresses when the deformation approaches its maximum possible value J_m .

However, rubber compounds currently used in tires are seriously inelastic, as described below, and attempting to describe their elastic properties with great precision is probably unwarranted. Examples of typical tire formulations are given in Table 2.1. They illustrate the complexity that results when compromises must be made to meet demanding but often conflicting requirements: stiffness, strength, resilience, good traction, wear resistance, durability, etc.

Figure 2.6: Experimental relation between tensile stress and elongation

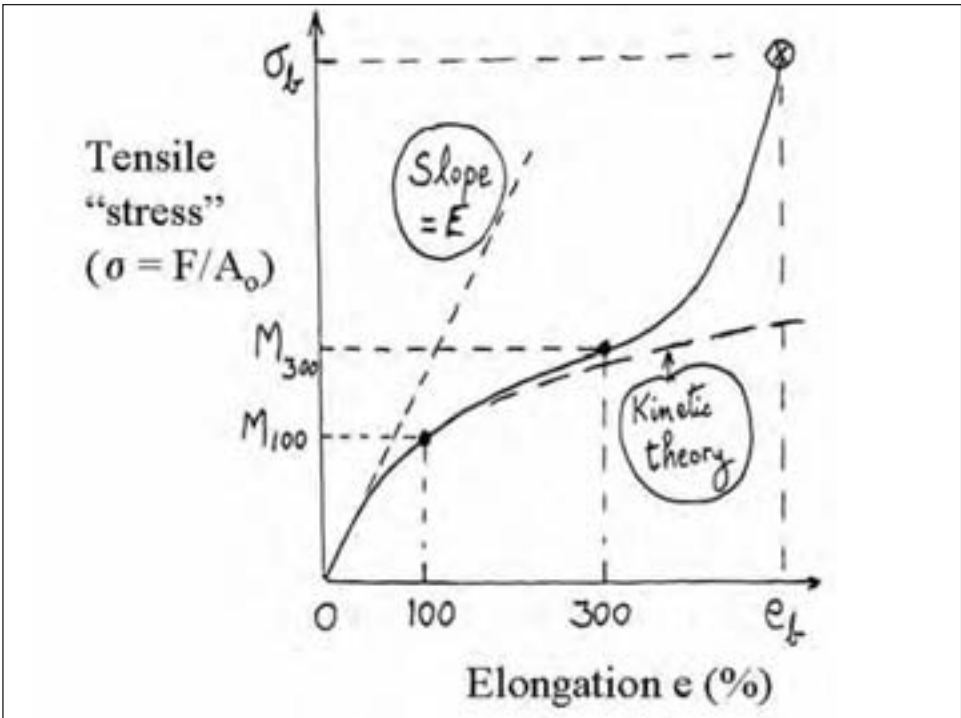


Figure 2.7: Stress-strain relation in tension

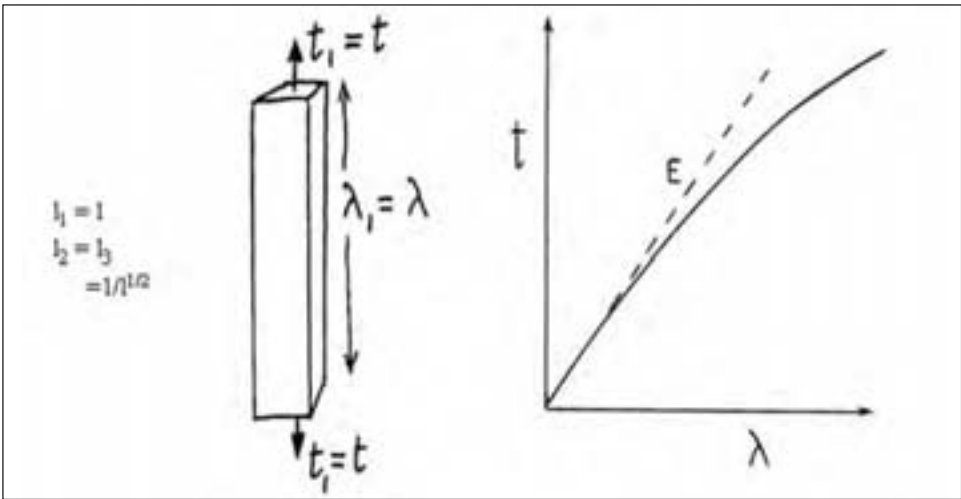
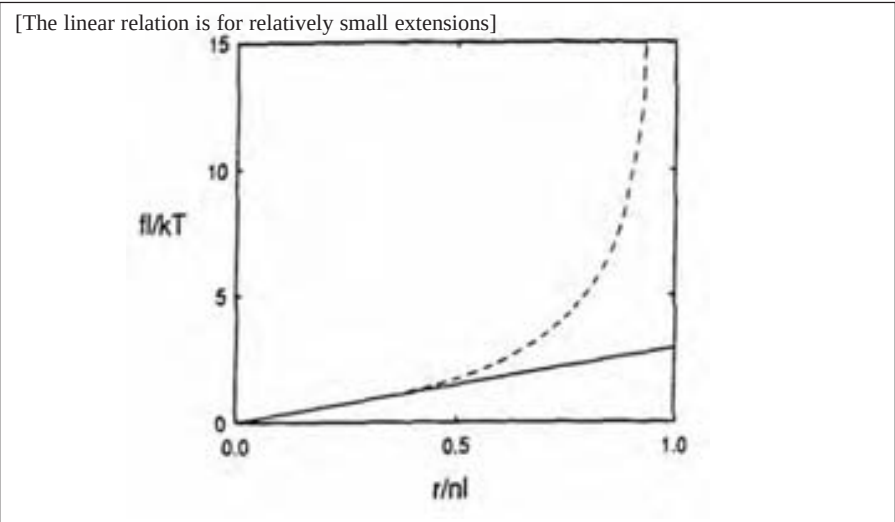


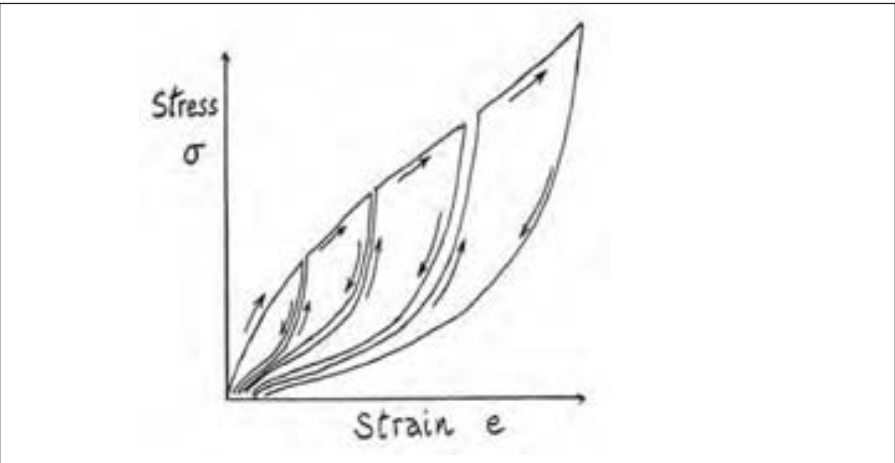
Figure 2.8: Strain hardening of a rubber molecule as it approaches full extension.



1.2.2 Inelastic behavior of filled rubber compounds

It is common to incorporate 30% or more by weight of solid particle fillers, usually carbon black or silica powder, into compounds for all tire components, treads, sidewalls, etc. Such compounds are considerably stiffer, by a factor of 3 or more, than the corresponding unfilled compound, and they are stronger, and much more resistant to abrasion. But highly-filled rubber compounds are seriously inelastic, in a characteristic way. They are softened by straining, and softened more the greater the pre-strain, as shown schematically in figure 2.9. Thus, the original stress-strain relation is not reproducible unless the sample is allowed to recover by resting for several months, or annealed by heating for an hour or so at temperatures of 100°C or higher.

Figure 2.9: Stress-softening of filled rubber (Mullins Effect)

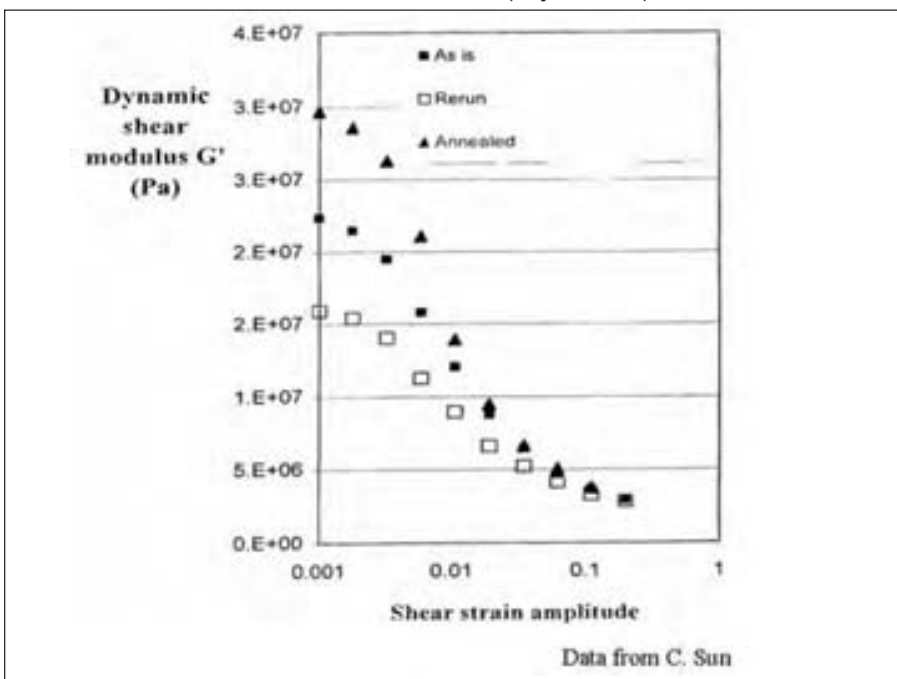


This large effect of strain history on the stress-strain behavior is termed the “Mullins” effect [1]. It appears to be due to slipping of rubber molecules over energy barriers on the surface of filler particles or becoming detached from the filler surface. It renders computer modeling of the stress-strain behavior of typical tire tread compounds extremely difficult. For example, we know very little about the effect of pre-strains other than tensile strains, or of complex strains as is, of course, the case for tire components, or about the rate of recovery from prior straining.

To make matters even more complicated, a similar effect is found when quite small strains are imposed, in the range, say, from 0.1% to 10%. Such measurements are usually carried out dynamically, by imposing a small oscillatory tensile or shear strain at a convenient frequency in the range 0.1 to 100 Hz, and reporting the results in terms of the effective dynamic modulus E' or G' , the ratio of peak stress to peak strain. E' or G' are found to decrease dramatically over this range of dynamic strain amplitude, often to only 1/3 or less of the initial value, figure 2.10. Again, although partial recovery by 30 to 50% occurs almost immediately on returning to small deformation amplitudes, complete recovery takes months of rest unless the sample is heated to accelerate the recovery.

This small-strain softening phenomenon is often termed the “Payne” effect [2]. It appears to be due to disruption of chain-like aggregations of filler particles within the rubber matrix. Because the effect is so large in highly-filled compounds, they are seldom used in rubber springs because the relevant “modulus” for calculations of spring rate and resonant frequency is ill-defined. And, again, it is difficult to take the “Payne” effect into account in modeling the stress-strain response of tire compounds in treads and sidewalls.

Figure 2.10: Stress-softening of filled rubber at small strains (Payne effect)



In summary, typical filled rubber compounds show two disturbing features: the **“Payne” effect**, a marked softening that starts at strain amplitudes of only 0.1 % or less, attributed to breakdown of weak inter-particle bonds, and **“Mullins” softening**, a further substantial softening at higher strains, up to the breaking strain, that is attributed to progressive rupture of bonds between rubber molecules and filler particles. Because these two processes overlap to a considerable degree, they cannot be easily separated. However, they appear to be a direct consequence of the high stiffening power of fillers of small particle size and highly interactive surfaces when they are incorporated into rubber.

Note that, because filled rubber compounds are not elastic, i.e., they do not follow reversible stress-strain relations, their behavior cannot be described successfully by any elastic constitutive law relating stresses to strains. Instead, the tire designer must accept quite approximate representations of the elastic properties of present-day tire compounds, recognizing that they are subjected to complex strains and strain histories that have major, and unfortunately ill-defined, effects on the corresponding stresses.

1.3 Visco-elasticity

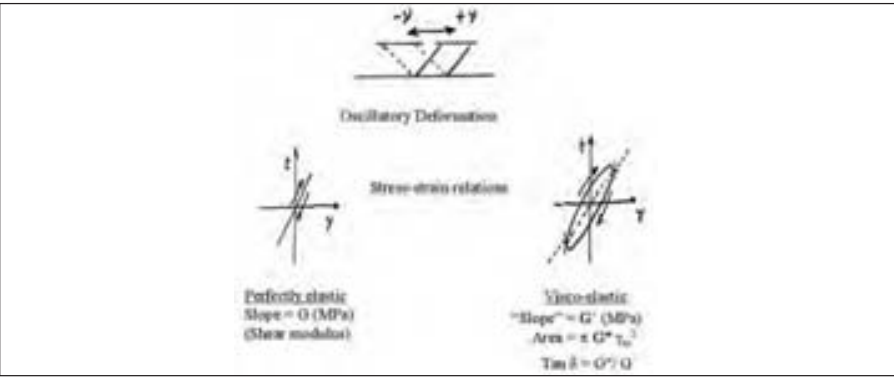
Under repeated oscillations of shear strain γ , the stress-strain relation becomes an ellipse, figure 2.11, provided that the strain amplitude is small. The slope of the line joining points where tangents to the ellipse are vertical represents a dynamic shear modulus G' (MPa) and the area of the ellipse represents energy U_d dissipated in unit volume per cycle of deformation, given by

$$U_d = \pi G'' \gamma_m^2 \tag{1.9}$$

where γ_m is the amplitude of shear strain and G'' is termed the dynamic shear loss modulus. (For an oscillatory tensile deformation the corresponding moduli are denoted E' and E'' .)

The ratio G''/G' (or E''/E') is the tangent of an angle δ , the phase angle by which the strain lags behind the applied stress. When the ellipse axes lie in the horizontal and vertical directions, δ is 90° ($\tan \delta$ is infinitely large), and the rate of strain reaches its maximum value when the applied stress is a maximum. This is the response of a viscous liquid. On the other hand, when the ellipse degenerates into a straight line, $\tan \delta = 0$ and the material is a perfectly elastic solid. Values of $\tan \delta$ for rubber compounds at room temperature range from about 0.03 for a highly resilient, “springy” material with low energy dissipation to about 0.2 for a typical tread compound with relatively high dissipation.

Figure 2.11: Oscillatory deformation: dynamic effects



Rebound resilience R is an inverse measure of energy dissipation. R can be determined by dropping a rigid ball onto a rubber block and measuring the rebound, or dropping a rubber ball onto a rigid plate. In both cases the fractional amount of energy returned after impact is:

$$R = h_2/h_1, \quad (1.10)$$

where h_1 is the drop height and h_2 is the rebound height. If the impact is regarded as one half-cycle of a steady oscillation, then

$$\ln R = -\pi \tan \delta \quad (1.11)$$

Equation 1.11 is based on rather severe assumptions so it must be considered as a rough approximation. However, rebound tests are simple to perform and widely used to estimate loss properties.

1.3.1 Heat generation

Energy dissipated by loss processes within a rubber compound is converted directly into heat. Under a steady oscillation the amount of heat generated per second in unit volume is given by fU_d , where f is the frequency of oscillation. Heat is lost by conduction through the rubber to surfaces in contact or to air. Consider, for example, a thin rubber block, of thickness H , that is subjected to an oscillatory shear deformation between two highly-conductive surfaces that act as heat sinks so that the interfaces are maintained at a constant temperature T_o . At steady state, the maximum temperature reached in the center of the block will be

$$T_m = T_o + fU_d H^2/8K \quad (1.12)$$

where K is the coefficient of thermal conduction for the rubber.

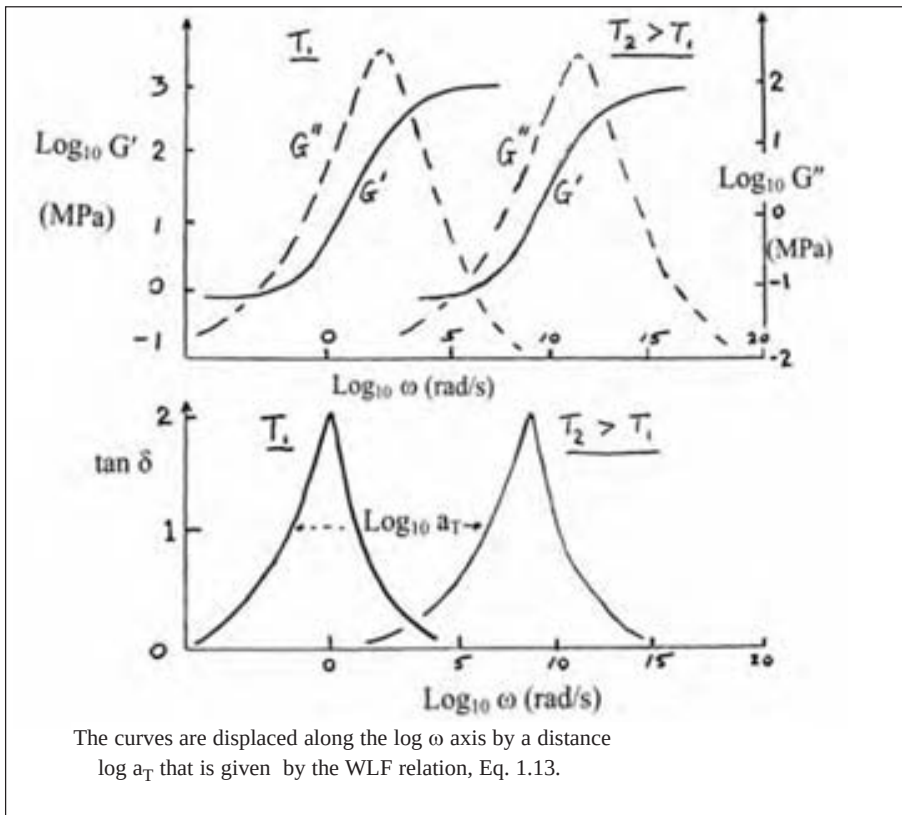
It is clear that heat conduction plays an important role in determining the temperature rise. Unfortunately, K is rather insensitive to compounding variables. All elastomers are poor conductors of heat, with values of K of about 0.2-0.3 W/m °C. Even when good conductors - for example, metal powders - are added to the rubber compound, K is not greatly increased because the metal particles become surrounded by a rubber layer and do not form continuous paths for conduction of heat.

The amount of heat generated per cycle depends strongly on the deformation amplitude $\gamma_{\max}$ of shear or $e_{\max}$ of tension/compression. Thus, under oscillations of constant *load* amplitude, a stiffer compound will show less heat generation and a smaller temperature rise if its resilience or $\tan \delta$ is unchanged. Indeed, this effect may well override the difference in loss properties between a stiffer and a softer compound. On the other hand, under a fixed *deformation* amplitude the material with lower loss modulus will generate less heat. Solid tires are an example of an application in which the load level is fixed. In rubber belting, on the other hand, the amplitude of strain (bending) is fixed by details of the application. Compounds would therefore be chosen for these two uses on different grounds. In any case, it is desirable to have compounds that generate a minimum of heat in use because the strength, durability and abrasion resistance of rubber compounds are all reduced as the temperature increases.

1.3.2 Effects of temperature and frequency of oscillation

We need to know values of G' , G'' and $\tan \delta$ at the frequency of loading and at the temperature at which the rubber is to be used, because the dynamic properties depend strongly on these variables. The dependence on frequency is shown schematically in figure 2.12. At low frequencies the dynamic modulus is low and rather constant but as the frequency is raised the compound becomes increasingly stiff until at high frequencies it is hard and glasslike. This striking transition, by about three orders of magnitude, reflects the change from facile response of molecular segments when stresses are applied at low frequency, to their complete inability to move under high-frequency stresses. Thus, the transition is centered at an oscillation frequency of the same order of magnitude as the natural frequency of motion of the molecular strands as a result of thermal agitation. Motion of a strand, in turn, arises from Brownian motion of the individual segments that make up the strand.

Figure 2.12: Dynamic properties vs frequency and temperature



The loss modulus G'' increases with frequency to an even more marked degree than G' , often becoming larger than G' in the transition range of frequencies, because G'' is a direct measure of viscous resistance to segmental motion. At sufficiently high frequencies, however, the segments become unable to respond to the rapidly-alternating applied stresses, and internal motion ceases. Energy dissipation that is associated with the motion of

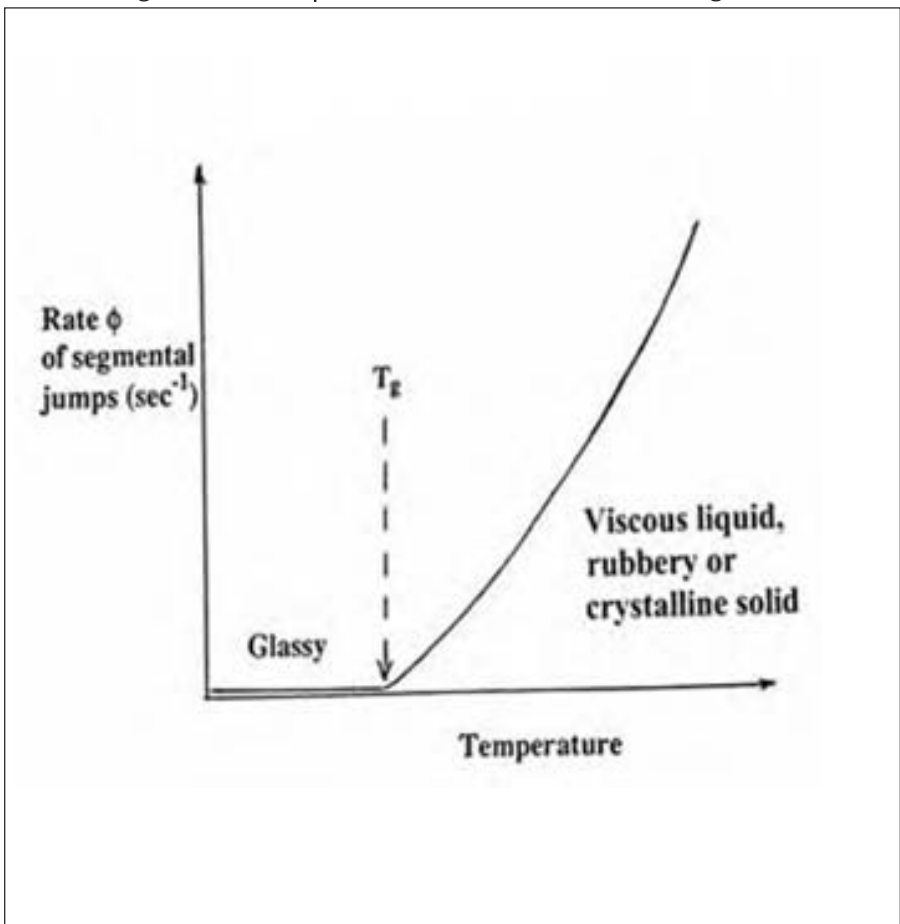
molecular segments in a viscous environment also ceases and G'' falls to the relatively low value characteristic of polymeric glasses.

The rate ϕ of Brownian motion of molecular segments depends only upon the internal viscosity and hence only upon temperature. Below T_g the polymer is glassy; above T_g it is liquid (if low in molecular weight), rubbery (if high in molecular weight or crosslinked), or crystalline (if the molecules are sufficiently regular), figure 2.13. The dependence of ϕ upon temperature, or more precisely upon the temperature difference $(T - T_g)$, follows a characteristic law [3]:

$$\log [\phi(T)/\phi(T_g)] = A(T - T_g)/(B + T - T_g) \quad (1.13)$$

where A and B are constants, having approximately the same values, 17.5 and 52°C, for nearly all rubberlike substances, and T_g is a reference temperature, the glass transition temperature, at which molecular segments move so slowly, about once in 10 seconds, that for all practical purposes they do not move at all and the material becomes a rigid glass. [By common consent, T_g is defined as that temperature at which the rate of Brownian

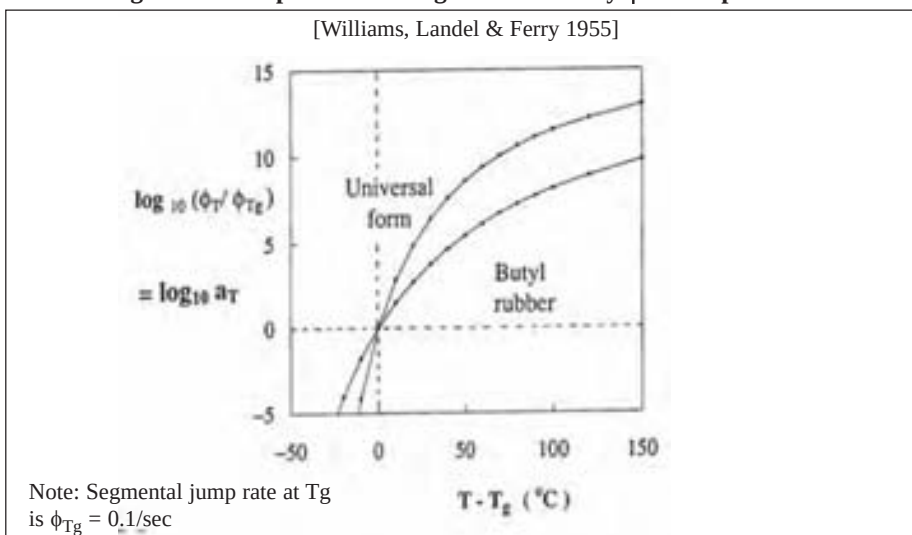
Figure 2.13: Rate ϕ of Brownian motion of molecular segments



motion $\phi(T_g)$ has fallen to 0.1 Hz.] Values of T_g for some common elastomers are given in Table 2. Equation 1.13 is represented graphically in figure 2.14.

In many applications molecular motion is required at frequencies much higher than 0.1 Hz. For example, for high resilience in a rebound experiment we require virtually complete rubberlike response in a time of impact of the order of 1 ms. But molecular segments will move in 1 ms only when the value of ϕ is about 1000 jumps per second.

Figure 2.14: Dependence of segmental mobility ϕ on temperature



From equation 1.13, that is only at a temperature about 16°C higher than T_g . Indeed, for coordinated motion of entire molecular strands consisting of many segments to take place within 1 ms, the segmental response frequency must be higher still, by a factor of 100 or so. This rate of response is achieved only at a temperature about 30°C above T_g . Thus, fully rubberlike response will not be achieved until the temperature is $T_g + 30^\circ\text{C}$, or even higher. On the other hand, for sufficiently slow movements taking place over several hours or days, a material would still be able to respond at temperatures significantly below the conventionally-defined glass transition temperature. This region is represented by the lower portions of the curves in figure 2.14.

It is important to recognize that the conventional glass transition temperature is defined in terms of relatively slow motions, taking place in about one minute, and requiring only small-scale motions of individual molecular segments rather than motion of entire molecular strands between crosslinks. The frequencies at which the entire rubber-to-glass transition occurs depend on temperature in accordance with Equation 1.13.

The numerical coefficients, 17.5 and 52°C , in equation 1.13 are about the same for a wide range of elastomers, because most elastomers have similar values of thermal expansion coefficient and the molecular segments are similar in size. However, an important exception is polyisobutylene and its derivatives, butyl rubber and halo-butyl. For these materials, the coefficients appear to be about 17.5 and 100°C , the latter being considerably different from the "universal" value that holds for other common elastomers.

Thus, the rate of segmental motion increases much more slowly above T_g as shown by the curve for butyl rubber in figure 2.14. Although the reason for this peculiarity is not well understood, it is probably associated with an unusually large size for the basic moving segment. Two important consequences are that butyl rubber and halo-butyl exhibit unusually low resilience, low gas permeability and good ozone resistance at temperatures well above T_g .

Equation 1.13 can be used to relate the dynamic behavior at one temperature T_1 to that at another, T_2 . For example, the dynamic modulus G' and loss modulus G'' are found to depend on the frequency of vibration as shown schematically in figure 2.12. When the temperature is raised to T_2 , the curves are displaced laterally by a fixed distance, $\log a_T$, on the logarithmic frequency axis, where $\log a_T$ reflects the change in characteristic response frequency of molecular segments when the temperature is changed from T_1 to T_2 . Thus $\log a_T$ is given by:

$$\begin{aligned}\log a_T &= \log [\varphi(T_2)/\varphi(T_1)] \\ &= 17.5 \times 52(T_2 - T_1)/(52 + T_2 - T_g)(52 + T_1 - T_g)\end{aligned}\quad (1.14)$$

from Equation 1.13. In this way, measurements at one temperature can be transformed into results at another. This is a powerful way of predicting viscoelastic response over wide range of frequency from measurements over a limited range of frequency but at many temperatures, using the general principle that a temperature shift is completely equivalent to a change in frequency:

$$\text{Log } f_T = \text{Log } f_{T_g} + \text{Log } a_T \quad (1.15)$$

As an approximate guide, valid at temperatures about 50°C above T_g , a temperature rise of about 12°C is equivalent to a factor of 0.1 change in frequency, or rate of strain, or speed of loading. Thus Equation 1.15 provides a powerful frequency-temperature and rate-temperature equivalence principle that enables one to correlate mechanical behavior over wide ranges of frequency and rate with temperature. For example, measurements taken over a limited frequency range at many different temperatures can be superposed by lateral shifts along the logarithmic frequency axis to construct a “master curve” as shown in figure 2.15. The lower curve (figure 2.15b) represents the expected response over an extremely wide frequency range at the chosen temperature. Moreover, the master curve can be made to apply at any other temperature by an appropriate lateral shift along the log frequency axis, calculated from equation 1.14.

However, there are instances where this broad simplification fails to hold. If the modulus is affected by a temperature-dependent process that is not controlled solely by the rate of molecular motion (for example, melting of crystallites), then the frequency-temperature equivalence given in equation 1.14 no longer applies. An example is discussed below.

1.3.3 Energy losses in filled rubber compounds

The same principle of frequency-temperature equivalence applies to the rubber molecules in filled rubber compounds and the same fitting constants are valid. Apparently, T_g and the molecular mobility of elastomer strands above T_g are not appreciably affected by the presence of fillers. But filled compounds show other effects, as described previously - the elastic modulus is decreased by a previously imposed strain, or by imposing dynamic deformations of increasing amplitude. This softening is accompanied by increased energy dissipation, probably associated with the work required to break bonds between rubber and filler particles or between the particles themselves.

Figure 2.15a: Modulus E vs oscillation frequency f for a polyurethane elastomer

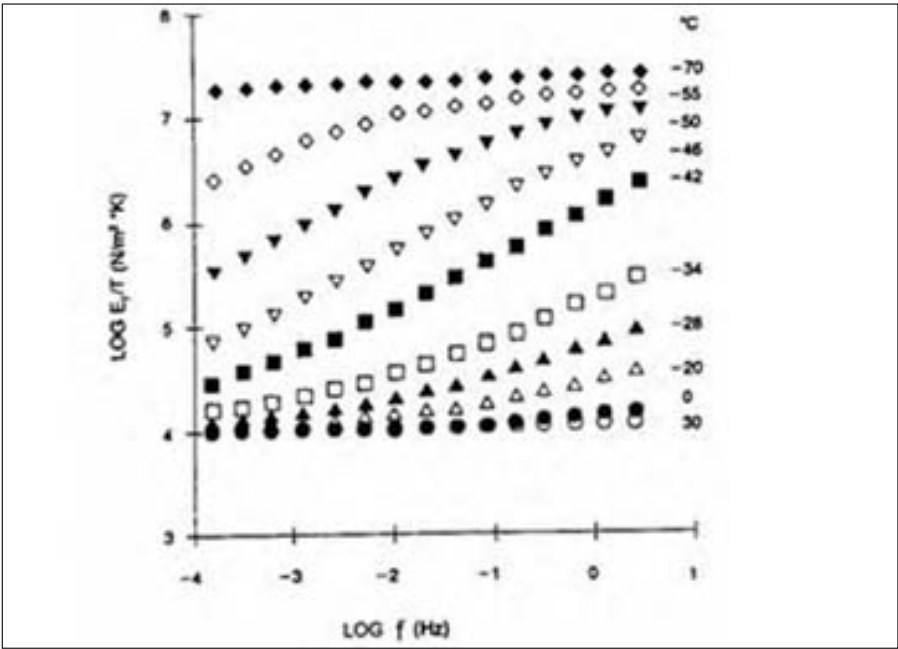
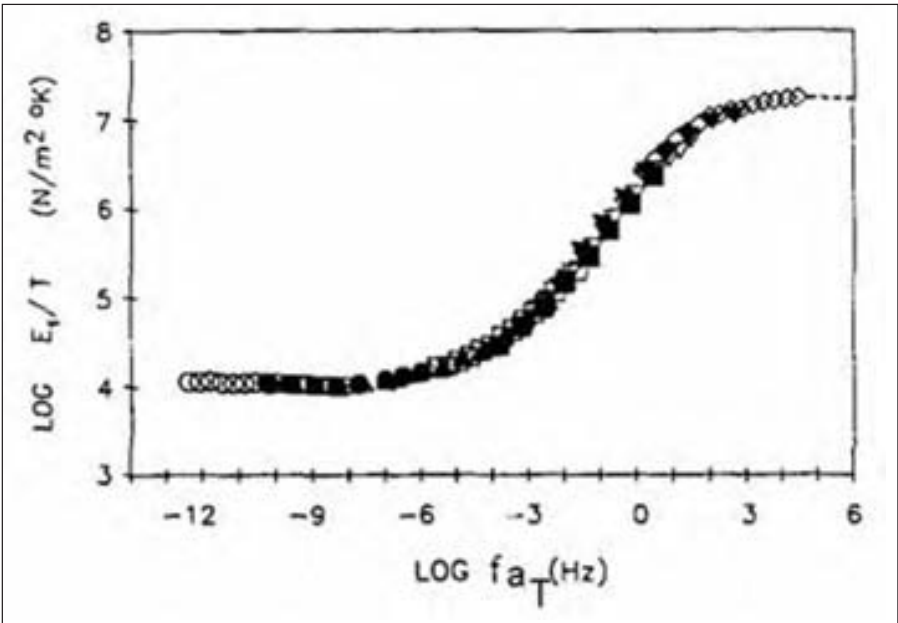


Figure 2.15b: Modulus E vs reduced frequency $f a_T$ at -42°C



The modulus of filled compounds is also decreased by raising the temperature, because the rubber-particle bonds become weaker. This effect is not directly associated with changes in molecular mobility and thus it cannot be represented by an equivalent change in frequency. Hence, equation 1.14 does not apply to the modulus of filled compounds without a correction for additional effects of temperature.

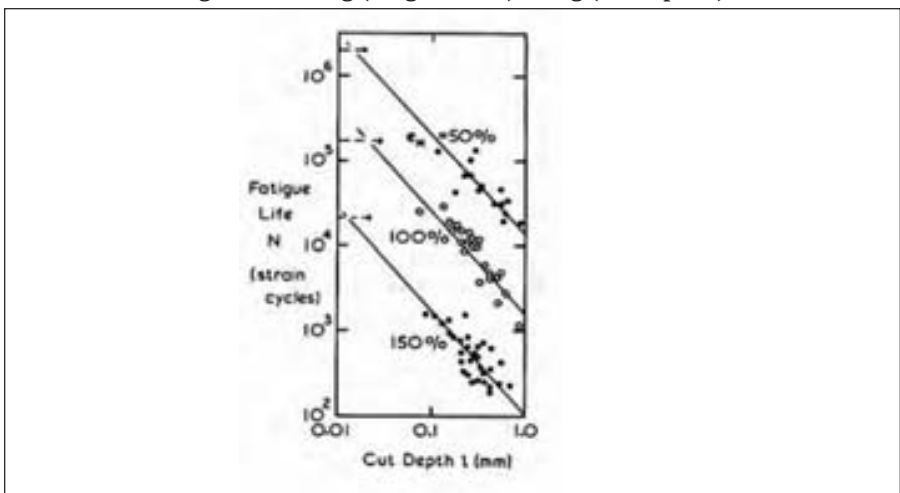
2. Strength of rubber compounds

2.1 Natural flaws and defects

Fracture mechanics has become the standard method of treating rupture of “brittle” materials, i.e. materials, like rubber, that break without undergoing widespread plastic deformation. In this concept, rupture is the result of growth of an existing flaw or defect. All materials contain such stress-raisers - rubber is no exception – and the size of naturally occurring defects can be estimated in various ways. For example the fatigue life, represented by the number N of times a tensile strain of fixed amount can be imposed on a tensile strip before it ruptures, is a strong function of the depth of a sharp cut placed in one edge of the specimen (see figure 2.16). The life N is shorter when the initial cut is made deeper. By extrapolating back to the fatigue life of a sample with no deliberately-introduced edge cut, a value can be assigned to the effective depth of cut that corresponds to the natural flaw or defect from which failure originated. The value obtained in this way is about 50 μm . Similar values are deduced from measurements of fatigue life at higher tensile strains, when all of the fatigue lives for cut specimens are reduced, or at lower tensile strains, when all of them are increased. And similar values are deduced from the dependence of tensile strength on the depth of an edge cut, and from studies of the quite low critical stresses needed for growth of an edge cut from chemical attack by ozone. In all of these cases, and for all of the elastomer compounds studied, fracture of an “uncut” specimen can be accounted for by assuming that the compound actually contains inherent flaws or defects equivalent to a sharp edge cut, about 50 μm long.

But so far, the presence of real defects of this size has not been established and their origin is still unknown. They may actually be smaller and sharper stress raisers than

Figure 2.16: Log (fatigue life N) vs log (cut depth c)



artificial cuts, and thus difficult to observe. Because the effective size deduced for all of the rubber compounds studied to date, both filled and unfilled, is similar, they might be the result of a common feature of rubber processing, for example a natural heterogeneity of crosslinking, or they may be created in the course of stressing rubber up to the point of rupture by a precursor mode of fracture. Local cavitation under tensile stress is one possibility.

Further studies are highly desirable because initiation of fracture is an important aspect of fracture mechanics. At present, we can account successfully for the strength of rubber under a variety of conditions on the assumption that inherent flaws are present, equivalent to sharp cuts about 50 μm deep.

2.2 Fracture energy and breaking stress

Fracture mechanics assumes that a characteristic amount of energy is required for crack growth per unit area torn through, analogous to surface energy and denoted fracture energy or tear strength, G_c (J/m^2). It is commonly measured for rubberlike materials by a simple tear test, as shown in figure 2.17. When the tear advances by a distance dc , the tear forces P supply energy of $2P \cdot dc$ and if this energy is consumed entirely in fracture, then the energy required is $G_c w \cdot dc$, where w is the width of the tear path (in this case, roughly the thickness of the sheet). Thus:

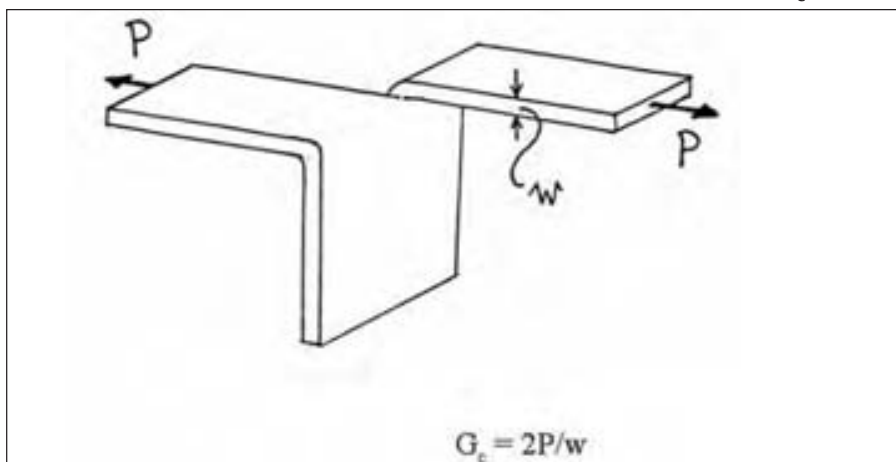
$$G_c = 2P/w \quad (2.1)$$

Similar considerations were applied by Griffith to tensile rupture of glass rods containing a small edge crack of length c [4]. Here the crack grows at the expense of strain energy W stored in the stretched sheet. When W is sufficiently high that the reduction $-dW$ caused by growth of the crack by a small amount dc is sufficient to meet the requirements for fracture, $G_c w \cdot dc$, then fracture ensues. The fracture criterion is:

$$G_c = - (1/w)(dW/dc) \quad (2.2)$$

where the derivative is taken at constant length of the sample to avoid including

Figure 2.17: Relation between tear force P and fracture energy G_c



further work input by the applied force. For a sheet of a linearly-elastic material (figure 2.18) the breaking stress σ_b and strain e_b are obtained in this way as:

$$\sigma_b = 1.26 (EG_c/\pi c)^{1/2} \quad (2.3)$$

and

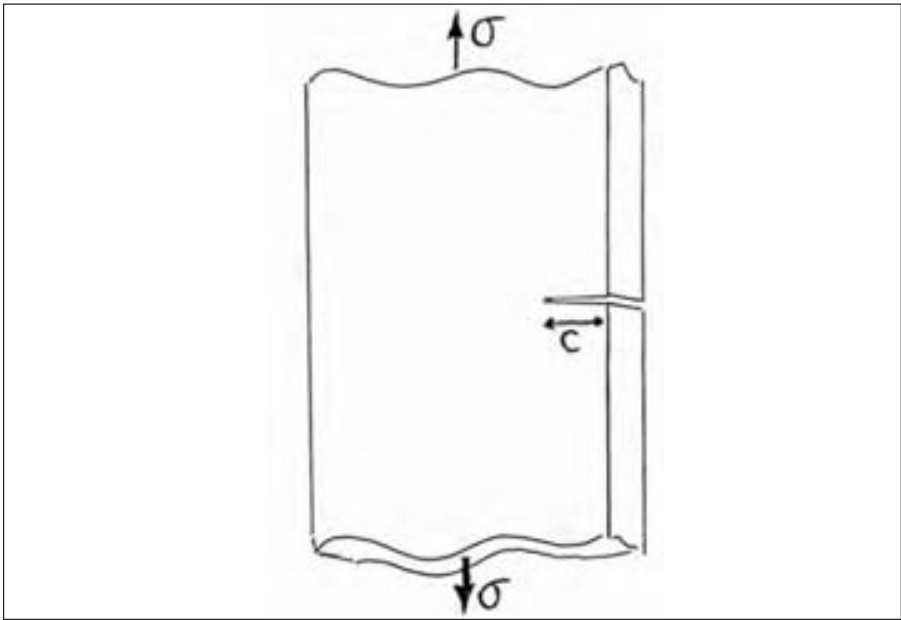
$$e_b = 1.26 (G_c/E\pi c)^{1/2} \quad (2.4)$$

where E is the tensile modulus of elasticity.

Note that a stiffer material with the same tear strength G_c will be stronger than a softer material. Thus fracture mechanics predicts that the strength of compounds will be rated differently under different test conditions. This is further illustrated by considering growth of a long crack in a sheet under constrained tension, figure 2.19. In this configuration, the sheet is unable to contract sideways because the long horizontal clamps prevent it. The initial crack is made quite long in comparison with the specimen height h to avoid end effects.

As before, energy required for rupture is supplied by strain energy in the stretched portion of the sheet. For a linearly-elastic material, the tensile stress at which the crack

Figure 2.18: Tensile strength test



will propagate is obtained as:

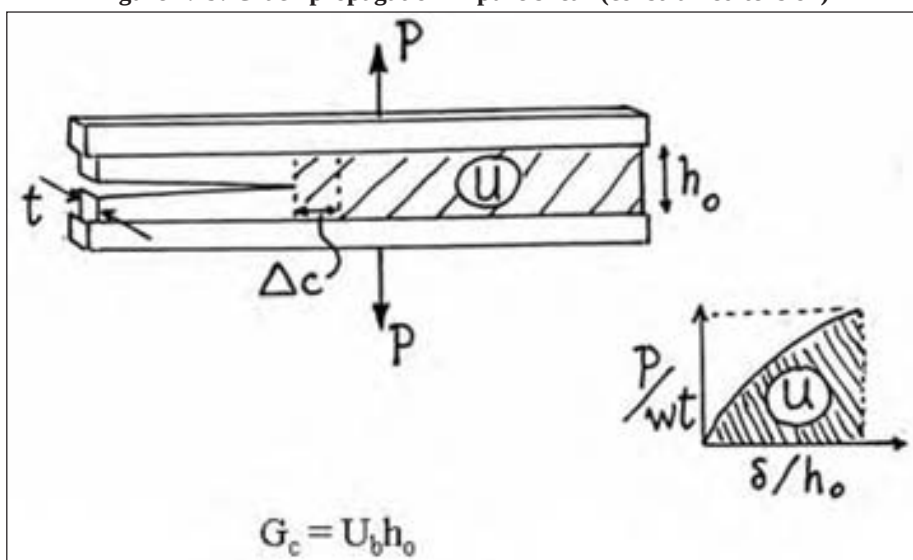
$$\sigma_b = 1.63 (EG_c/h_0)^{1/2} \quad (2.5)$$

where h_0 is the unstrained height of the strip, a measure of the amount of material from which strain energy is released as the crack passes. Note that the breaking stress now depends on the sample height h_0 and not on the crack length c .

On comparing Equations 2.3 and 2.5, the breaking stress is seen to be much lower in a

constrained tensile test than in a regular tensile test because the initial height h_0 of the specimen, usually several mm, is much greater than the depth c of an accidental edge flaw in a simple tensile specimen, typically only about $50\text{ }\mu\text{m}$. Thus the applied stress at which rupture occurs is not a valid criterion for fracture. Moreover, the breaking stress at the crack tip, which would presumably be a valid fracture criterion, is virtually impossible to measure. On the other hand the fracture energy for a rubber compound can be measured in several ways, including those sketched in Figures 2.17, 2.18 and 2.19, and proves to be a simple, consistent and reproducible fracture criterion. It has therefore been widely adopted. We now turn to consider theoretical and measured values of G_c for typical rubber compounds.

Figure 2.19: Crack propagation in pure shear (constrained tension)



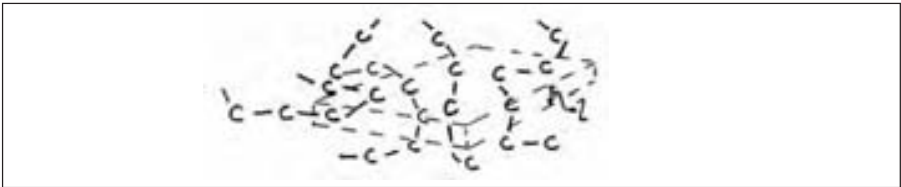
2.2.1 Theoretical values of fracture energy

By adding the carbon-carbon bond dissociation energies for all of the bonds that cross unit area, figure 2.20, Berry [5] deduced that the fracture energy for a polymer with C-C backbone bonds would be about 1 J/m^2 , about 50 times larger than the energy needed to separate Van der Waals bonds in a simple liquid. However, this is far below the observed tear strengths for rubber compounds, that range from about 300 J/m^2 to very high values, of the order of $100,000\text{ J/m}^2$, depending on crack speed and temperature. When the high extensibility of rubber molecules is taken into account, Berry's theoretical value is raised by a factor of approximately $n^{1/2}$, where n is the number of segments in a molecular strand between crosslinks [6]. Using a representative value for n of 100, this increases the theoretical value for G to about 10 J/m^2 , still far below experimentally-measured strengths. Thus, a fundamental question in the mechanics of rubber fracture is: Why is the observed strength so much higher than expected? The answer is found by examining the effect of speed of crack propagation and temperature.

2.2.2 Dependence of tensile strength on rate of extension and temperature

Measurements of the tensile breaking stress σ_b and breaking extension e_b for a non-crystallizing elastomer SBR were found to depend on rate of extension and temperature in accordance with the WLF rate-temperature equivalence, equation 1.12 [7]. By applying shift factors calculated from Equation 1.15, data obtained at different temperatures could be superposed to yield “master” curves for σ_b and e_b as functions of rate of stretching, figure 2.21. The success of this superposition shows how important in the strength and extensibility of elastomers are the internal dissipative processes that arise from segmental motion.

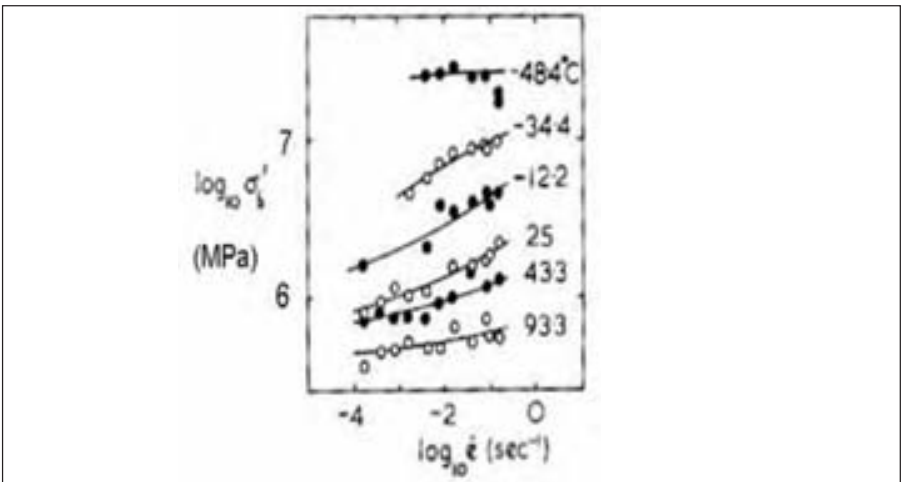
Figure 2.20: Sketch of molecules crossing a fracture plane



2.2.3 Dependence of fracture energy on crack speed and temperature

The same rate-temperature equivalence has been shown to hold for the fracture energy G_c . Measurements of energy G_c for a simple unfilled rubber compound are plotted in figure 2.22 as a function of tear rate at various temperatures. The values are seen to change by a large factor, about three orders of magnitude, as the test conditions change from low tear speeds at high temperatures to high tear speeds at low temperatures. Plotted using a logarithmic scale for tear speed, they resemble viscoelastic functions, superposable by horizontal shifts in the same way that G' , G'' and $\tan \delta$ are superposable, figure 2.12.

Figure 2.21a: Tensile strength vs rate of extension



Indeed, using WLF shift factors calculated from Equation 1.13, as shown schematically in figure 2.23, the results from figure 2.22 are accurately superposable; see figure 2.24. This proves that the high tear strength exhibited at low temperatures is associated with

Figure 2.21b: Tensile strength vs reduced rate of extension at -10°C

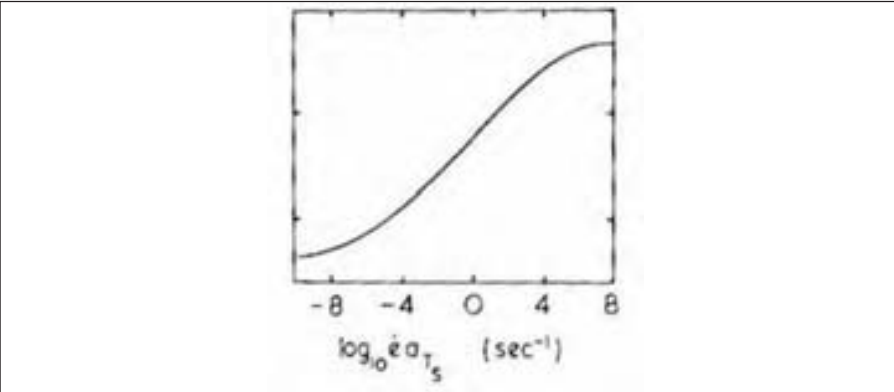
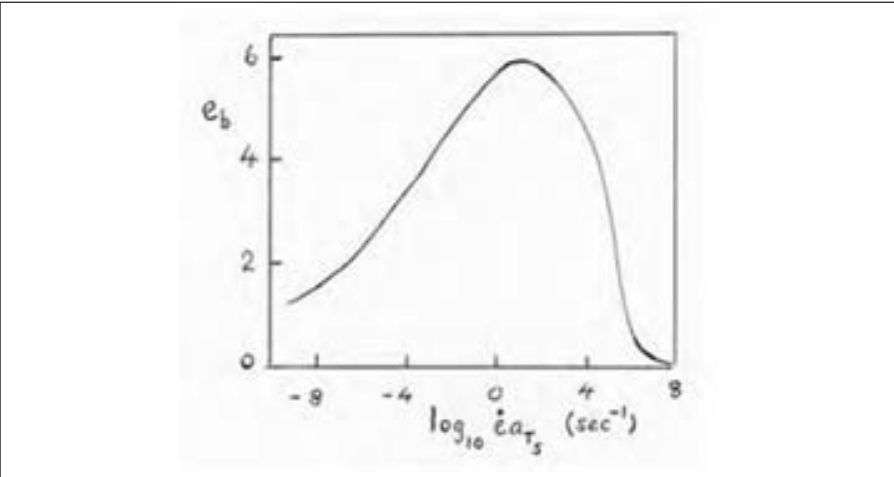


Figure 2.21c: Elongation at break vs reduced rate of extension at -10°C



reduced molecular mobility, and not with a change in the intrinsic strength of the rubber molecule.

It was pointed out earlier that the molecular mobility of butyl rubber is anomalous - it increases more slowly as the temperature is raised above T_g than for other elastomers. We would therefore expect the tear strength of butyl rubber compounds to decrease more slowly as the temperature is raised, and this turns out to be the case [8].

2.2.4 Threshold strength

At low speeds and high temperatures the tear strength approaches a lower limit G_0 , of about 50 J/m^2 , figure 2.22. This limiting value, termed threshold strength, is of the same order of magnitude as the theoretical value for the intrinsic strength of an elastomer network in the absence of viscous energy dissipation, see section 2.2.1. Moreover, values of G_0 are found to increase with the length M_c of the molecular strands in the network, roughly in proportion to $M_c^{1/2}$, in good agreement with the Lake-Thomas theory of thresh-

old strength [6]. Note that the threshold strength is *inversely* related to the degree of crosslinking - it decreases as the degree of crosslinking is increased. [This raises an important practical issue. Because the threshold tear strength is reduced by crosslinking whereas the elastic modulus is increased (equation 1.1), the appropriate level of crosslinking for a particular rubber compound will depend on the anticipated service conditions.]

The tear strength under non-equilibrium conditions appears to be a product of two terms, the inherent strength G_0 of the molecular network and a factor reflecting dissipative processes. Indeed, when the relative value G_c/G_0 is plotted against tear speed at a temperature of T_g , obtained by applying shift factors calculated from equation 1.13 to experimental measurements of G_c at various temperatures, the same curve is obtained for three elastomers having quite different chemical structures and different T_g 's, figure 2.24 [9]. Results are shown for polybutadiene (BR) with a T_g of -96°C , an ethylene-propylene

Figure 2.22: Fracture energy (tear strength) vs. rate and temperature for HS-SBR vulcanizate ($T_g = -30^\circ\text{C}$)

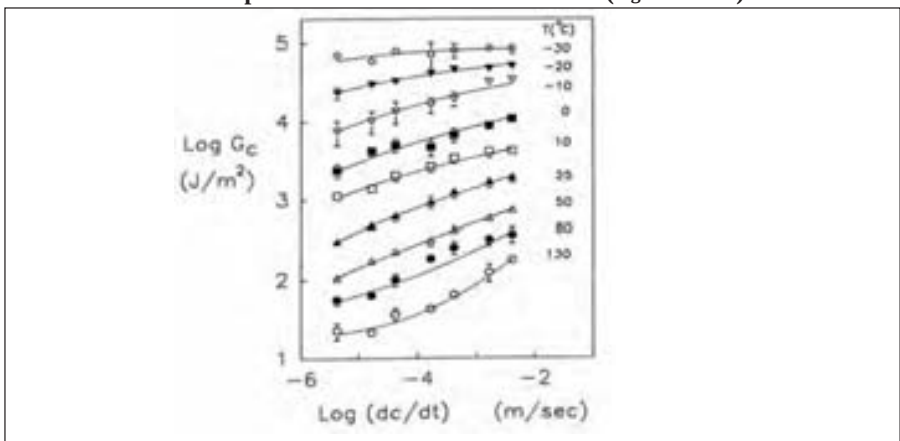
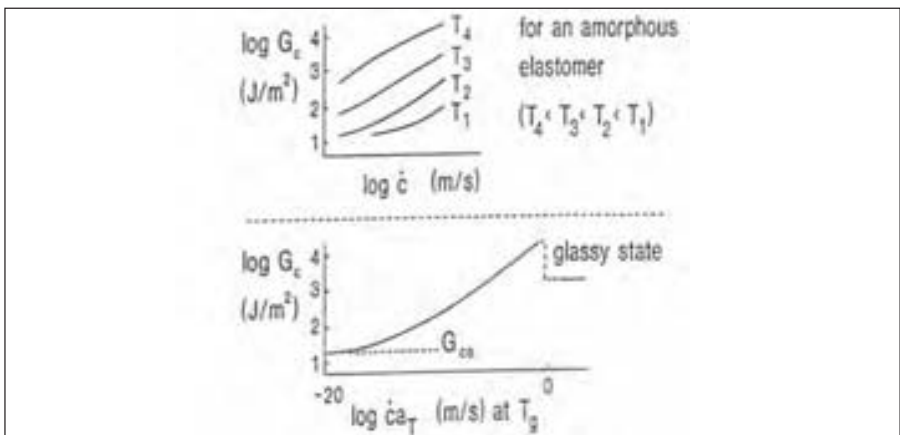


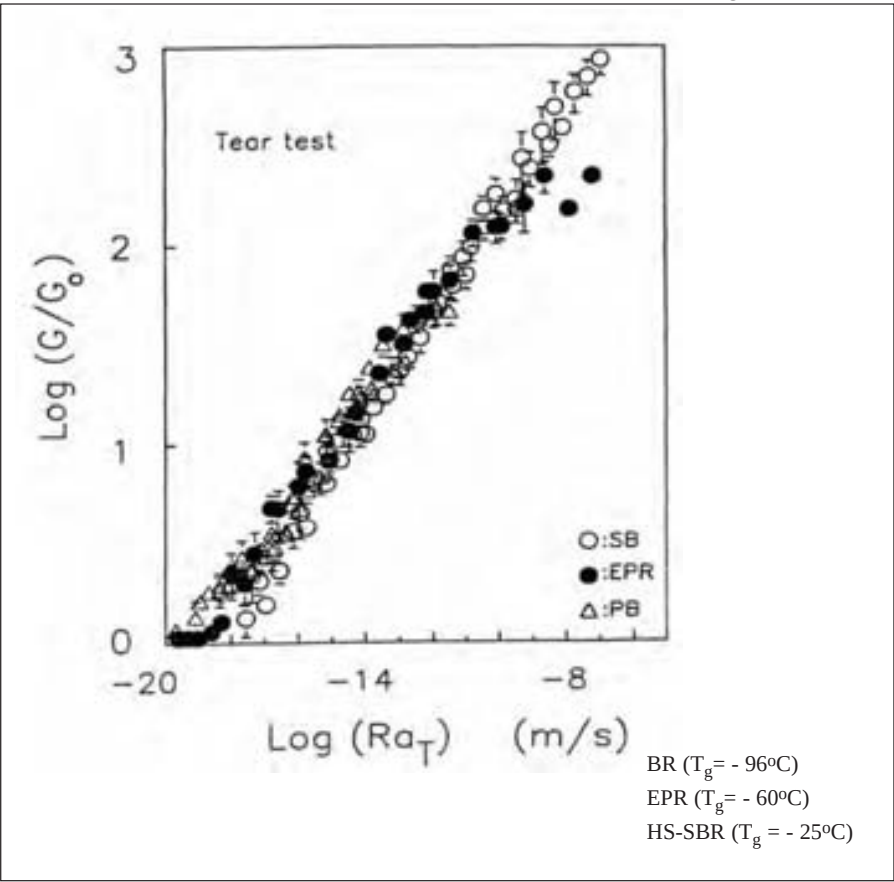
Figure 2.23: Use of the WLF principle to construct a “master curve” of tear strength vs. tear rate (schematic)



copolymer (EPR), with a T_g of -60°C , and a high-styrene butadiene-styrene copolymer (HS-SBR) with a T_g of -25°C . They are indistinguishable in this figure. Thus, when the molecular mobility is the same, the tear strength is the same, regardless of the chemical structure. Moreover, using the WLF rate-temperature equivalence, the tear strength of a simple rubber compound can be predicted at any tear speed and at any temperature from two basic parameters, the glass temperature T_g and the degree of crosslinking, represented (inversely) by the length of network strands. This is a remarkable achievement of the fracture mechanics of rubbery materials. However, the form of the “universal” curve of strength vs. reduced rate of tearing has not yet been satisfactorily accounted for. It resembles the dependence of elastic modulus G' on reduced frequency of deformation [10] but the linear dimension required to bring the two scales, rate and frequency, into accord is unreasonably small, only about 1 nm.

We now turn to methods of improving (reinforcing) the basic strength of a simple crosslinked rubber for use in practical applications.

Figure 2.24: Tear strength vs equivalent tear rate at T_g



2.3 Reinforcement

Internal dissipative processes obviously make a large contribution to the strength of rubber. This raises two important questions:

1. Is it possible to create a strong material with low dissipative properties, because at first sight these properties appear to be incompatible?
2. What other reinforcement mechanisms can be employed?

The apparent dilemma posed in the first question can be circumvented by recognizing that high strength is only required in highly stressed regions, near a stress-raiser. If a dissipative mechanism is activated only at high stresses, then both requirements can be met: low dissipation under “normal” low-stress conditions that exist in the bulk of the material, and high dissipation at high-stress sites, where needed.

One mechanism of this type is strain-induced crystallization. Certain elastomers, notably natural rubber, have a regular molecular structure capable of being closely packed, and they crystallize rapidly when stretched by more than about 300%. As a result, they become transformed into tough partially-crystalline fibrous solids that break only when crystallites in the tear path are pulled apart plastically, with considerable energy dissipation. At lower strains, before crystallization occurs, they are resilient, highly-elastic solids with low energy losses.

Employing the same principle, we can postulate a desirable feature in the reinforcement of elastomers by incorporating particulate fillers, for example carbon black. We require the rubber molecules to be bonded to filler particles, with bonds that do not fail at low stresses and cause unwanted energy dissipation under normal operating conditions. But the bonds must not be as strong as the elastomer itself, because then they would not fail at all. They should be somewhat less strong, and break before the elastomer molecules do, thus creating a dissipation mechanism at high-stress sites, where it is needed, without rupture of the molecular network.

Although this would be a highly desirable mode of reinforcing rubber by fillers, at present the bonds between rubber and particles appear to have a wide range of strengths, so that some energy dissipation occurs even at low stresses, considerably more than in the corresponding unfilled compound.

Rubber is usually crosslinked by sulfur, often by polysulfidic -S-S-S- crosslinks. The resulting materials have greater strength than those with carbon-carbon crosslinks. We note that sulfur crosslinks are weaker than C-C crosslinks and main-chain bonds, and postulate that they serve a sacrificial function – by breaking first, they reduce the tension in the elastomer molecule and permit it to survive. This function can also be interpreted as providing a dissipation mechanism at points of high stress.

Other common reinforcing mechanisms that can be interpreted in the same way are :

- Plastic yielding of inclusions
- Friction at internal interfaces
- Formation of internal cavities
- Detachment from fibers

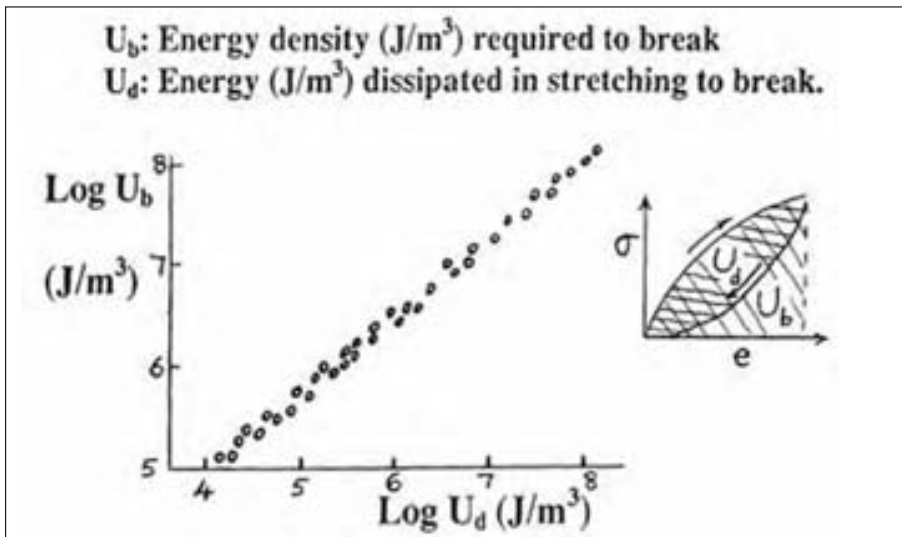
The conclusion that strength is directly related to energy dissipation was recognized quite early [11]. A comparison was made of the work-to-break a rubber sample in tension U_b with the energy lost in stretching a similar sample nearly to the breaking point U_d and then relaxing it. The two quantities are in principle independent, but in practice an excellent correlation was found to hold between them for a large number of rubber

compounds including a wide range of elastomers, degree of crosslinking, types and amounts of particulate fillers, test speeds, temperatures, etc. The correlation is shown in figure 2.25. The linear relation shown is:

$$U_b = 420 (U_d)^{2/3} \quad (2.6)$$

both quantities being measured in J/m^3 . As the amount of energy dissipated U_d cannot possibly exceed the work-to-break U_b , Equation 2.6 suggests that the maximum possible tensile breaking energy of a rubbery material is about 80 MJ/m^3 . However, Equation 2.6 is wholly empirical and, even though it applies successfully over an enormous range of tensile strengths, any extrapolation of it must be treated with caution.

Figure 2.25: Correlation between breaking energy U_b and dissipated energy U_d



2.4 Blunting of the tear tip

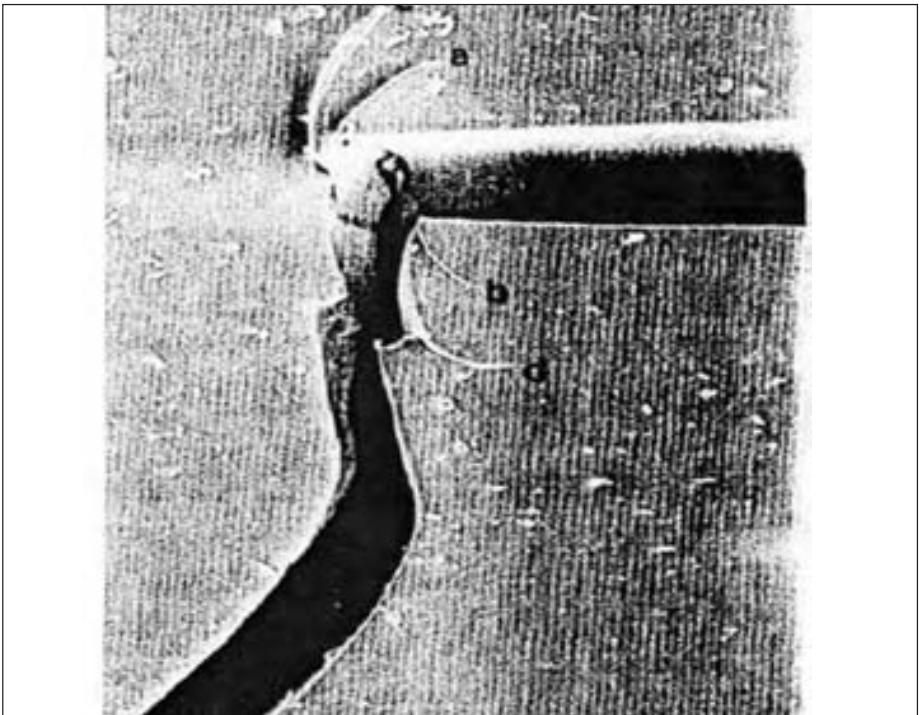
A singular feature of rubber compounds reinforced with particulate fillers is that a sharp cut or tear will often fail to grow across the direction of tension. Instead it turns sideways and runs more-or-less parallel to the tension for a short distance, and then stops. To propagate the tear further, another crack tip must form and grow, but again the new tear turns sideways and stops.

Examination of the tip of a precursor edge cut in a tensile test piece reveals that as many as five or six separate tear initiation steps took place at the cut tip before one finally succeeded in running in the “normal” direction, across the specimen, figure 2.26. This phenomenon is clearly a powerful strengthening mechanism, because the sharp initial cut is severely blunted and energy is wasted in making several ineffective lateral tears.

Finite element analysis reveals that a substantial fraction, about 50%, of the energy available for “normal” tear propagation can be employed to drive a tear sideways, especially if the material is highly stretched before the initial edge cut grows at all [12]. Thus if the stretched material is substantially weaker, by more than 50%, for tearing in the

direction of stretching, then deviation of a growing tear into that direction would be inevitable and the material would be effectively self-reinforcing. Note that this mode of reinforcement is not based on enhancing the strength of the material; it is attributed to developing *low strength* in the strain direction, leading to ineffective tearing and blunting of the tear tip. At least some of the reinforcing ability of particulate fillers appears to arise from this mechanism.

Figure 2.26: Multiple tears at the tip of a cut in one edge of a tensile test-piece: “Knotty” tearing



2.5 Crack growth and mechanical fatigue

We have discussed how to measure the tear strength or fracture energy G_c . If the applied force is too small to cause immediate failure, then the energy available for growth of a tear is termed the “Strain Energy Release Rate”, denoted G (J/m^2). In linear elastic fracture mechanics, the corresponding quantity is the stress intensity factor K , with a critical value denoted K_c , where K is related to G as follows:

$$K = (EG)^{1/2} \quad (2.7)$$

When energy G ($< G_c$) is made available for fracture, even though large-scale tearing does not occur, a tear tip is found to grow by a small distance dc each time the stress is applied. The growth step dc depends strongly on G , following a simple empirical relation:

$$dc/dN = B[(G/G_0) - 1]^\alpha \tag{2.8}$$

where B and α are crack growth constants. Although an equation of this form is widely used to predict growth of a crack under fatigue conditions, that is, under many applications of sub-critical stresses, the actual behavior is more complex, see figures 2.27 and 2.28, and equation 2.8 is only a useful guide over a limited range of values of G , from somewhat higher than the threshold strength G_0 to about one-tenth of the catastrophic tear strength G_c .

When the stress is relaxed to zero between each application, the value of the crack growth constant B is found in all cases to be a molecular distance, about 0.05 nm. Thus, under threshold stresses a crack advances by an extremely small step, less than the size of a molecular strand, at each load application. On the other hand, the exponent α is quite different for compounds based on different elastomers. For example, α is about 2 for natural rubber compounds, 3 – 4 for butadiene-styrene (SBR) compounds, and 4 – 6 for polybutadiene compounds, and appears to depend inversely on the dissipative properties of materials. For highly-dissipative materials, α appears to approach a lower limit of 2, whereas for perfectly elastic, non-dissipative materials α appears to become infinitely large. Between these two limits, values of α for partially-dissipative materials can be represented empirically by the relation:

Figure 2.27: Tearing under repeated stressing (fatigue cracking)

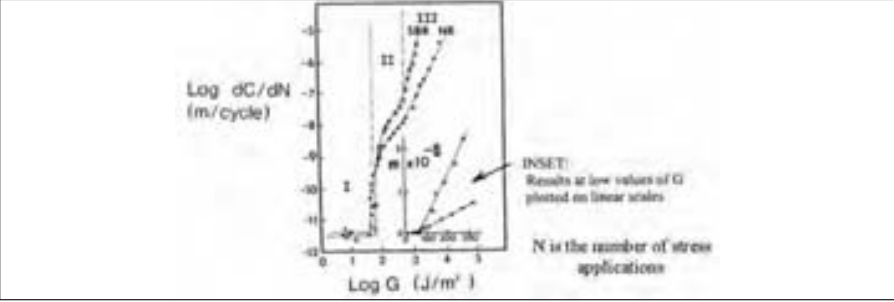
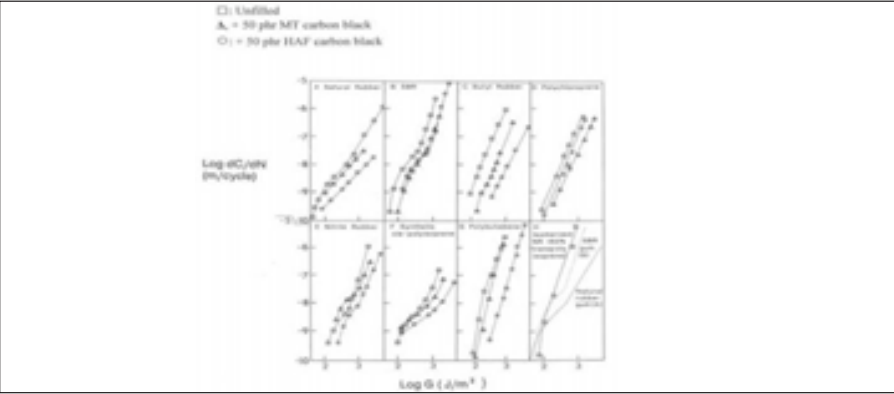


Figure 2.28: Crack growth rates for several rubber compounds



$$\alpha = 2/(1 - R) \quad (2.9)$$

where R is the resilience and $1 - R$ is the fraction of input strain energy that is dissipated. Filled rubber compounds are more dissipative than their unfilled counterparts and the value of α is found to be correspondingly smaller. For typical filled natural rubber compounds α is about 1.5 instead of 2, and for typical filled SBR compounds α lies between 2 and 3 instead of between 3 and 4.

Why are values of α for natural rubber compounds, which are highly-resilient, in fact more appropriate for highly-dissipative materials? It is thought that strain-induced crystallization of natural rubber takes place at high stresses, especially at the tips of stress-raising flaws, figure 2.29, and leads to marked dissipation of energy as a crack advances.

2.5.1 Fatigue life

When a tensile strain is applied to a sample containing an edge cut of length c , the energy available for crack growth is given by:

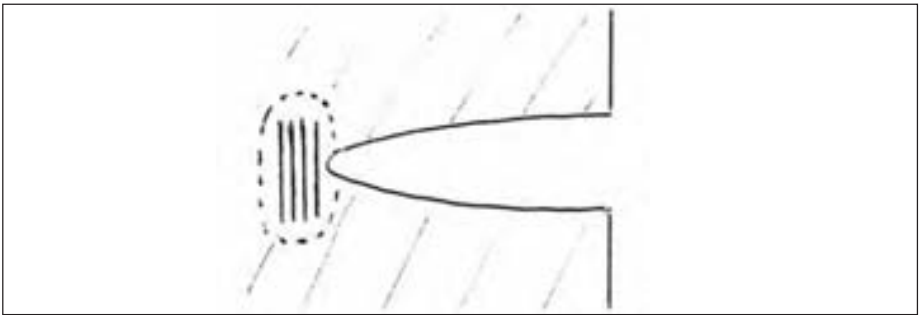
$$G = 0.62\pi E e^2 c \quad (2.10)$$

from equation 2.2, assuming for simplicity that the material is linearly-elastic. Using Equation 2.9, the growth of a crack each time the strain is applied is:

$$dc = B(G/G_0)^\alpha dN = B (0.62\pi E e^2 c / G_0)^\alpha dN \quad (2.11)$$

where N denotes the number of strain applications. By integrating from $c = c_0$ to an infi-

Figure 2.29: Strain-induced crystallization at a crack tip



nitely large value of c , the fatigue life N_f is obtained as:

$$N_f = (1/B) (G_0 / 0.62\pi E e^2)^\alpha [(\alpha - 1)/c_0^{(\alpha - 1)}] \quad (2.12)$$

Although approximate, equation 2.12 gives useful pointers to the effect of various parameters on the tensile fatigue life of rubber specimens. It shows, for example, that the fatigue life N_f decreases rapidly as the imposed strain e is increased. Taking α as 2 for natural rubber compounds, when the strain is increased by a factor of 2, the fatigue life is predicted to decrease by a factor of 16. For an SBR compound, the corresponding change

in N_f is predicted to be much more severe, by a factor of 256. Thus, the fatigue life of SBR and similar non-crystallizing elastomers falls sharply as the imposed strain is increased.

The dependence of fatigue life on the depth c of an initial defect or flaw is also large, and different for different materials. For natural rubber compounds the fatigue life is seen to be approximately proportional to $1/c$, and thus is decreased by a factor of 2 if the depth of an accidental flaw is increased by a factor of 2. On the other hand, under the same conditions the fatigue life of an SBR compound is decreased by a factor of 8. Thus, fatigue failure of SBR and similar compounds is extremely sensitive to the severity of accidental nicks or flaws.

When natural rubber compounds are subjected to repeatedly-applied strains, starting from zero strain, some tearing takes place at the crack tip while strain-induced crystallites are simultaneously being formed there. The crack growth steps are generally smaller than for non-crystallizing elastomers, as discussed above. But natural rubber compounds show a remarkable resistance to fatigue cracking if the imposed strain is not reduced to zero in each strain cycle, figure 2.30. Apparently, the crystallites that develop at the crack tip, even at modest overall strains, do not melt unless the strain is reduced to zero or close to zero, and thus they persist and prevent further crack growth when the strain is increased again. No comparable effect is expected for non-crystallizing elastomers such as SBR.

Some classic observations of the fatigue life of bonded cylinders of natural rubber subjected to repeated tensile or compressive strains are shown in figure 2.31 [13]. The fatigue life N_f is seen to be a minimum when the applied strains were relaxed to zero during each strain cycle, both for tensile and compressive strains. On the other hand, if the minimum level of strain in each cycle was not reduced to zero, then the fatigue life was greatly increased, by a factor of up to 100 times. Indeed, the mechanism of failure may change altogether under non-relaxing conditions, from mechanical rupture of the elastomer molecules, now protected by crystallization, to molecular scission by reaction with atmospheric ozone.

Figure 2.30: Effect of non-relaxing strain on tensile fatigue life N of unfilled NR

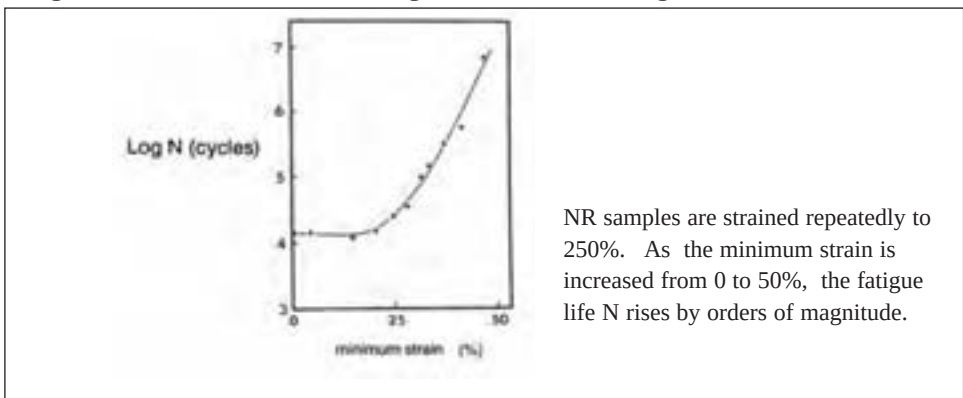
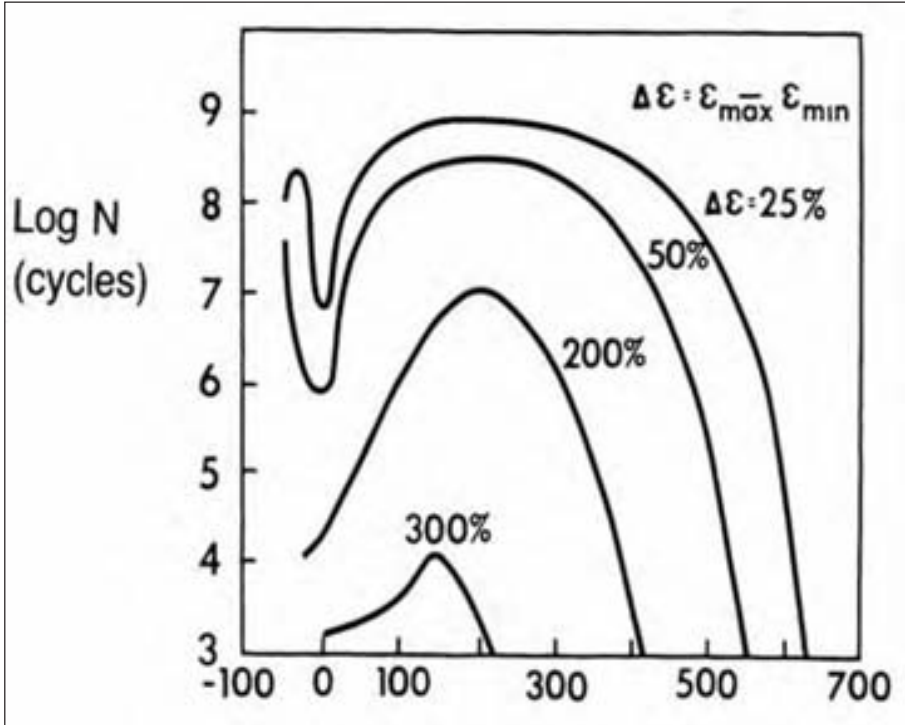


Figure 2.31: Fatigue life N for cylinders of NR cycled between a minimum strain $\epsilon_{\min}$ and a maximum strain $\epsilon_{\min} + \Delta\epsilon$



2.6 Failure of an adhesive bond

Fracture of the bond between rubber and another material can be treated by fracture mechanics in the same way as rupture of rubber itself. We denote the energy required to separate unit area of the interfacial bond as G_a to distinguish it from the fracture energy G of rubber itself and note that if G_a is lower than G , then the interface would be expected to separate cleanly, whereas if G_a is higher than G , then the rubber close to the interface will tear apart, leaving an attached rubber layer behind.

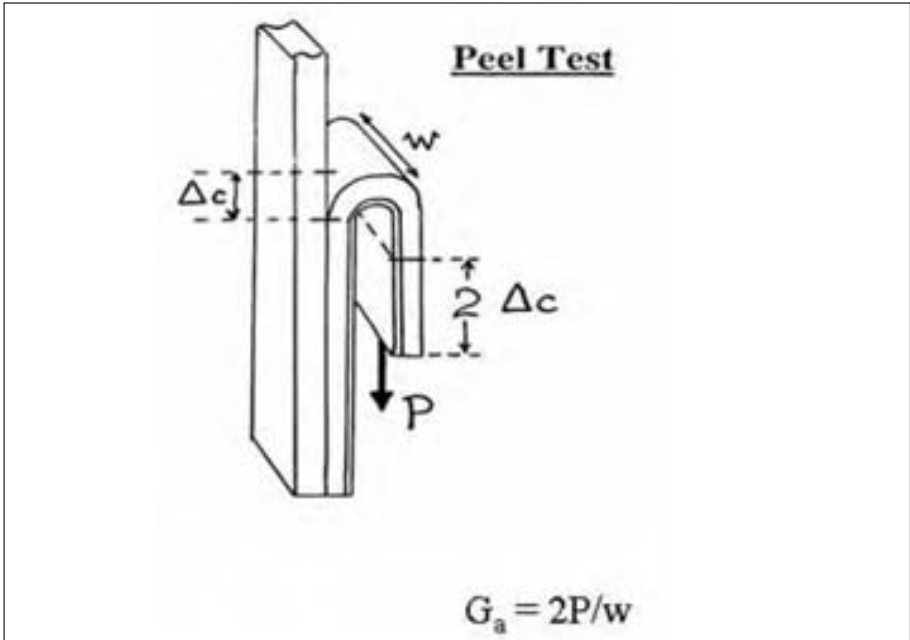
A common method of evaluating the strength of adhesion is by a peel test, figure 2.32, analogous to simple tearing, figure 2.17. G_a is given by

$$G_a = 2P/w \quad (2.13)$$

where P is the peel force and w is the width of the bonded layer.

Unfortunately, even when G_a is lower than G , failure tends to occur within the rubber, instead of at the interface, if the difference in fracture energy is not large enough. From mechanical considerations, more energy is available for fracture at a plane somewhat removed from the interface. Thus a bond may appear to be stronger than it really is. A more stringent test is needed, in which failure is induced to occur at the interface. A test of this kind, especially suitable for evaluating rubber-to-cord adhesion, is described later.

Figure 2.32: 180° peel test



In tire building, layers of different rubber compounds and rubber-cord laminates are joined to construct the raw tire. These layers must adhere together during handling of the raw tire and inserting it into the tire mold for final shaping and vulcanization. Thus, good adhesion of unvulcanized rubber is an important requirement in tire manufacture. It is commonly assessed using peel tests. In this case, energy is largely dissipated in viscous processes as the unvulcanized rubber layer is pulled away. Thus, the apparent strength of adhesion reflects viscous dissipation of energy in tensile flow. Note that for this to be the major factor, the rubber must flow without breaking under a tensile flow stress that is smaller than the strength of the interfacial bond itself. This principle of optimizing energy dissipation under the constraint of a limiting stress is employed in the design of pressure-sensitive adhesives.

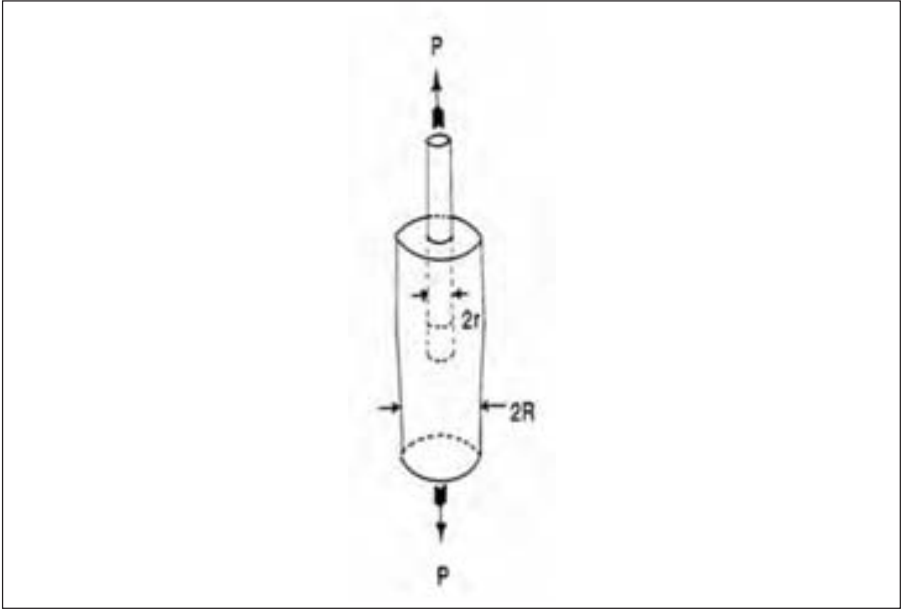
For assessing the strength of adhesion of vulcanized rubber to cords, another test arrangement, shown in figure 2.33, has been proposed. Using linear elastic fracture mechanics, an estimate of the pull-out force P is obtained as:

$$(P/A)^2 = 4\pi(r/A)EG_a \quad (2.14)$$

for an inextensible rod or cord embedded partway in a rubber block, where r is the radius of the rod or cord, A is the cross-sectional area of the rubber block in which it is embedded, and E is the modulus of elasticity of the rubber. Because the pull-out force increases with r , i.e., as the fracture path moves away from the interface, failure in this test arrangement is induced to occur at or near the interface.

Note that equation 2.14 resembles Griffith's result for a edge crack, Equation 2.3,

because energy is again made available for fracture by stretching the lower part of the block. (The upper part is rendered inextensible by the embedded rod.)



An interesting feature of this experimental arrangement is that the total force required to pull out simultaneously n cords embedded in the same block increases in proportion to $n^{1/2}$. The reason for this surprising result is that the energy required to pull out n cords is proportional to n , whereas the energy stored in a linearly-elastic device is proportional to P^2 , where P is the applied force. Experiments on wire cords embedded in rubber blocks have confirmed this result [14] which is clearly important in maximizing the strength of cord-rubber laminates.

3. Frictional sliding of rubber (see chapter 11 also)

3.1 Effect of normal load on frictional force

Conventionally, the resistance to frictional sliding of one surface on another is characterized by the Coulomb frictional coefficient μ , given by the ratio of frictional force F to normal force N :

$$\mu = F/N \quad (3.1)$$

But for soft rubber sliding on a smooth surface, the frictional force is found to be more or less constant, independent of the load N , or pressure P , as the applied load or pressure increases from small initial values, probably because complete contact is achieved between soft rubber and a smooth countersurface at quite small loads. Beyond this point, further increases in normal load cannot increase the degree of interaction between the two materials and so the frictional force no longer increases. Consequently the “coefficient” of friction decreases continuously as the pressure increases, as shown schematically in figure

2.34.

However, for harder rubber compounds sliding against a rough surface, the frictional force does increase, approximately in proportion to the applied load or pressure, and thus a “coefficient of friction” can be defined in this case that is largely independent of pressure. Apparently, contact is incomplete, figure 2.35, for harder rubber compounds such as those used in tire treads. An increase in pressure creates a larger true area of contact and hence a larger frictional force.

Figure 2.34: Dependence of friction coefficient on contact pressure

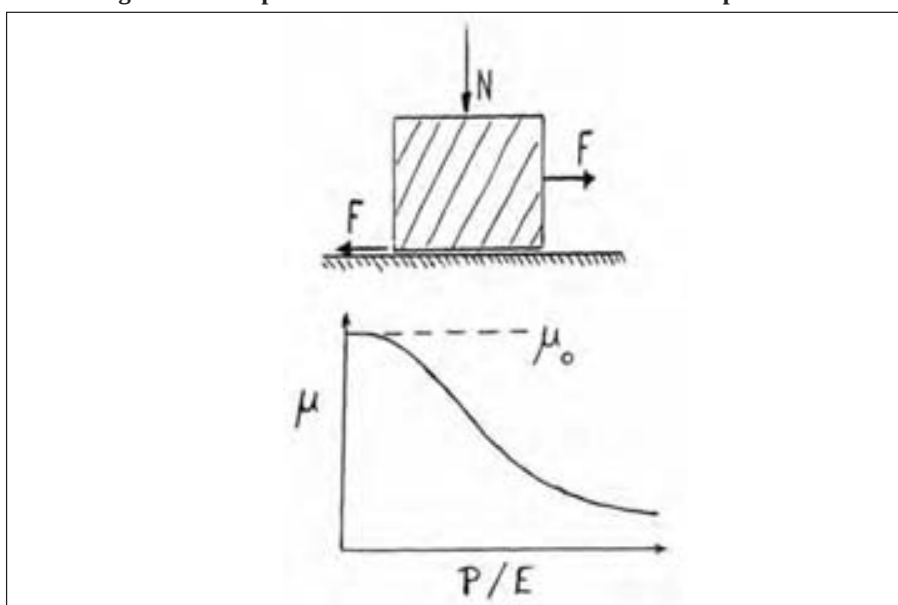
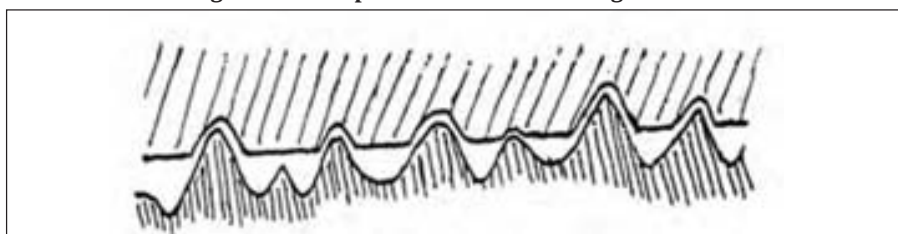


Figure 2.35: Imperfect contact on a rough surface



3.2 Rolling friction (see chapter 12)

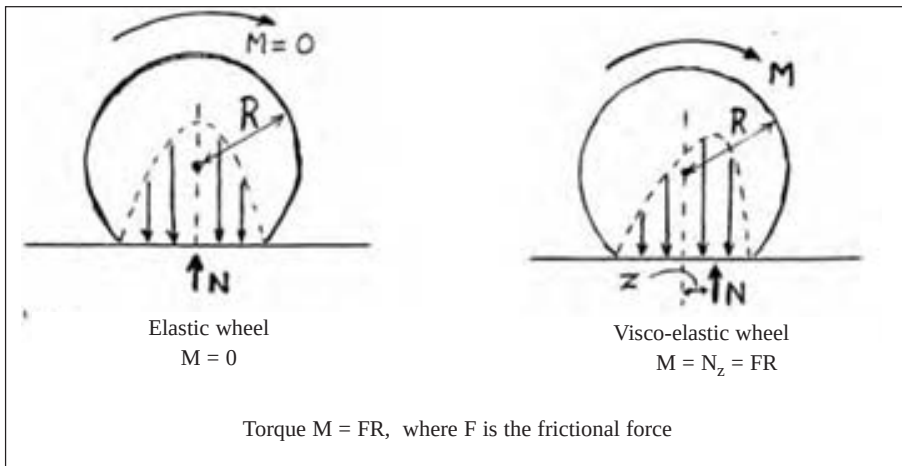
It is helpful to consider rolling friction first, because the physical origin of the frictional drag force is clearer in this case. Consider the pressure distribution set up in the contact zone when a rubber cylinder rolls on a rigid countersurface. For a dissipative material, the center of pressure will not be located at the center of the contact zone, but displaced toward the leading edge, because stresses set up on loading are higher than those set up

on unloading, figure 2.36. This is a universal feature of dissipative materials in general, and of viscoelastic materials in particular. Moreover, the displacement z of the center of pressure, and hence the torque $M (= z F)$ required to maintain the motion, will depend on speed and temperature in the same way as the loss factor, $\tan \delta$ [15]:

$$M = 0.33 (P_n / G^* R^2)^{1/3} \tan \delta \quad (3.2)$$

where $G^* [(G'^2 + G''^2)^{1/2}]$ is the complex dynamic shear modulus and R is the cylinder radius. (The term in parentheses is a measure of the length of the contact zone.) This simple theory successfully accounts for rolling friction in terms of energy dissipated as rubber is compressed and released in the contact patch. But $\tan \delta$ must be measured at the effective frequency of rolling (about 10 Hz at 30 mph) and at the service temperature because rolling friction depends on speed (frequency) and temperature in the same way that $\tan \delta$ depends on frequency and temperature.

Figure 2.36: Rolling friction

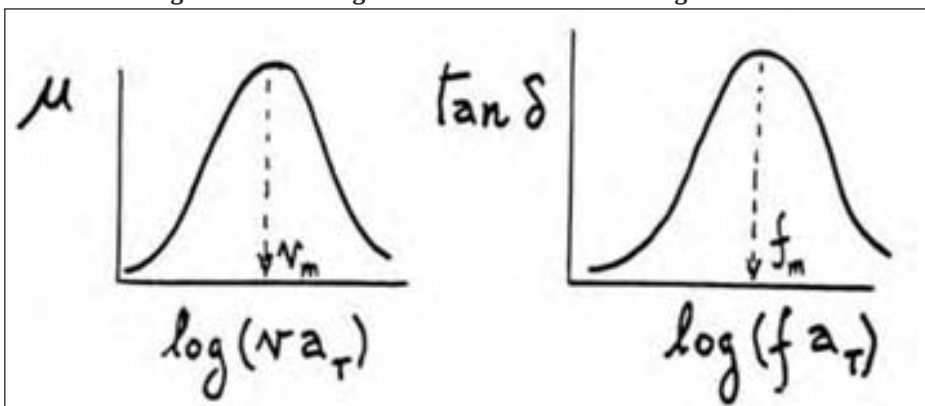


3.3 Sliding friction on a lubricated rough surface

Grosch [16] measured the friction coefficient for a nitrile rubber block sliding over a lubricated rough surface (an abrasive paper), for a wide range of sliding speeds and test temperatures. He noted that a master curve for frictional coefficient μ as a function of $\log$ (sliding speed, v) could be built up from measurements over a limited speed range at various temperatures, by applying shifts calculated from the WLF rate – temperature equivalence, Equation 1.13. The master curve obtained in this way bears a striking resemblance to the master curve for $\tan \delta$ vs. oscillation frequency f , figure 2.37. By comparing the two master curves at the same reduced temperature, i.e., relative to T_g , Grosch obtained a characteristic length d , given by v_m/f_m , where v_m and f_m denote the speed and frequency at which the frictional coefficient and $\tan \delta$, respectively, exhibited a maximum, measured at the same temperature. The value of d obtained in this way was about 1 mm, approximately equal to the spacing of asperities in the rough countersurface. Thus, sliding friction on a rough lubricated surface can be attributed to energy dissipated

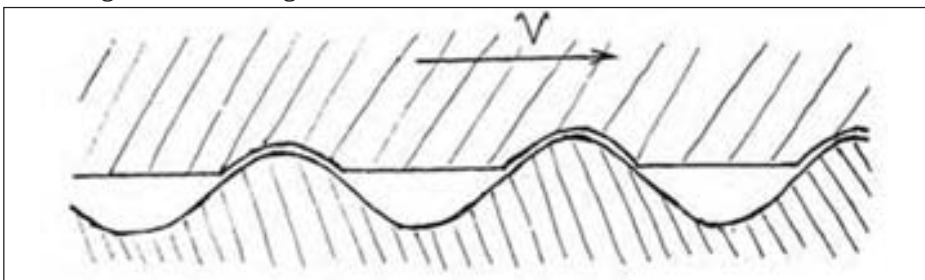
as rubber is compressed and released by passage over road asperities.

Figure 2.37: Sliding friction on a lubricated rough surface



Schapery developed a quantitative theory for the energy dissipated in lubricated sliding of a block of a simple viscoelastic solid over a sinusoidally-wavy surface, figure 2.38 [17]. In the limit, when the pressure is sufficient to bring about complete contact, the amount of dissipated energy calculated in this way corresponds to a coefficient of friction of about 0.25. This is substantially lower than the maximum coefficient of friction measured for rubber sliding on a rough lubricated surface, about 1 to 2 (similar to the maximum value of $\tan \delta$). The discrepancy has been accounted for, at least in part, on the grounds that multiple scales of roughness exist on real surfaces, with each scale giving rise to energy dissipation and hence contributing independently to the total measured friction.

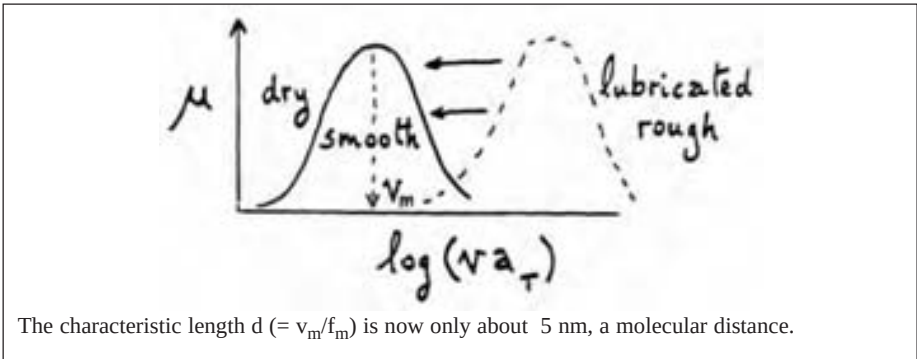
Figure 2.38: Sliding of a viscoelastic material over a sinusoidal surface



3.4 Sliding friction on dry surfaces

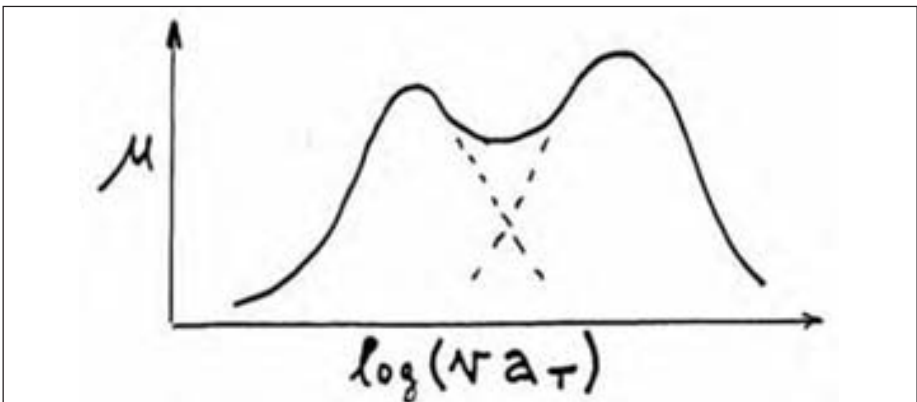
Grosch also studied the frictional properties for the same nitrile rubber sliding on a dry smooth surface. The results were quite similar in form to those described in the preceding section, but the curve for frictional coefficient vs. reduced sliding speed was displaced on the (logarithmic) speed scale to much lower speeds, reduced by a factor of about 10^{-5} . This is shown schematically in figure 2.39. Thus, the characteristic length $d (= v_m/f_m)$ for sliding on a dry smooth surface was deduced to be only about 5 nm, a molecular distance, in place of 1 mm. Grosch therefore concluded that sliding friction on a dry smooth surface is due to energy dissipated as rubber sticks and slips on a molecular scale.

Figure 2.39: Dry sliding on a smooth surface



From these model experiments Grosch was able to explain the more complex process of sliding on a dry rough surface. In this case, both dissipative processes appear, at quite different speeds corresponding to the different length scales of track asperities and molecular strands, figure 2.40. And in the case of rubber sliding on a lubricated smooth surface, sliding is frictionless because there is no mechanism for energy dissipation: both molecular contact between rubber and countersurface and deformations by asperities are now absent.

Figure 2.40: Dry sliding on a rough surface



3.5 Controlling rubber friction

Grosch's pioneering study revealed that several contributions to friction can arise at the same sliding speed from stick-slip or deformation-and-release processes occurring simultaneously at different length scales. This understanding has led to increased control of the frictional properties of real rubber compounds on real surfaces. For example, the importance of road textures and micro-roughness has become recognized. Moreover, the rubber compounder can adjust $\tan \delta$ by using elastomers with different glass temperatures, by using blends of two or more elastomers, and by incorporating plasticizing oils. Values of $\tan \delta$ appropriate to the road surface, sliding speeds and operating temperatures encoun-

tered in service can be selected so that tires exhibit the desirable and yet apparently contradictory features of low rolling resistance and high sliding friction.

4. Abrasion (see chapter 13 also)

4.1 Abrasion during sliding

Schallamach [18] suggested that a simple proportionality exists between the volume abraded away when a rubber block slides over a rough surface and the frictional work expended in sliding, figure 2.41. This leads to the relation:

$$\delta = AW_f \quad (4.1)$$

where δ is the loss (m) in height of the block, W_f is the work expended in sliding per unit of apparent contact area (J/m^2), and A is a coefficient, termed “abradability”, (m^3/J). Typical values of A ranged from 0.1 - 0.5 mm^3/J . They depended markedly on the test speed and temperature, in accordance with the WLF rate-temperature dependence, Equation 1.13. Minimum abrasion occurred at high speeds, near the glass transition, when the tear strength is a maximum, figure 2.42. Indeed, the abradability was found to follow an inverse proportionality to the strength of the rubber compound, represented by the work U_b (J/m^3) of tensile rupture,

$$A \approx C/U_b \quad (4.2)$$

where C is a fitting constant. Schallamach noted that the correlation shown in Equation 4.2 required that the tensile breaking energy U_b be measured at high rates of strain, about 10^4 strain units per sec.

The empirically-determined constant C , about 1×10^{-3} , represents the ratio of the volume of rubber abraded away to that volume which would be brought to rupture if an amount of strain energy equal to the work expended in sliding friction were applied to stretch the rubber uniformly up to the breaking point. It is clear that only a small fraction of the frictional work causes rupture - the major part, over 99%, must be dissipated in other ways.

Figure 2.41: Measurement of abrasion

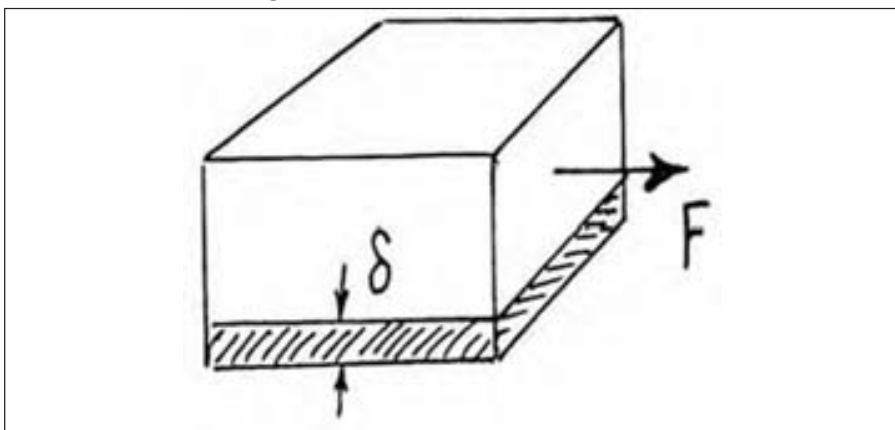
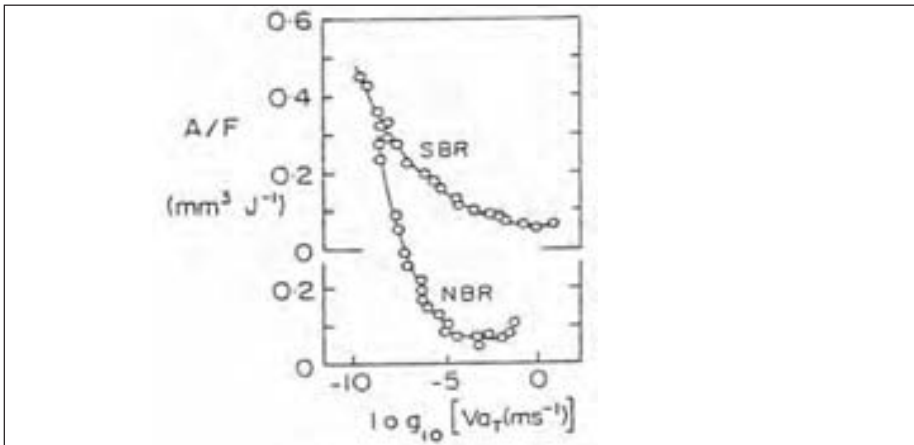


Figure 2.42: Abradability A under frictional force F vs. reduced sliding velocity va_T



Later work showed that equation 4.1 was inadequate - the rate of abrasion is not strictly proportional to the work expended in sliding but increases at a faster rate. A modified relation was proposed [19]:

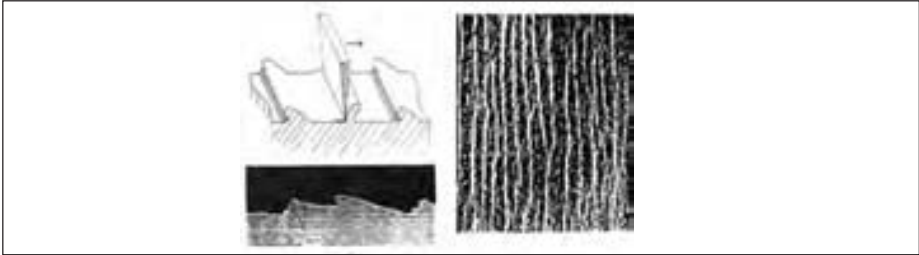
$$d = A'W_f^\alpha \quad (4.3)$$

with an exponent α of about 1.3 instead of 1.

It should be noted that these experiments were carried out by sliding a rubber block over a rough abrasive surface. In other experiments, where a rubber block was abraded by scraping it with a knife-blade held at right angles to the rubber surface, the rates of abrasion were consistent with equation 4.3 only when much higher values of α were used, between 2 and 3 [20-22]. Thus, these two abrasion experiments lead to conflicting results, indicating that the rate of abrasion does not depend solely on the amount of frictional work. In order to predict the rate of abrasion it is clearly necessary to take into account the sharpness of the scraper, as well as the frictional work expended in sliding.

4.2 Schallamach abrasion patterns

When rubber is abraded by sliding a scraper repeatedly in the same direction, a characteristic surface pattern appears. It takes the form of a series of ridges lying at right angles to the sliding direction, with abrasion occurring mainly at the base of the ridges, as shown in figure 2.43 [23]. This mode of abrasion of soft rubbery materials is known as a Schallamach abrasion pattern. It is strikingly different from the abrasion of hard materials, where long scratches are formed parallel to the sliding direction. The characteristic abrasion pattern in rubber is attributed to repeated erosion at the base of ridges which become bent backwards and stretched by the frictional force, as shown schematically in figure 2.44. Thus, regions of the surface lying on the lee slopes are protected from abrasion. The abrader slides along, and off, the stretched ridge tip and makes contact again at the base of the next ridge. Repeated abrasion taking place at the base of ridges causes

Figure 2.43: Abrasion by a scraper: “Schallamach abrasion pattern”

them to become progressively undercut. Eventually the tips fall off as large particles of debris, 50 to 1000 μm in size.

Thus two abrasion processes occur: a small-scale intrinsic abrasion at the base of ridges resulting in small particles, 1 – 5 μm in size, and detachment of relatively large fragments from the ridge tips. Although much fewer in number, the large particles generally account for most of the weight loss.

Because the ridges of a Schallamach abrasion pattern are unsymmetrical, leaning towards the abrader, they can be used to deduce the direction of sliding. For example, if the center rib of a tire exhibits abrasion ridges lying perpendicular to the circumference, then abrasion must have taken place as a result of fore-and-aft sliding motions. If side ribs have abrasion ridges lying at an angle to the tire circumference, then sliding occurred primarily in that direction. Moreover, because an abrasion pattern is unidirectional, leaning forwards in the direction of motion of the rubber, one can deduce whether the ribs slid outwards or inwards against the abrading surface - the road.

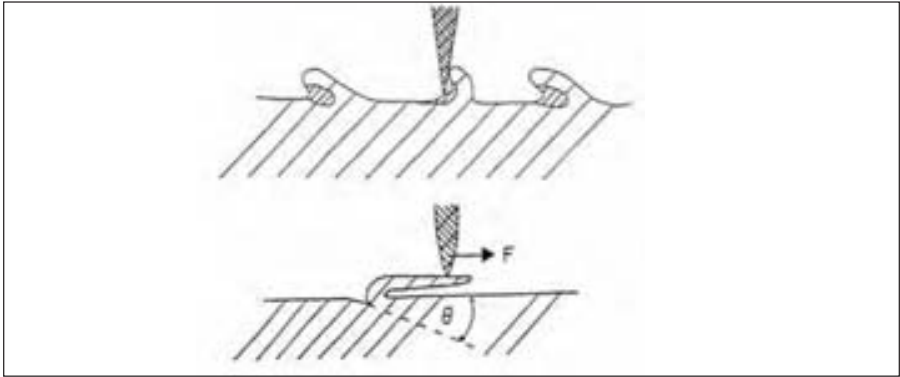
Both the ridge height and ridge spacing increase with increasing severity of wear, i.e., for sharp abrasives, with high frictional forces, and for soft rubber. When the frictional force is increased to reach the tear strength of the rubber, then the rate of abrasion abruptly increases and the mode changes to a gross gouging of the surface without a characteristic pattern being formed.

The Schallamach abrasion pattern also does not form if the direction of sliding is changed repeatedly. Abrasion then takes place more slowly and on a finer scale – a few μm rather than the 50 μm to 1000 μm characteristic of pattern spacings – by an intrinsic abrasion process in which small particles of rubber, only a few μm in size are plucked out from the surface by frictional forces. This process is closely related to tensile rupture, as described in section 4.1.

4.3 Abrasion as fatigue crack growth

In pattern abrasion under moderate frictional forces, the ridges move slowly backwards against the direction of sliding as a result of the gradual loss of ridge tips. This process may be regarded as the gradual advance into the rubber of a series of cracks, each crack corresponding to the leading edge of a ridge. A theoretical treatment of pattern abrasion along these lines has been developed by Southern and Thomas [20, 21], relating the rate of abrasion to the crack-growth resistance of the rubber.

A single ridge under a frictional force F is shown in figure 2.44. The pseudo-crack grows at the base of the ridge, at a shallow angle θ to the surface of the rubber. The energy G available for tear propagation is given by $F(1 + \cos \theta)$. The crack will therefore

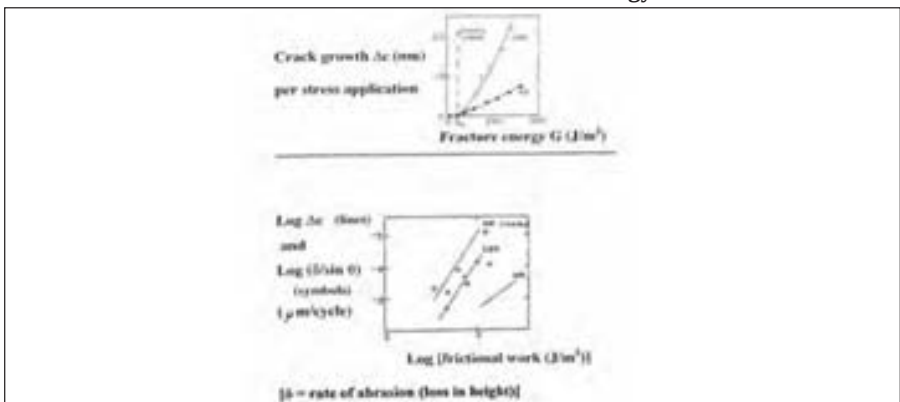
Figure 2.44: Abrasion as a fatigue cracking process

advance by a distance Δc , given by equation 2.8. This leads to a loss in thickness of rubber of $\Delta c \sin \theta$. Thus,

$$A = DF^n(1 + \cos \theta)^n(\sin \theta)/G^n \quad (4.4)$$

The angle θ may be estimated by direct inspection of the way in which abrasion patterns move over the surface during wear. It is found to be small, 5 – 10 degrees. Turner has accounted for these small values by considering the severe tilt of the principal tension directions in highly-sheared blocks [24]. All other terms in equation (4.4) can be determined from tear-growth measurements. Thus, the theory does not involve any arbitrary fitting constants. Figure 2.45 shows a comparison by Southern and Thomas of rates of abrasion (points) with rates of crack growth (lines). Good agreement was found in two cases: SBR and an isomerized NR (non-crystallizing). But NR (triangles), which has excellent fatigue resistance but poor abrasion resistance, is anomalous.

Thus, although the theory is remarkably successful in accounting for the rate of abrasion of two unfilled elastomers, the agreement is unsatisfactory for natural rubber which abrades much more rapidly than crack-growth measurements would predict. It is

Figure 2.45: Crack growth vs fracture energy and abrasion rate vs frictional energy

possible that, under abrasive conditions, natural rubber does not undergo strain-induced crystallisation and therefore lacks the fatigue resistance that it usually demonstrates, and cracks grow rapidly. It should be noted also that filler-reinforced rubber compounds abrade more slowly than would be predicted on the basis of crack-growth measurements. Further work is needed to clarify these points, which are of great practical importance.

4.4 Chemical effects

Under mild abrasion conditions, chemical changes within the elastomer become important in abrasion [25]. The particle size remains small but in some cases the particles show signs of molecular rupture and adhere together to form larger particles, several mm in size. Indeed, filled compounds of cis-polyisoprene and poly(ethylene-co-propylene), for which molecular rupture under shearing conditions is well known, both develop a tarry liquid surface during abrasion. In contrast, cis-polybutadiene shows no signs of structural deterioration - the debris appears to be unchanged chemically and is not sticky. Evidently, different chemical changes are undergone by different elastomers.

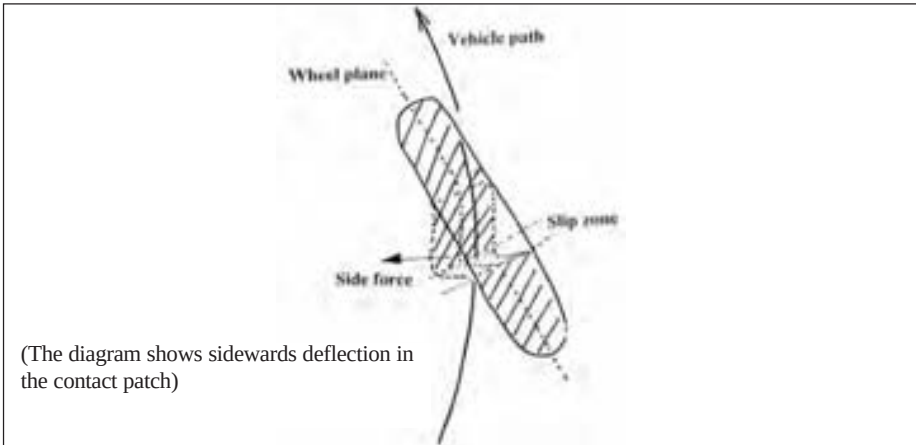
Two reactions can occur during abrasion: oxidative degradation due to frictional heating in the contact zone and mechano-chemical degradation initiated by shear-induced rupture of chemical bonds. Present evidence favors the latter process. For example, in the absence of oxygen the abrasion of cis-polyisoprene changes to resemble that of cis-polybutadiene whereas the abrasion of poly(ethylene-co-propylene) is unaltered. These observations are in accord with the known response of these materials to free-radical reactions.

Surprisingly, the products of chemical changes within the elastomer are capable of causing rapid erosion of metal abraders [26]. For example, a stainless steel knife-blade abradar becomes blunted during abrasion and the volume of metal removed from the blade is substantially greater when the elastomer itself undergoes chemical deterioration. This chemical erosion of the metal scraper is attributed to attack of reactive polymeric species, probably free radicals, during frictional contact. Similar "chemo-abrasion" has been observed with other polymers when molecular rupture takes place in sliding against a hard countersurface [27].

4.5 Wear of slipping wheels [28] (see chapters 7 and 13)

We turn now to predicting the rates of wear of tires from laboratory measurements of the rate of abrasion of tread compounds, represented here by the abrasability A (mm^3/J). For simplicity, we assume that the rate of abrasion is proportional to the frictional work W expended in sliding, although as described in preceding sections this is a gross approximation. Nevertheless, it reveals the main factors governing tire wear.

Figure 2.46 shows the sideways (lateral) deflection of the contact patch of a tire as a vehicle corners. The associated side force S set up at the tire-road interface is needed to enable the vehicle to follow the curved path. The lateral deflection increases progressively from the front of the contact patch, where the tire first makes contact with the road, towards the rear. When the frictional limit is exceeded, the tread starts to slide back to regain its undeflected state. Assuming that the tire is linearly-elastic under side forces, and that the total lateral deflection is small so that sliding back occurs only at the rear of the contact patch, the total side force S is given approximately by $L^2\theta/2C$, where L is the length of the contact patch, θ is the slip angle between the direction of travel and the direction in which the tire is steered, and C is the compliance of the tire for lateral deflections for unit length of tire circumference. (The units of C are m^2/N .)

Figure 2.46: Tire distortion and side-slip in cornering

For a given side force S , the slip angle θ and hence the sliding distance $x_{\max} (= \theta L)$ will be greater for tires that have greater compliance. Thus, abrasion will be greater for tires that are more compliant for sideways deflections.

The amount of energy expended in deforming the tire is given approximately by $S\theta L^2/2 = S^2C/L$. However, only a fraction R of this energy is expended in sliding, where R is the resilience of the tire, because the tire will not return all of the input energy. Thus, the expected rate of wear of a cornering tire is given by

$$d \propto AS^2CR/L \quad (4.5)$$

and is clearly affected by several other factors besides the abrasability A of the tread compound. The lateral compliance C of the tire will contain a contribution from deformation of the carcass in addition to the tread compliance. The contact patch length L is of course governed by structural aspects of the tire and will be insensitive to properties of the tread compound. And the most significant factor in tire wear is seen to be the side force S , largely set up the driver. As far as the tread compound is concerned, three physical properties are important: intrinsic abrasability A , sideways compliance C , and its contribution to deformational energy losses represented by the effective tire “resilience” R . These properties are not necessarily related. For example, a harder, less compliant compound may well be less resilient. Thus a successful tread formulation requires a judicious balancing of sometimes conflicting requirements.

Although, for simplicity, the foregoing discussion dealt with the case of a cornering tire, the same factors govern wear under driving and braking forces. The compressive or stretching deformation of the tire increases through the contact patch until slip takes place when the local circumferential force at the interface exceeds the maximum that friction can support. Strain energy built up in the tire by the circumferential deformation is then released to provide the work of sliding against friction. Note, however, that in driving and braking the relevant tire compliance is in the circumferential direction. It may be considerably different from the lateral tire compliance (C in the previous paragraph), depending on the geometry of cords and belts.

5. Aging of rubber

Rubber undergoes profound changes on storage that are accelerated at higher temperatures. Deleterious changes occur in tire properties after storage at ambient temperatures for five years or after use on cars for similar periods [29]. They are caused by a variety of chemical reactions:

(i) Ozone attack. Although the concentration of ozone in the atmosphere is quite small, typically only a few parts per 100 million, ozone reacts rapidly and efficiently with the unsaturated elastomers commonly used in tire compounds, leading to molecular scission. However ozone cannot penetrate deeply into the material – reaction takes place at the exposed surface and produces a relatively-innocuous thin degraded surface layer, about 20 μm thick, which protects the interior. However, if a small tensile strain of the order of 10% is present in the rubber surface, then the scission reaction with ozone causes characteristic sharp cracks to form in the surface and grow inwards, continuously exposing new material to further attack. The cracks grow surprisingly rapidly. They become about 1mm deep after only two weeks exposure of an unprotected rubber compound to normal outdoor air with an ozone concentration of about 5 parts per hundred million. Thus ozone cracking is potentially a serious problem in tire sidewalls where tensile stresses are commonly present both in storage and in use. Special additives, termed antiozonants, inhibit ozone cracking when added to the rubber compound in sufficiently large amounts, about 3 %, probably by competing with rubber molecules for reaction with ozone. Butyl rubber is much less susceptible to attack by ozone than other common elastomers, at least at ambient temperatures, because it contains only a relatively small fraction of reactive C=C bonds in the molecular backbone.

(ii) Oxidation. Another cause of aging is reaction with atmospheric oxygen. Oxidation is slower than ozonolysis and oxygen therefore penetrates for some distance into the material before reacting. Thus oxidation does not cause cracking directly although the oxidized material is often brittle and cracks on flexing. Depending on the relative rates of diffusion and reaction, the affected depth can range from several mm at ambient temperatures, when the process takes years to reach a significant stage, or a fraction of 1 mm at elevated temperatures when oxidation is rapid, taking only a few hours. Typical hydrocarbon elastomers undergo an autocatalytic reaction that results in addition of oxygen groups to the molecule and formation of new crosslinks by interaction with neighboring molecules. As a result the material generally becomes harder and eventually brittle. However another, generally minor, consequence of the complex oxidation reaction is occasional molecular scission and hence softening. This provides a convenient way of characterizing the sensitivity of a rubber compound to oxidation. Samples are stretched and aged in an oven at various temperatures, usually in the range 70°C to 130°C, and the tensile stress is monitored continuously over a period of several days. As oxidation proceeds and some elastomer molecules break, the stress falls and gives an indication of the extent of oxidation. The rupture reaction follows an Arrhenius dependence on temperature to a first approximation, with an activation energy of about 25 kcal/mole. Thus an increase in temperature of 10°C causes an increase in rate of oxidation by a factor of about 2x.

Another way of assessing the sensitivity of a rubber compound to oxidation is to expose samples for various periods at elevated temperatures and then measure the remaining strength and extensibility at room temperature. A typical specification for aging resistance would require that the tensile strength does not change by more than a specified fraction, say 20%, and the extensibility does not decrease by more than a

specified fraction of the original value, say 30%, after a period of aging of 7 days at 70°C or 22 h at 100°C.

(iii) Additional vulcanization. Vulcanization does not stop when the cured compound is removed from the mold. Continued curing takes place subsequently but at much lower rates, of course, depending on the temperature. As a result if tires are stored or used at elevated temperatures the material hardens as more crosslinks are introduced, or softens (a phenomenon termed reversion) as those crosslinks already formed gradually decompose. These processes are a consequence of a series of complex reactions involving elastomer molecules, existing crosslinks, residual sulfur, activators and accelerators, and byproducts of the various intermediary steps in the crosslinking reaction. In conventional aging measurements these processes are difficult to distinguish from the effects of oxidation, but they can be studied separately by aging samples in an oxygen-free environment. In thick rubber articles, material far from the surface, say over 10 mm deep, may undergo solely anaerobic aging because oxygen reacts before it diffuses so deeply. Passenger car tires, on the other hand, operate for long periods at moderate temperatures, so that oxygen may diffuse extensively before reaction. Thus oxidation is regarded as the normal mode of aging of tire components.

(iv) Weathering. This mode of aging is rather ill-defined. Insofar as new aging processes occur, other than oxidation and ozone attack, they appear to be associated with irradiation by UV and sunlight. Radiation causes free-radical reactions that can initiate or catalyze oxidation and ozonolysis, as well as being itself a direct cause of crosslinking and/or molecular scission.

6. Concluding remarks

Rubber compounds used in tires today are astonishingly effective and durable, as a result of a long period of semi-empirical research and development. Even better materials could presumably be developed with a better understanding of the mechanics and chemistry of strength, fatigue, friction and wear. An outline has been given of our present understanding of basic rubber science but there are clearly substantial and serious deficiencies, notably in the areas of filler reinforcement and chemical changes on aging, that call for further study.

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Test Questions

1. If a rubbery material has a small-strain elastic modulus **G** in shear of 1 MPa, what is small-strain elastic modulus **E** in tension?

What is the approximate value of International Rubber Hardness (IRHD)?

What is the value of the coefficient **C₁** in the neo-Hookean strain energy function, $W = C_1 (\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - 3)$?

If a thin block of the same material with an area of 100 x 100 mm was subjected to a shear force of 10 kN, what would be the angle of heel (the shear angle)?

2. A constrained tension test is one in which the sample is not free to contract laterally when it is stretched. If a sample of the above material is stretched in constrained tension by 200%, what are the values of the stretch ratios $\lambda_1, \lambda_2, \lambda_3$?

How much energy **W** is stored per unit of volume?

3. An uncrosslinked sample of a “raw” (i.e., uncrosslinked) elastomer with a T_g of -90°C has a flow viscosity of 10^8 Pa.sec. at room temperature (20°C).

[Note: viscosity is inversely proportional to molecular mobility.]

What would the viscosity be at 120°C ?

What would the viscosity be at -40°C ?

4. If $\tan \delta$ for a lightly-crosslinked sample is 0.1 when measured at a frequency of 10 Hz at 20°C , at what frequency would $\tan \delta$ again be 0.1, if the test temperature is now 120°C ?

5. Rebound resilience is used as a rough measure of energy dissipation and rolling resistance. It is measured at a low temperature, say 0°C . The contact time is quite short, about 2 msec, equivalent to a test frequency of about 250 Hz. Under these test conditions, are the results relevant to the rolling resistance of a tire in service, at say 50 mph and at a temperature of 60°C ?

If the tread material has an effective T_g of -50°C , what test temperature would make the measurement of rebound resilience more relevant to the service conditions?

6. In a test for adhesion of cured sheets of rubber, two wide strips are bonded together over a narrow section, 20 mm long and 6 mm wide. The peel force **P** is measured as the strips are peeled (torn) apart. If **P** is 48 N, what is the strength **G** of adhesion?

If the speed of tearing was increased from 1 mm/sec to 100 mm/sec, what increase would you expect in the tear force **P**, approximately: 50%, 100%, 500%, 1000%?

If the test temperature was raised, would **F** increase or decrease?

2. Derive an equation for the rollover threshold for a vehicle traveling around a superelevated curved highway with a transverse slope angle? Discuss the implicit role that tire properties may have, if any, on the results.

Chapter 15

Introduction to Tire Safety, Durability and Failure Analysis

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Chapter 15

Introduction to Tire Safety, Durability and Failure Analysis

by J.D. Gardner and B.J. Queiser

1. Introduction

Over time, as science, engineering, and manufacturing technology have advanced, tires have offered an increasingly higher degree of utility, reliability, and value. However, tires can become damaged, or when pushed beyond their limits, they will fail. Pneumatic tires have always had a certain failure rate, and for this reason, vehicles have typically carried spare tires—in the early days, more than one. Over time, failure rates have decreased, but not vanished.

Tires are subjected to a wide variety of use and operating conditions, depending on the vehicles they are attached to, the use and maintenance habits of their operators, the environment in which they operate, and random events that can inflict damage or affect their operation. While great strides have been made in design and manufacturing, with rare exception, it is what a tire experiences or is exposed to in the field that determines whether it will fail in service.

Still more complicated is the issue of safety. Tire failure during operation, for instance on a highway at speeds safe for conditions, is the precursor to an inconvenience, i.e. pulling over and applying the spare, or, it is the first in a series of events that may lead to loss of control, and in some cases an accident. However, the vast majority of the time tire disablements do not result in an accident [1].

Performing a failure analysis on a tire is a scientific process that begins with an understanding of the product, including its materials, mechanics, and operational characteristics. These items are evaluated as evidence that tells a story through testing, inspection, and evaluation.

The goal of this chapter is to outline elements of tire safety, basic mechanics and factors pertinent to tire durability, including common tire failure modes and analysis. These subjects can be very broad, thus it is not practical to deal with all of them. The tire photographs and examples shown in this chapter are intended to illustrate the concepts being addressed and do not include all of the possible variants that can occur in testing or result from use in the field.

2. Tire safety

2.1 Definition

The issue of tire safety is more complex than assessing the mere occurrence of a tire failure; because a tire has failed does not necessarily mean that it was unsafe. If that were true, all tires could be deemed unsafe because all tires can be made to fail under some conditions. Tire safety is usually part of a complex relationship involving the tire itself, human beings, a vehicle or service equipment, and other external elements. There are two primary areas of tire safety that pertain to failure:

- Tire servicing and maintenance
- On-vehicle, in-service conditions

In the first case, potential harm or injury is associated with mounting and demounting tires, performing maintenance on wheels and rims, and in making repairs. In the second case, the definition of tire safety is essentially the same as that for vehicle safety. Tires are part of a system that has the function to transport humans and goods as quickly, comfortably, efficiently, and ecologically sound as possible, without causing an unreasonable risk of harm or injury [2]. Tire safety in this context includes proper tire selection for the vehicle (including load, inflation, speed, and other performance parameters); proper tire design for durability and resistance to failure; and a dependency on the end-user for care and maintenance.

2.2 Tire Servicing/maintenance safety

Typical tire servicing safety issues involve mounting/demounting and maintenance/repair. Some of the potential situations that may result in serious injury or death include the following:

- **Tire/Wheel Mismatch**—The wheel is too large or too small for the tire bead diameter. During inflation, in an attempt to seat the beads, the tire could burst or de-bead if the inflation pressure exceeds safe levels.
- **Bead Hang-Up**—The tire is not properly fitted to the wheel or one of the components is out of tolerance or inadequately lubricated. If excessive inflation is applied to seat the bead(s), the tire could burst or de-bead.
- **Improper Rim Parts/Assembly**—Mismatched, damaged/deteriorated multipiece rim components, or incomplete assembly. During inflation, or subsequently, the rim assembly could burst apart.
- **Ether**—Use of a volatile gas to assist in seating beads and inflation can cause an explosion of the tire.
- **“Zipper” Rupture**—During handling or inspection of a pressurized tire with suspected damage, fatigued ply cords may break one after another until a rupture occurs, typically in the upper sidewall, with explosive force and instantaneous air loss.
- **Welding**—Repair of a wheel component by welding, brazing, or otherwise heating while a tire is mounted and inflated to it can cause excessive pressure to build up within the tire and result in an explosion.

Tire and wheel servicing should be done only by specially trained persons using proper, prescribed procedures and equipment. For instance, the tires and wheels themselves are designed to facilitate the process of mounting/demounting; tires have strong, but flexible, beads, and wheels for passenger cars and light trucks are typically a single-piece, drop-center design [3]. In addition, warnings, recommendations, and step-by-step procedures are outlined by the Rubber Manufacturers Association (RMA) and the Occupational Safety and Health Administration (OSHA) [4 - 9].

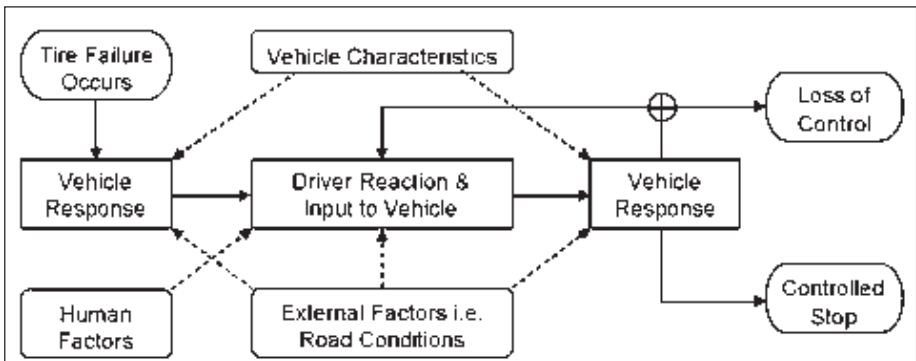
2.3 On-vehicle, in-service tire safety

When a tire fails in service, the safety aspects are far more complex than the servicing issues outlined previously. Additional variables are involved, such as different vehicles, different drivers, and different operating conditions. These variables combine to influence

the ultimate result of a tire failure. A flow chart of the occurrences and influences is shown in Figure 15.1.

Whether a tire failure in service is a safety issue depends upon numerous factors. Therefore, assessing tire safety in this context can be difficult.

Figure 15.1: Processes/influences following in-service tire failure [1, 10]



2.4 Crash data perspective

Nearly 3 trillion (3,000,000,000,000) vehicle miles were traveled and 6.3 million crashes were reported in the United States for 2003. While the trend in the number of crashes during the previous 15 years was essentially flat, the number of miles traveled each year steadily increased. The resulting crash rate, therefore, steadily declined, and the vehicle occupant crash fatality rate for 2003, the data most currently available at the time of writing, was at an all time low since record keeping began in the mid-1970's [11].

Data trends that began in the 1990's indicate a shift of fatalities from passenger cars to sport-utility vehicles (SUVs) and other light trucks, which correlates with an increase in popularity of these vehicles. However, the data indicates that increasing light truck fatalities, particularly those for SUVs, have been offsetting fatality reductions credited to increased seat belt use, reduced drunk driving, increased use of child restraints, and the proliferation of airbags [11 - 13].

2.5 Tire failures and crash causation

In 2003, nearly 300,000,000 new passenger and light truck tires were shipped [14] to supply the U.S. fleet of about 230,000,000 registered vehicles [11]. For myriad reasons, tires fail in use every day. For instance, in 2002, AAA responded to 2,400,000 "flat tire" service calls [15].

However, in-service tire failures result in a crash, presumably from loss of vehicle control, only a fraction of the time, from 0.06% [1] to about 0.50% [16] of overall occurrences. These statistics indicate that very few accidents are caused by tire failures. In fact, the mere inclusion of a readily-accessible spare tire as a vehicle component indicates that it can be applied when needed, i.e. at the side of the road after pulling over.

2.6 Warranty and adjustment data

Historically, the tire industry and the National Highway Traffic Safety Administration

(NHTSA) have relied upon warranty or adjustment data as a measurement of tire performance and customer satisfaction in the field. An adjustment refers to the credit a customer receives at a retail outlet when a tire is exchanged under the terms of a warranty, or for goodwill. Therefore, the data may include adjustments made on tires that are not under warranty or for conditions not covered by a warranty, simply to maintain or foster customer satisfaction.

Adjustment data is prolific enough to provide statistical significance. It streams in continually to the tire manufacturer where it is coded to identify the reason for the adjustment, which can be for a variety of reasons, including durability, ride, comfort, and cosmetics. By compiling and monitoring the data, a tire manufacturer can identify product performance and/or customer satisfaction trends. This feedback can be used to implement countermeasures on a timely basis, to enhance business relationships, and for future product development. Because of its commercial value, tire manufacturers keep adjustment data confidential.

There is no standard within the tire industry or government regarding the evaluation of adjustment statistics; for instance, there is no level which automatically triggers attention. In addition, adjustment data for one tire may not necessarily be meaningfully compared with data for other tires. For instance, performance trends that are apparent from a review of data for a large, conglomerate population of tires may not apply to a particular tire because of differences in such parameters as design or application. Essentially, to evaluate the performance of a particular tire, it is necessary to examine that tire's unique performance history.

2.7 Personal injury and property damage claim/lawsuit data

Additional information is received by tire manufacturers in the form of personal injury and property damage claims or lawsuits that may allege harm from a tire failure. While there is no industry definition for a claim, for purposes here, a claim is a request for compensation made directly to a tire manufacturer for alleged property damage or personal injury (or both) incurred from a tire failure. A tire company may have a standard policy or procedure to handle these claims. A lawsuit involves a legal complaint against the tire manufacturer filed in a civil court. Similar to claims, lawsuits pertaining to alleged tire failures usually involve property damage or personal injury (or both).

Property damage claims, typically the greatest portion of the data, are usually made for the costs of repairing minor sheet metal or paint damage and/or replacing a damaged wheel as a result of a tire failure. Personal injury claims are typically made for medical and/or compensatory expenses associated with bodily harm incurred in an accident after a tire failure. Lawsuits involve similar issues, however, usually to a greater degree, particularly in situations where an accident has resulted in serious injuries or death.

Tire companies take these matters very seriously for a variety of reasons. Inspections of the tire(s) are undertaken by company personnel, and often independent consultants. Accident investigations/reconstructions, depositions, and requests for documents/records may also be completed. It is in the best interest of the tire manufacturer to determine the validity of the allegations and the cause of the tire failure.

Claims and lawsuit data differs from adjustment data in numerous ways. For instance, it is not generally as voluminous; therefore, its statistical significance is limited. As well, the data is not as timely as that of adjustments. Lawsuits, in particular, are typically not filed soon after an incident and the tire(s) in question may not be made available for

inspection for months, even years. In some cases alleging tire failure, the tire may no longer be available, or may not be provided for inspection, making it practically impossible to determine the cause of the alleged failure.

Another fundamental difference between a claim/lawsuit and an adjustment is that an adjustment related to tire durability is commonly made before the tire has sustained a complete failure. This is accomplished through routine inspection of tires by the consumer or tire service professional or because of other warning signs, such as loss of inflation, vibration, and irregular wear. Almost all claims and lawsuits could have been an adjustment if the tire was removed from the vehicle sooner. Failed tire adjustments are also examples of a failure that does not result in an accident, contrary to some allegations involving claims and lawsuits.

2.8 Early warning data systems

The adjustment, claims, and lawsuit data may be monitored concurrently with “early warning” database and analysis systems. By monitoring trends related to safety, such as accidents, the tire manufacturer may be able to identify product performance that is not meeting expectations or other potential issues. Resulting actions may be to more closely monitor a specific product or application, issue a technical service bulletin or consumer advisory, or initiate a replacement campaign or recall.

2.9 Consumer recommendations

While it is not practical to list all of the relevant tire safety warnings and recommendations here, the following basic advice is often repeated:

- Check tire inflation monthly and before long trips or when carrying extra load. Use a pressure gauge, since radial tires can be deceptively low on pressure even if they pass a quick visual check. Follow the vehicle manufacturer’s recommendations for inflation as indicated on the vehicle tire placard or vehicle owner’s manual.
- Properly load the vehicle and tires. Do not exceed tire load capacity and follow vehicle manufacturer’s recommendations as indicated on the vehicle tire placard or owner’s manual.
- Routinely rotate and evaluate tires for tread wear and damage or unusual conditions, such as bumps, bulges, cracks, worn areas, etc.
- Tires must be properly repaired—an improper repair can be inadequate and can contribute to an eventual tire failure.

Information may be found at tire retail outlets and on-line, at www.rma.org (Rubber Manufacturers Association), www.nhtsa.gov (National Highway Traffic Safety Administration), and tire manufacturer websites.

3 Fundamentals of tire durability

3.1 The nature of tire durability

Tires are the vehicle component which transfers forces and moments to the vehicle in response to driver and vehicle dynamics directives, the least of which being to carry the load of the vehicle and occupants. In addition, tires can be exposed to a plethora of road (and off-road) surfaces, environments, operating conditions, maintenance habits, and damaging events.

For purposes of this chapter, the term “durability” refers to the structural integrity of

the tire in service. The rate of wear of tread rubber may constitute a durability parameter in some cases, but it is not addressed here.

Tire engineers and chemists optimize the tire structure for performance factors relating to traction, wear, ride comfort, handling, durability, rolling resistance, and more. Cost or economy is a factor as well. Within the limits of science and engineering, certain parameters may conflict with one another, or require engineering trade-offs. For this reason, the marketplace contains a wide range of tire products designed with different operating and performance parameters in mind, such as those necessary for off-road versus highway, high speed use. From a durability perspective, the tire is designed to provide a balance of desired attributes, while relying on the end-user for basic care and maintenance.

Because a tire has failed does not necessarily mean that there was anything deficient in its design or manufacture. Structural failure of a tire can occur at virtually any point in its expected lifetime, whether it is brand new with full tread depth, or nearly worn out after years of use. Any tire can fail. The objective is to design a product that meets internal company, industry, and government standards, and performs according to the consumer's needs until the tire is worn out and replaced. However, as previously noted, external factors such as severe service conditions or damaging events can affect the tire's ability to endure and shorten or end its service life.

3.2 First principles of tire durability

Fatigue is a common cause of failure of a steel belted radial tire in use. Within the tire structure, fatigue occurs through a process of progressive fracturing from excessive stress and strain during cyclic loading [17]. As a viscoelastic material, contributing factors to the strength of rubber include temperature and rate of loading [18]. Additional influences include damage inflicted upon the tire structure from breakage, tearing, puncturing, contamination, and intra-carcass pressurization. Damage to the tire may accelerate the fatigue process or cause an immediate failure.

3.3 Deflection

The most basic factor that affects tire durability performance is the vertical deflection. Using the simple model shown in Figure 15.2, when a tire is bearing a load P the deflection d is the difference between the unloaded radius r_o and the loaded distance r_L between the wheel center and the ground:

$$d = r_o - r_L$$

Considering the pressurized tire as a vertical spring, and applying Hooke's Law:

$$P = K d$$

where the vertical stiffness, K , is primarily attributable to the internal inflation pressure. (It should be noted that the precise load/deflection behavior is more complex than this model; see chapter 5.) The work W done in compressing a linear spring is

$$W = \frac{1}{2} K d^2$$

As the deflection increases, more work energy is imparted to the tire, whether from situations involving a decrease in K (such as from reduced inflation pressure) or an increase

in load. As the tire rolls, a mechanical energy loss mechanism manifests itself through the generation of heat [19 - 21]; see chapters 2, 11 and 12. As the tire deflection and/or load increases, the energy loss increases as well, as shown in Figure 15.3 for a steel belted radial tire.

Figure 15.2: Unloaded and loaded tires

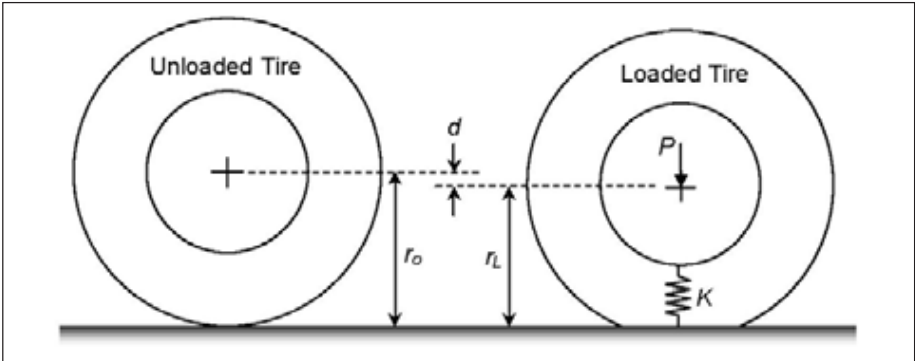
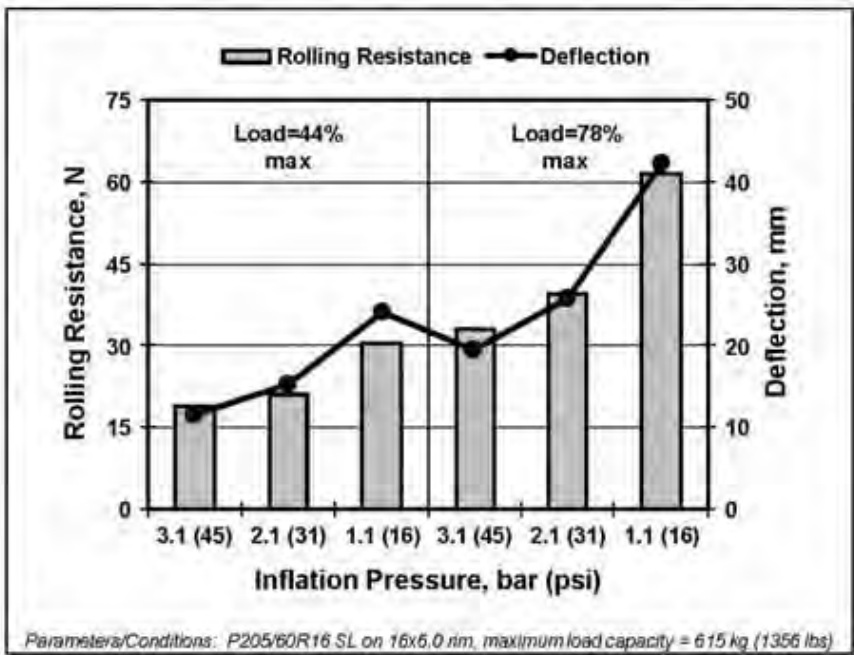


Figure 15.3: Rolling resistance and deflection of a passenger tire



The effect of the tire deflection can be seen by observing the size, shape, and pressure of the contact patch—also known as footprint—of a tire on a flat surface, as shown in Figure 15.4. The length of the footprint in the circumferential direction increases with an

increase in load or a decrease in inflation pressure, which is correlated to the amount of deflection (chapter 5).

In Figure 15.4, note that the footprints at the lowest inflation pressure, particularly at the highest load, indicate a tendency of the tread to lose contact pressure in the outer shoulder groove locations; essentially due to a buckling of the tread and belt structure; see chapter 7 for further details.

Of interest to tire durability is the strain energy density in the location between the belt edges in the shoulder areas of the tire. The interlaminar strains developed in the belt package are due to bending and stretching of the tread area that occurs during the deflection process. These strains are concentrated at the belt edges [22]. The fundamental mechanics of stress and strain development are now evaluated using finite element analysis (FEA) techniques. One such example is shown in Figure 15.5, where a solid element cyclic strain energy density (SED) plot is given for a P215/55R18 standard load (SL) tire.

Figure 15.4: Flat surface contact conditions of a passenger tire

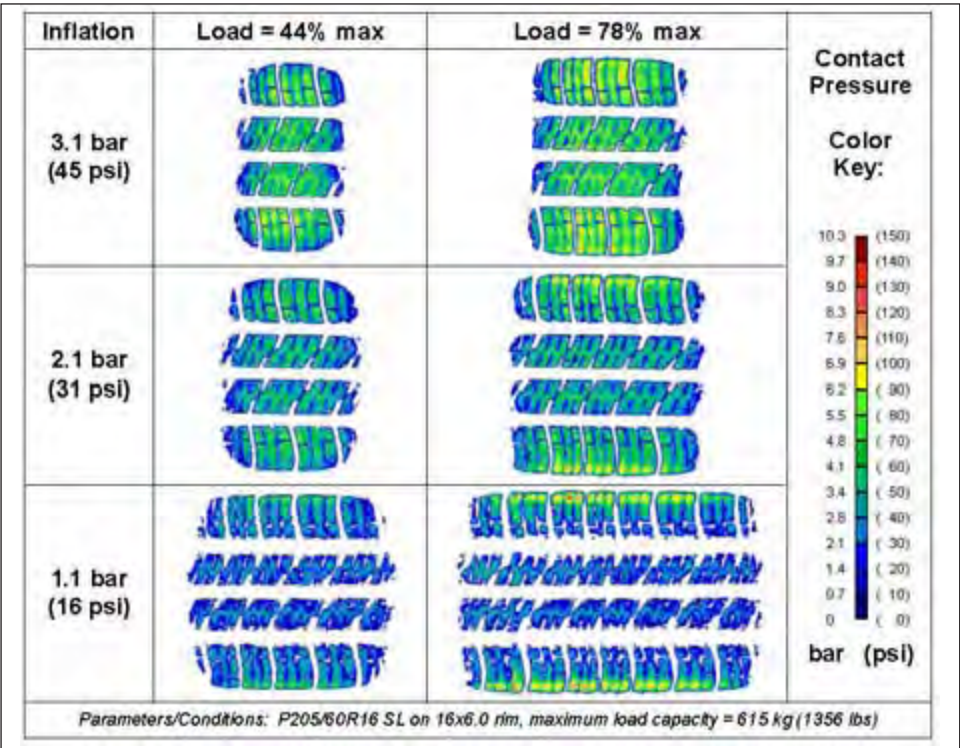
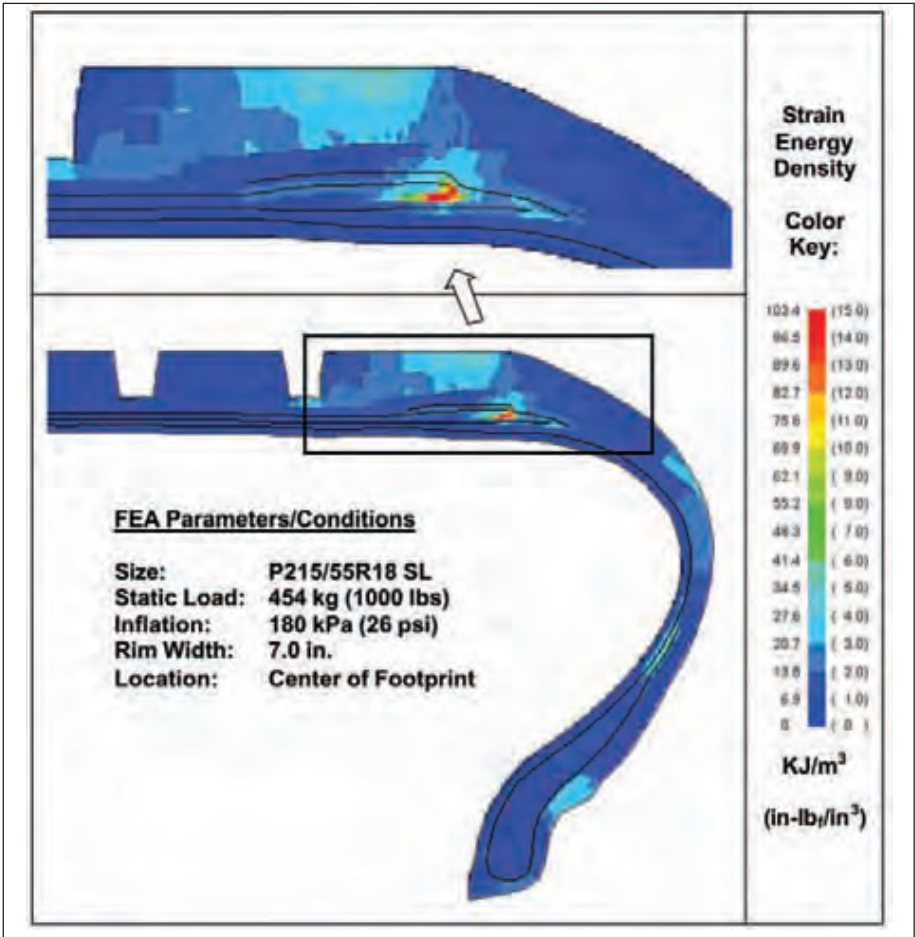


Figure 15.5: Example of FEA solid element cyclic strain energy density



3.4 Heat

As previously mentioned, tires develop heat as they are operated. As a tire is cyclically deflected, it reaches thermal equilibrium in terms of its internal component temperatures, and in terms of the contained air temperature within the tire cavity. Changing operating conditions and physical changes to the tire structure itself can change the state of equilibrium.

Elevated and extended heat generation is a primary factor in the breakdown of a tire. Increased heat decreases rubber tear resistance which promotes crack initiation and propagation [18]; see chapter 2. Permanent degradation of material properties from exposure to elevated temperatures occurs as well, depending on the exposure history.

The shoulder areas of a radial tire are generally the highest in heat generation. Figure 15.6 illustrates the increasing temperatures that develop in the shoulder area when a tire is operated with increasing deflection. Rubber deterioration (reversion) from excessive heat build-up results in a decrease in tensile strength and a general softening. This break-

down from heat is an additive effect that can drive the temperature higher still. Ultimately, a component or portion of the tire can reach a critical temperature range where the deterioration of the rubber can cause detachment from the tire of pieces or whole sections of the tread. Reverted rubber has a porous appearance, such as the pieces of reverted tread rubber shown in Figure 15.7. Other components may melt, such as the polyester body cord shown in Figure 15.8.

Figure 15.6: Thermographic images of a tire operated with decreasing inflation [23]

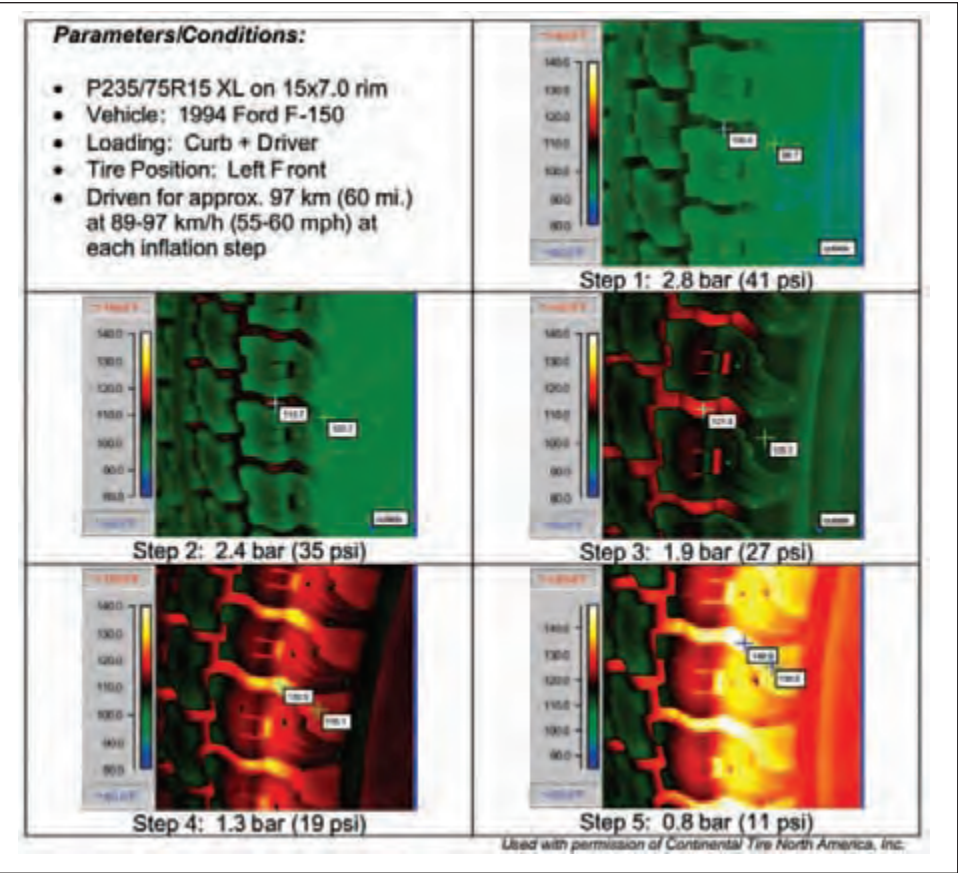


Figure 15.7: Examples of reverted tread rubber



Figure 15.8: Melted polyester cord (lower sidewall)



3.5 Speed

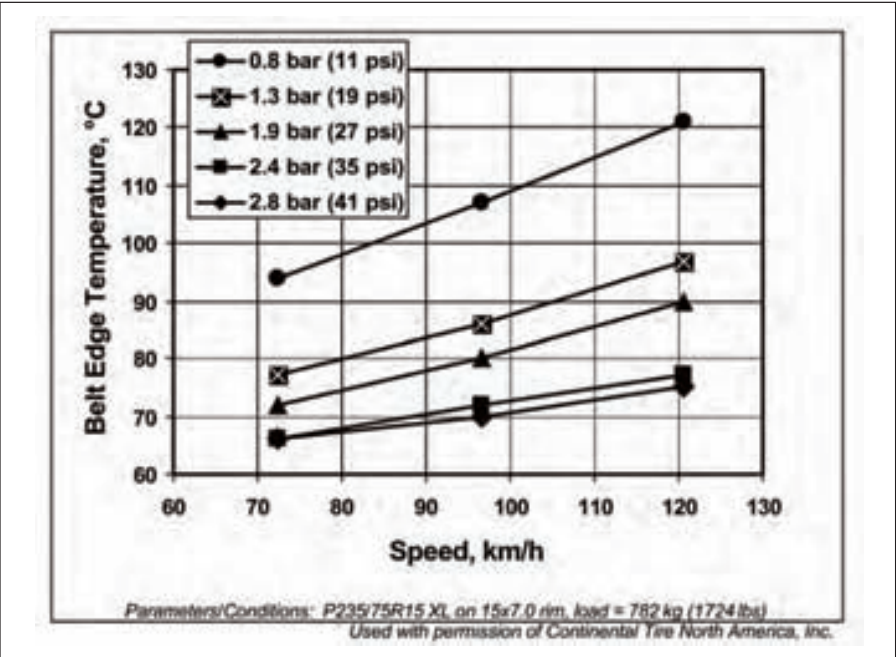
Changing the speed of tire rotation affects the centrifugal force and frequency of the deflection cycle. Corresponding changes in the stresses and strains developed in the tire components affect the tire’s heat build-up characteristics. Additional deflections occur from “standing waves”, treated in chapter 10. This phenomenon depends upon the size, construction, stiffness, and especially the rotational speed of the tire.

The fundamental effect of speed is its influence on the frequency of cyclic deformation. With each rotation, a given radial section of the tire undergoes a stress-strain cycle as it passes through the contact patch. Increasing the cyclic frequency increases the heat that develops, and hence affects the performance of the tire as a whole, particularly parameters that relate to durability.

The centrifugal force acting on a body is directly proportional to the mass, the distance from the axis of rotation, and the square of the angular speed of rotation. For a tire, the tread and belt structure is located the greatest distance from the center of rotation and comprises a substantial portion of the tire mass. It is thus evident that centrifugal force can affect the tread area, particularly the shoulders, which are concurrently undergoing a stress/strain cycle with each rotation.

Testing has verified that increasing speed causes an increase in tire temperature, particularly in the shoulder area [23, 24]. In Figure 15.9, results are shown for a tire tested at speeds up to 120 km/h (75 mph) with numerous inflation pressure settings at constant load. The results indicate a near-linear relationship between speed and temperature, with increasing slope as the inflation pressure was decreased.

Figure 15.9: Belt edge temperature of a tire operated with increasing speed at various inflation pressures

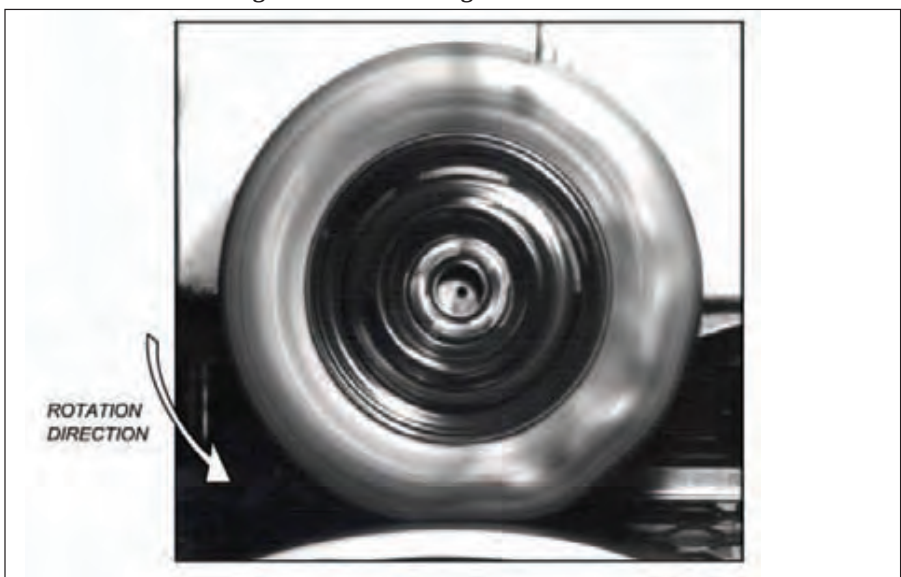


Combating the effects of centrifugal force may be accomplished in various ways. Other than reducing tire size or mass, which may not be practical, a common design solution is the use of a circumferential reinforcement in the tread area. The tire industry typically refers to this feature in a tire construction as a cap ply, strip, or layer, which may be a single or multiple component. It is typically placed beneath the surface of the tread around the steel belts, often at the shoulders. In essence, these components act to restrict the growth of the tire that results from the effects of centrifugal force during high speed operation. Generally, for passenger car tires, the speeds at which these design features are particularly necessary are usually greater than 180 km/h (112 mph). However, light truck tires, or tires with heavy tread lugs, for instance, may require reinforcement at lower speeds.

For a tire with certain construction and stiffness parameters, the standing wave phenomenon emerges at a specific rotational speed; see chapter 10. Essentially, a standing wave forms when the tire tread and sidewalls do not recover from the effects of one deflection before re-engaging with the contact surface and initiating another deflection cycle. Figure 15.10 exemplifies this wave deformation in a tire operating at relatively high speed; note the rippling of the sidewall and tread that is initiated at the contact patch and extends nearly 180° around the tire. Standing waves are particularly destructive due to additional stress, strain, and heat generation. Increasing the stiffness of the tire and reinforcing the tread region, such as through the use of cap ply materials, effectively shifts the onset of standing wave generation to higher speeds.

Note that design changes to counter the effects of centrifugal force and standing waves do not alter the frequency of cyclic deformation and do not usually influence the stress/strain durability performance of a tire performing at typical highway speeds or lower. Therefore, addressing tire durability performance in one range of speeds may not meet the preferred tire design methodology and engineering parameters in another speed range.

Figure 15.10: Standing wave deformation



3.6 Lateral force / turning

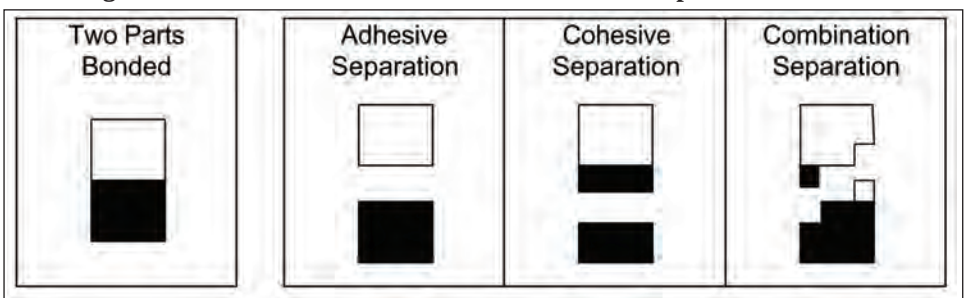
Beyond the scope of this chapter, but addressed in chapters 4 and 8, is the contribution to tire stress and strain through the simple matter of turning or applying a lateral force to a deflected tire, as on the steering axle of a vehicle. Particularly relevant are the contortions of the tread and belt plies through the contact patch during turning, not only in creating additional stress and strain, but also in contributing additional heat from increased hysteresis and tread abrasion. Variables affecting the magnitude of this effect include the duration and rate of turning and the slip angle history through the turn.

3.7 Tire structural failures

With a sufficiently high applied stress or strain, every material is subject to failure. In use, tire materials are subjected to the effects of fatigue, wear, heat, corrosion, and other external damage. The magnitude and frequency of externally applied forces and moments can ultimately cause rubber to fatigue and tear or cause steel and polyester cords to rupture. The process of tire structural failure can progress slowly, or be essentially immediate; it depends upon the structure itself, the magnitude and rate of imparted energy, and external conditions such as temperature.

When a tire is cured, the separate tire layers and components do not mix or become homogeneous. Rather, during the vulcanization process, the materials chemically bond to one another. Fracture and crack propagation can occur between the materials at their interface, within an individual material, or along a failure surface that is a combination of both, as shown schematically in Figure 15.11.

Figure 15.11: Adhesive, cohesive and combination separation fractures



Cracking of rubber can begin at or near an interface with a tire cord, as in the case of the polyester cord shown in Figure 15.12. Such cracking may progress around the cord itself, creating a condition known as socketing. Continued crack growth can result in smaller cracks meeting one another and progressing further. Figure 15.13 shows a typical separation between the steel belt edges. Fracture of cords or filaments can lead to structural weakness that causes a whole-tire rupture or leads to more slowly developing internal ply separation, depending on the extent of the damage. Tensile fracture of a steel cord filament is shown in Figure 15.14.

Figure 15.12: Incipient cracking adjacent to polyester cord

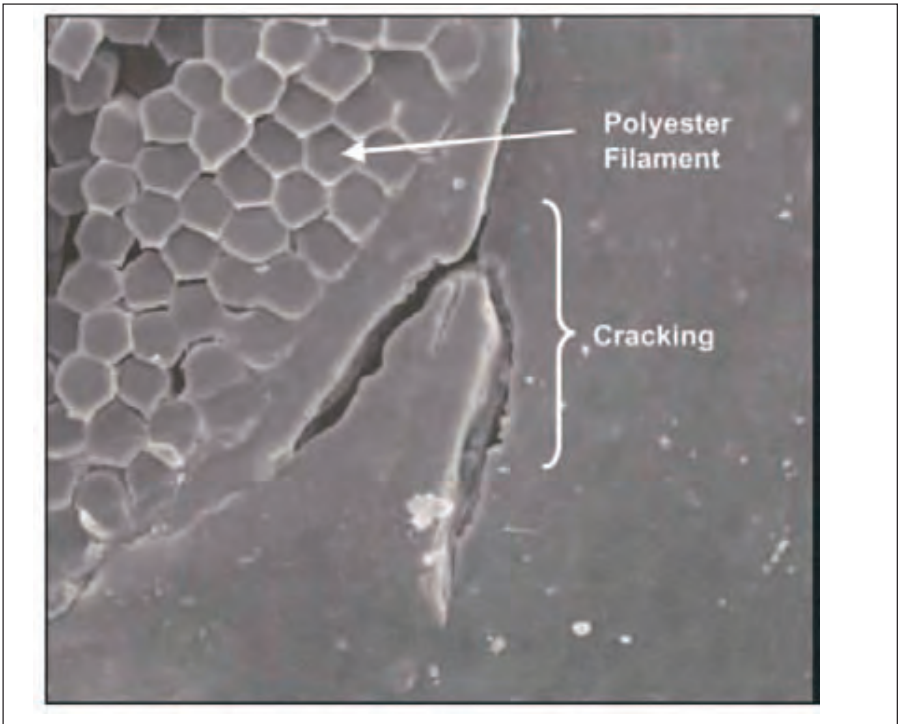
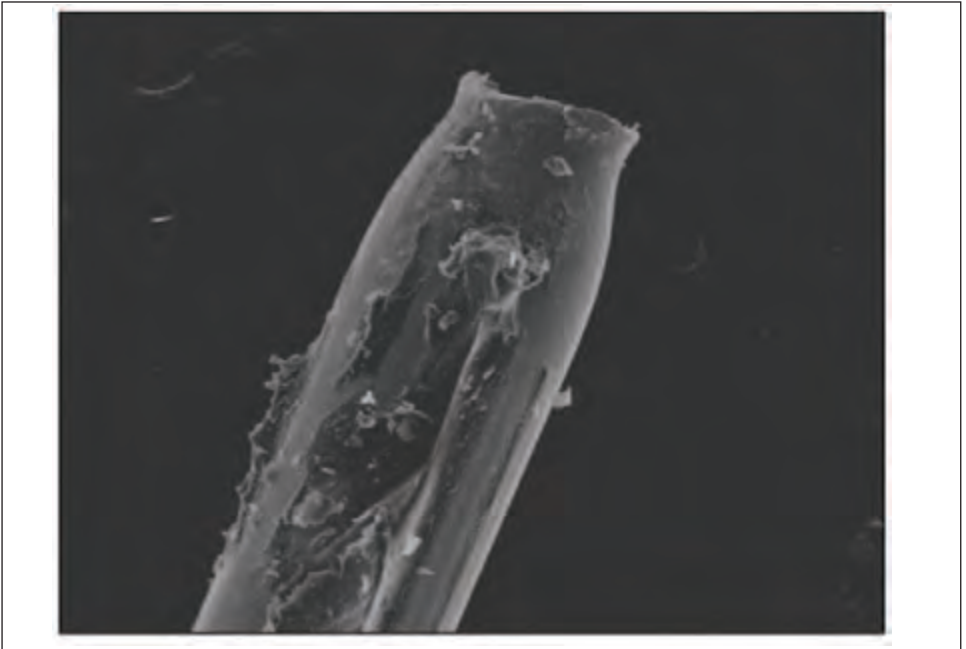


Figure 15.13: Cracking between steel belt edges



Figure 15.14: Tensile fracture of steel cord filament



4. Fundamental tire failures and analysis

4.1 Common in-service tire failure modes

In-service tire failures, although increasingly rare, occur in one of three common modes: a run low, sidewall flex break; a belt and/or tread detachment; and a rapid loss of air through a break in the tire.

4.2 Run low / flex break

If a tire is run in a grossly overdeflected condition at highway speeds, at or near flat condition, it is severely flexed in the upper sidewall and tread shoulder regions. Flex fatigue and extreme heat build up in these areas of the tire, and even melting of polyester radial body cords as in Figure 15.15, ultimately result in circumferential breakage of one or both sidewalls from the entire tread structure. It is common for these failures to arise from continued loss in inflation pressure during operation.

Figure 15.15: Broken, heat-fused polyester body cords, upper sidewall

4.3 Tread/belt detachment

If a tire is operated with a propagating separation in the tread region, the separation can progress to a level that results in one or more stabilizer plies (i.e. steel belts) and/or the tread rubber to be torn from the remainder of the tire body, as in Figure 15.16. Incipient separations grow circumferentially around and laterally across the tire before reaching a threshold that results in the detachment. These failures commonly occur at highway speeds when the centrifugal force is sufficiently high.

Figure 15.16: Exemplar tire after tread/belt detachment



4.4 Rapid air loss

When a cut or break occurs in a tire, the air within the cavity will escape through the opening. Obviously, the rate of air loss depends on the size of the hole. Rapid air loss, or sudden deflation, occurs when the size of the opening is substantial, i.e. greater than 6.4 mm (0.25 inch), as in Figure 15.17. This failure mode is sometimes referred to as a “blow out.”

Figure 15.17: Upper sidewall break through to cavity

4.5 Common causes of in-service tire failures

Since it is not practical to address here all of the possible conditions and causes of failure, this section presents the types of tire failure causations that occur most frequently.

4.6 Overdeflection

As noted previously, the deflection of a tire is a dominant parameter in tire performance because it determines stress, strain, and heat generation. When a tire is designed and tested for a rated load and inflation pressure, it has a specific deflection and will perform satisfactorily at that deflection within a reasonable tolerance. Overdeflection is defined as a deflection that is greater than that intended for the rated load and inflation pressure. Overdeflection occurs when the load is excessively high, or the inflation pressure is too low, or when a combination of load and inflation pressure creates an excessively high deflection. A moderate degree of overdeflection, depending on speed and other operating parameters, can initiate and propagate steel belt edge separation and tread/belt detachments. Severe, gross overdeflection, generally at nearly flat-tire conditions, commonly causes sidewall flex break failures.

If overdeflection occurs for a short period of time, the tire failure itself may be the only evidence of overdeflection. If the overdeflection occurs over a longer period of time, it can be evidenced by conditions such as rim grooving [23], balance weight impressions, and/or tread wear patterns.

4.7 Intracarcass pressurization

Since the advent of tubeless tires in the 1950's, intracarcass pressurization has existed. A tubeless tire is a pressurized air container. The pressure inside the cavity is higher than atmospheric pressure, hence there is a tendency for the air molecules to migrate out from

the air cavity to the atmosphere. First, they must pass through the innerliner which is specifically formulated to resist air permeation, typically through the use of halogenated butyl rubber. Any air molecules that pass through the innerliner then continue through the remainder of the tire until they eventually reach the atmosphere. The overall rate of air permeation through the tire depends on many factors. Loss in inflation pressure is generally 1-2 psi per month for steel belted radial passenger and light truck tires.

During the process of air permeation a pressure gradient exists within the tire structure. Over time, this pressure gradient attempts to reach equilibrium. If the interior of the tire is breached by a puncture, impact, tear to the bead, etc., pressurized air within the tire cavity can pass directly into the tire structure. This creates two problems. First, the air brings moisture and excess oxygen into the tire structure, which can break down chemical bonds and consequently the adhesion/cohesion of internal components. Secondly, since the tire cavity pressure is higher than the equilibrium gradient pressure within the tire structure, the pressurized air will tend to force the structural components of the tire apart, particularly at high stress/strain areas of the tire such as the belt edges. These two conditions can lead to or aggravate separations, including in some cases tread/belt detachment.

4.8 Cuts and punctures

Cuts and punctures usually refer to tire damage by relatively sharp objects that penetrate into the tire or through the tire into the tire cavity. Some cuts and punctures are from objects that may also be considered an impact or road hazard injury, the resulting damage from which is addressed in a subsequent section.

Cuts and punctures that are small, at the time they enter the tire, cause an opening in the tire that extends partially or completely through the tire. The damage to the tire is localized and does not initially affect the structure of the tire beyond the immediate area. Obviously, the primary concern with a puncture through to the tire cavity is the loss in inflation pressure that inevitably occurs, if not immediately. If the hole does not penetrate into the cavity, the potential for, and manner of, any tire failure depends on the location and size of the hole and whether moisture or other contamination can enter into the tire structure through the opening. If the hole is large or in a high stress/strain area, such as the steel belt edge or upper sidewall, the hole can grow in size to a point where a rupture of the tire occurs. For tread penetrations, contact pressure between the tire and road can drive moisture and other contaminants further into the tread and belt structure—i.e. along the steel cords—causing corrosion and an adhesion failure separation, ultimately failing in a manner such as tread/belt detachment.

If the hole penetrates into the tire cavity, the tire must be discarded unless it meets the criteria for puncture repair set by the tire manufacturer or RMA [25, 26]. If a repair is performed against recommendations and the tire is returned to service, it is likely that the repair will be inadequate or fail, as discussed in the following section.

When a tire is operated with an unrepaired cut/puncture that extends into the cavity, the tire is likely to fail as a result of underinflation, intracarcass pressurization, or a combination of these. Underinflation occurs statically and/or dynamically when the puncturing object comes out of the tire or it does not completely seal the hole allowing air to escape to the atmosphere. As previously addressed, intracarcass pressurization occurs when the hole is not sealed within the tire cavity, i.e. at the innerliner, but is sealed or partially sealed from the atmosphere. In this situation, air is forced into the tire structure causing a pressurization of the tire carcass itself, leading to separation and failure.

4.9 Improper repair

Improper repairs typically fall into two categories: repairs that were made after the tire was excessively damaged in service and repairs that were performed against tire manufacturer or industry recommendations. If a repair is not done in a timely manner, the tire can be damaged through continued use in an underinflated condition and/or from air migrating into the structure around the object causing intracarcass pressurization. In this situation, no matter how well the puncture repair is made, internal separation or other structural damage cannot be repaired and may certainly progress until the tire fails in service. Thus, careful inspection of the tire for externally apparent signs of damage to the tire structure, including an examination of the cavity/innerliner, is required prior to performing a repair.

Once a tire has been determined to be suitable for repair, if proper procedures and repair materials are not utilized, the tire is more likely to fail after returning to service. For instance, current industry recommendations stipulate that passenger and light truck tire repairs should only be made if they are in the central portion of the tread region of the tire, excluding the shoulder ribs. In addition, the puncture hole should be no greater than 6.4 mm (0.25 inch) in diameter [25]. If the hole is larger, it is likely that structural damage has occurred that weakens the tire or that even after the hole is filled, moisture or other contamination will enter into the tread and belt structure causing the adhesion to break down. If structural damage, such as broken steel cords, is large enough, the tire is likely to rupture at the repair location as in Figure 15.18(a/b).

A puncture hole must be filled with a plug material and sealed with a patch on the innerliner surface. Without a patch, as in Figure 15.19(a), air can migrate into the tire structure causing intracarcass pressurization. If the hole is not filled, as in Figure 15.19(b), moisture or other contaminants can migrate into the tread and belt structure from the external environment and cause a breakdown of adhesion.

Even when the proper materials are used, if repair procedures are not followed properly, the tire can be damaged further and lead to a failure. For example, in Figure 15.20, excessive buffing of the innerliner has exposed the polyester body cords; this condition permits air to migrate into the tire structure causing intracarcass pressurization.

Figure 15.18: Excessive puncture damage with rupture at repair location

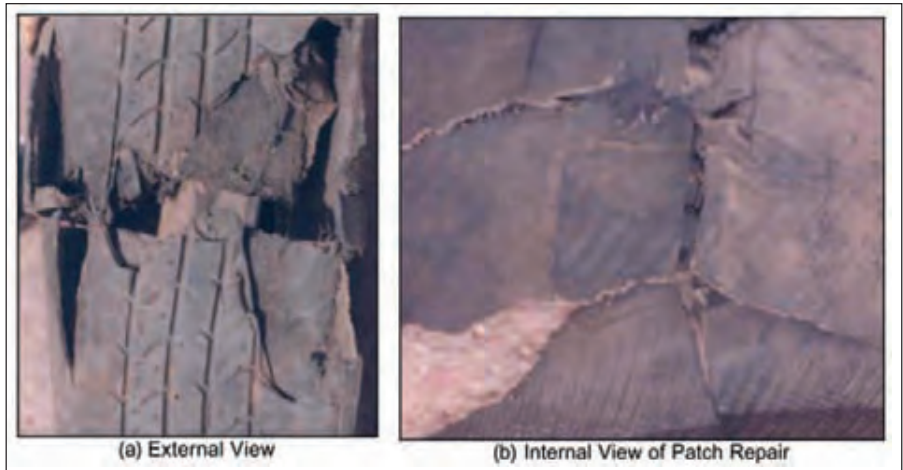


Figure 15.19: Examples of improper puncture repair

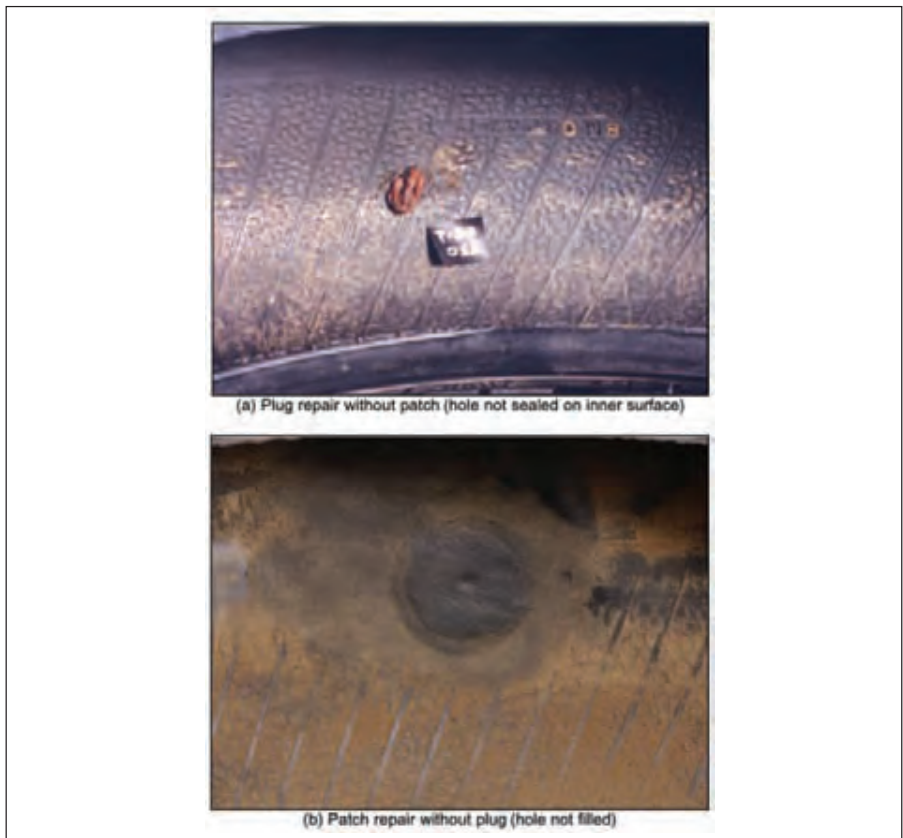
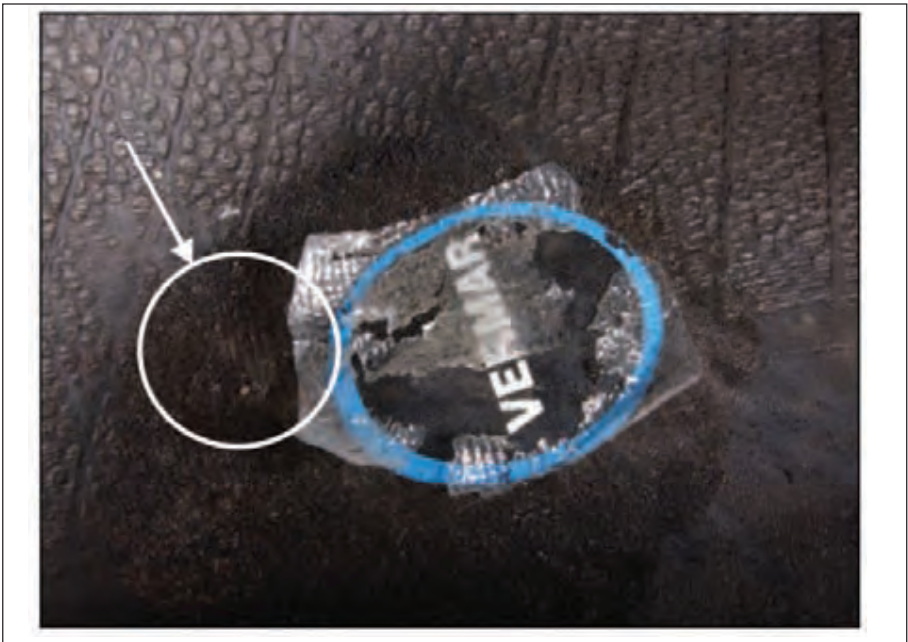


Figure 15.20: Excessive buffing has exposed polyester cords

4.10 Impact / road hazard

Tire impacts, or road hazard injuries, are one of the most common initiators of tire failures [27]. They occur when a tire operating in service encounters an object or irregularity in the roadway. Despite the improvements in highway design and maintenance over the years, studies have found that debris clutters highways throughout the United States [28]. In addition, deterioration of the roads and highways themselves present obstacles that tires can hit while in service. A resulting road hazard-related tire failure can occur immediately, or hundreds or thousands of miles after the impact. When a tire strikes a relatively small object such as a nail, the tire is likely to be punctured, as previously addressed. When the object is larger, what happens to the tire depends on several factors:

- The size and shape of the object.
- The texture and sharpness of the object.
- The orientation of the object and tire; where and at what angle the object impacts the tire.
- The inflation pressure in the tire and the load on the tire.
- The rate at which the object deforms the tire.
- The degree of damage that occurs to the tire structure during the impact and how that damage propagates or grows over time if the tire remains in service.

From an engineering point of view, impact damage is simply the result of energy imparted to the tire. One must therefore understand how the structural elements of a tire are loaded and how that loading changes when the tire attempts to absorb the energy of an impact.

The body cords, belt cords, beads and any other reinforcing materials in the tire are under tension due to the inflation pressure [29]. When a tire is loaded and deflected, cor-

nering and other loads are superimposed on the inflation loads [30]. When a tire encounters an object or irregularity in the roadway such as a pothole, rock, or other debris, the part of the tire (i.e. tread, sidewall) that comes in contact with the object attempts to take the shape of the object by deforming around it. Hence, the initial orientation of the reinforcing cords and rubber must change to accommodate or envelope the object. Moving a reinforcing cord relative to its rubber matrix has been studied in the laboratory by pulling cords (steel, polyester, etc.) out of rubber pads or other configurations. The results of such testing depend on the rate and degree of strain applied to the cord and its surrounding rubber material. At lower strains, the cord rubber matrix changes shape and no damage occurs. At higher strain levels, the cord or the rubber matrix fractures. For a group of cords, a combination can occur. Figure 15.21 shows the results of a steel cord pull test from a rubber block matrix; in this case the cord fractured.

Figure 15.21: Steel cord tensile pull test, resulting in cord fracture



The same phenomenon can occur in a tire during an impact [31]. The additional stress/strain loading imparted by an impact is different for different cords within the same tire. Thus, after an impact injury, a unique damage pattern will exist in the tire. In some cases the damage pattern will be so extensive that a hole will be present and an immediate loss of air will result, as in Figure 15.17. In other cases, the tire will be damaged internally, but capable of continued operation until it fails sometime after the impact.

If, when, and how the tire fails depends on the initial damage pattern and the type and severity of the subsequent operation. The failure modes can be as diverse as the damage pattern. They can be localized to the impact area or spread circumferentially around the tire. If the impact causes a tear between the belts, broken cords, or a combination of these, the damage can propagate and result in a tread/belt separation or detachment.

In some cases, an opening or radial split of the tire cavity, particularly the innerliner, will occur at the time of the impact. Over time, air will migrate through the split into the tire causing intracarcass pressurization (previously addressed). The tire can subsequently fail from a tread/belt detachment or other related failure mode.

Rarely is the object that the tire impacted available for inspection or the cord loading and orientation at the time of the impact known. Impact failures are analyzed by examining any damage the impact caused, such as rubber tears, fractured steel cord as in Figure 15.22, broken body ply cords, radial splits, propagation patterns, surface damage to the tire, and wheel deformations.

Figure 15.22: Broken steel cords of a stabilizer (steel belt) ply



4.11 Tire defects

The word “defect” has different meanings to different people depending on the context. For example, a police officer investigating an accident might refer to a worn out tire or an impacted tire as a “defective” tire, even though the tire was designed and manufactured flawlessly. Lawyers and judges attach a legal meaning to the word “defect.” Hence, care should be used when using the word so that the intent is clear. Modifiers in front of the word such as “manufacturing” will make the meaning clearer. In some cases, engineers use words such as “anomaly” to avoid confusion.

A tire design defect usually refers to a defect that occurs in a tire during the design and development phase of the tire. In other words, the tire was manufactured in compliance with the specification and allowable manufacturing tolerances, but still has a defect. A tire manufacturing defect usually refers to a defect that occurs during the manufacturing process. In other words, the tire was properly designed and developed, but during production it deviated from the design specification and/or allowable manufacturing tolerance.

Design and manufacturing defects generally fall into two categories: those that affect the performance of the tire and those that affect other things such as the appearance of the tire. The categories that affect the performance of the tire include those that are safety related and those that are not. Missing or misplaced components, improper vulcanization, and foreign material are examples of manufacturing defects. However, whether a defect such as a misplaced component is a performance or safety related issue depends on where and how the components are misplaced.

Because the major tire manufacturers have been in business for decades and have extensive research, design, development, manufacturing, and quality control activities and procedures—and employ thousands of specially trained scientists, engineers, and production personnel—design and manufacturing defects in tires are extremely rare. Because of this, defects tend to be one-of-a-kind occurrences and are typically evaluated accordingly.

4.12 Bead breakage / mounting accidents

Mounting accidents are rare, but occasionally occur when safe mounting procedures are not followed. An accident of this nature typically happens when a tire bead ruptures during the initial inflation process to seat the beads on a rim. Safety procedures in effect to prevent injury are designed to prevent a bead from breaking in the first place, and to protect a person in the event that a bead does break.

Typical passenger and light truck tire beads are constructed of one or more strands of bronze plated steel wire formed into a hoop called the bead bundle. When the tire is operating in service, the bead bundle is fully seated on the rim and all the wires in the bead bundle are ideally carrying an equal share of the load. Thus, the total strength of the bead bundle is equal to the sum of the strength of the individual bead wires.

During the mounting process of a tire on a drop center rim, the beads must move from the drop center of the rim to the bead seats of the rim. This process is called bead seating and is accomplished through increasing inflation pressure, which pushes the beads onto the bead seat area of the rim. If this process is impeded because of a lack of centering, improper lubrication, a corroded rim, an improper diameter rim for the tire, etc., the bead can become “hung up” and fail to seat properly. In this situation, the circular bead bundle will attempt to straighten (chord) in the location of obstruction. Because the length of a chord is different from the segment of the circle that includes the wires within the bundle, the individual wires will attempt to assume different lengths. As this occurs, the loading on the wires will vary and the strength of the bundle is lowered to the strength of the strand of wire with the highest load. If that wire breaks because the inflation pressure is excessive, the load shifts to the next wire, and so on, until the entire bundle ruptures. When the bundle ruptures, the bead goes over the flange and a person may be injured if they are in the trajectory of the tire/wheel assembly.

In the proper mounting of a passenger or light truck tire, the pressure should never exceed 40 psi to seat a bead. If this rule is followed, the bead will not break even if the tire is in a “hung up” condition. During the bead seating process, the operator should stand clear of the trajectory of the tire/wheel assembly by using a clip-on inflation chuck and an in-line inflation gauge with the tire in a safety cage or secured to the mounting machine. In addition, the components must be matched properly (i.e. 16” tire mounted to a 16” rim), and be clean and free of corrosion, and the beads must be well lubricated and centered before an attempt is made to seat them [6 - 8].

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Attachment E

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The P

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Bibliographic Record - OCLC Number: 862786102

LDR Record Status 'c' - Corrected or revised
 Type of Record 'a' - Language material
 Bibliographic Level 'm' - Monograph/Item
 Type of Control ' ' - No specified type of control
 Encoding Level 'M' - Added from a batch process
 Descriptive Cataloging Form 'i' - ISBD punctuation included

001 862786102
 005 20240721002116.3
 008 Date Entered on File '130128'
 Type of Date/Publication Status 't' - Publication and copyright date
 Date1/Beginning Date of Publication '2013'
 Date2/Ending Date of Publication '2013'
 Place of Publication, Production, or Execution Code 'mau' - Massachusetts
 Illustrations 'a '
 Target Audience ' ' - Unknown or unspecified
 Form of Item ' ' - None of the following
 Nature of Contents Code 'b '
 Government Publication ' ' - Not a government publication
 Conference Publication '0' - Not a conference publication
 Festschrift '0' - Not a festschrift
 Index '1' - Index present
 Literary Form '0' - Not fiction
 Biography ' ' - No biographical material
 Language Code 'eng' - English
 Modified Record ' ' - Record is not modified
 Cataloging Source Code 'd' - Other

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 ment of Chemistry, University of Cincinnati, Cincinnati, OH 45221-0172, USA, C. Michael Roland, N
 aval Research Laboratory, Chemistry Division, Code 6120, Washington, DC, USA.

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 504 Includes bibliographical references and index.
 650 0 Rubber.
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 650 6 Caoutchouc.
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 700 1 Mark, James E., **\$d** 1934- **\$e** editor. **\$1** <https://id.oclc.org/worldcat/entity/E39PBJvMDWjwRTMf3px9Vk3WjC>
 700 1 Roland, C. M. **\$q** (Charles Michael), **\$d** 1952- **\$e** editor. **\$1** <https://id.oclc.org/worldcat/entity/E39PCjF3G3V8PmHYvRkkgQmBMX>
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082 04 678.2|223
245 04 The science and technology of rubber.
250 Fourth edition /|bedited by James E. Mark, Burak Erman,
Mike Roland.
264 1 Oxford :|bAcademic,|c2013.
300 xiv, 786 pages :|billustrations ;|c24 cm
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336 still image|2rdacontent
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338 volume|2rdacarrier
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Attachment H

Know Your Tires with Tire-Track™

Improve Safety • Manage Tire Maintenance • Track Tire Performance
Ensure Maximum Tire Life • Avoid Vehicle Downtime • Reduce Tire Costs



Tracking Systems LLC

Your cargo is valuable – whether you haul freight or a bus load of first graders

Make certain your cargo reaches its destination safely and on time by ensuring your fleet's tires are properly maintained and managed. Tire-Track™ is a fully-integrated tire identification and tracking system that helps manage your fleet's tires – to avoid tire failures, predict tire maintenance, and reduce emergency roadside repair.

The complete system includes:

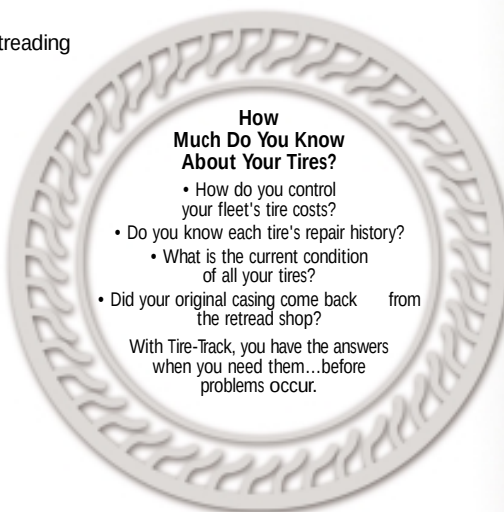
- Tire-Track ID Units
- Software
- Handheld Scanners
- Installation, Training, and On-going Technical Support

The Tire-Track System captures important information for managing your fleet's tires, stores it, and communicates it in a customized report – whenever you need it.

- Track the repair history of every tire in your fleet
- Control tire expenses
- Justify purchasing costs
- Reduce average operating costs
- Manage tire costs for an entire fleet
- Report on the current condition of all your tires
- Issue work orders
- Identify your original casing after retreading
- Formulate tire comparison reports

Protect your tire investment

Tires and associated service costs make up the second largest expense in a fleet's budget. Tire-Track allows you to identify the specific reason a tire needs to be serviced and record that service into the tire's history.



Get the most out of your tires

Tracking performance is an essential part of ensuring maximum tire life. Tracking means following a tire from cradle to grave, citing service history to tread wear. Tire-Track delivers an analysis program that helps you identify the causes for tire failure, evaluate tire performance from multiple vendors or models, and review relationships between vehicle type and tire performance.



Tire-Track™ System

The Tire-Track ID Unit:

- Permanently bonds to new or used tire casings
- Resists fading, staining, and will not wear off
- Applies easily without heat or expensive tools

The Tire-Track System starts with the Tire-Track ID Unit, a permanent label containing a unique serial number that can be read electronically. The Tire-Track ID is applied to the sidewall of each tire casing, and contains an engraved barcode with corresponding eye-readable backup information. Add your company's name for fast identification, or to deter theft or substitution.

Available Bar Codes:

Code 39 2-D Data Matrix
Code 128 a,b,c PDF-417
i2 of 5



The barcode is cut deeply into the rubber for permanent identification, so it cannot wear off.

Tire-Track™ Software/Operating System

The Tire-Track software is easy to use and installs on your existing office computer. The software utilizes the Palm OS (the standard operating system for mobile applications) that interacts with the scanning device to download data of all of the events and activities for every tire. The software interacts with the user to ensure your information is always accurate.

Design your own Tire-Track system to fit your organization. Choose from the criteria below, or create your own:

- | | |
|---|------------------------|
| • User ID | • Vehicle Type |
| • Mileage | • Tire Brand Name |
| • Tread Type | • Tire Size |
| • Tire Cost | • Tread Depth |
| • Tire Position on the Vehicle/Rotation History | • Air Pressure |
| • Repair History | • Location of Activity |
| | • Warranty Information |



Hardware Components



1. Handheld Scanning Device – Reads the Tire-Track bar code on the tire and saves data. These scanning units are designed specifically for the transportation industry. Tire-Track is compatible with the latest Symbol™ Scanners or any handheld system supporting Palm OS v 3.0 or greater.
2. Scanner Cradle – Imports or exports data and charges the scanner when not in use. Wireless Local Area Networks (WLAN) can be incorporated with Tire-Track to improve the efficiency of importing and exporting data.

Outfit your entire fleet with no downtime!

The Tire-Track™ ID Unit can be applied to a new or used casing without removing the wheel or pulling the vehicle out of service. Tire-Track ID Units are not affected by the retreading process; the bond is actually improved.

*Apply the Tire-Track ID Unit just like a repair patch...**No Heat Required!***



Buff the tire surface.



Brush on cement.



Apply the Tire-Track ID Unit.

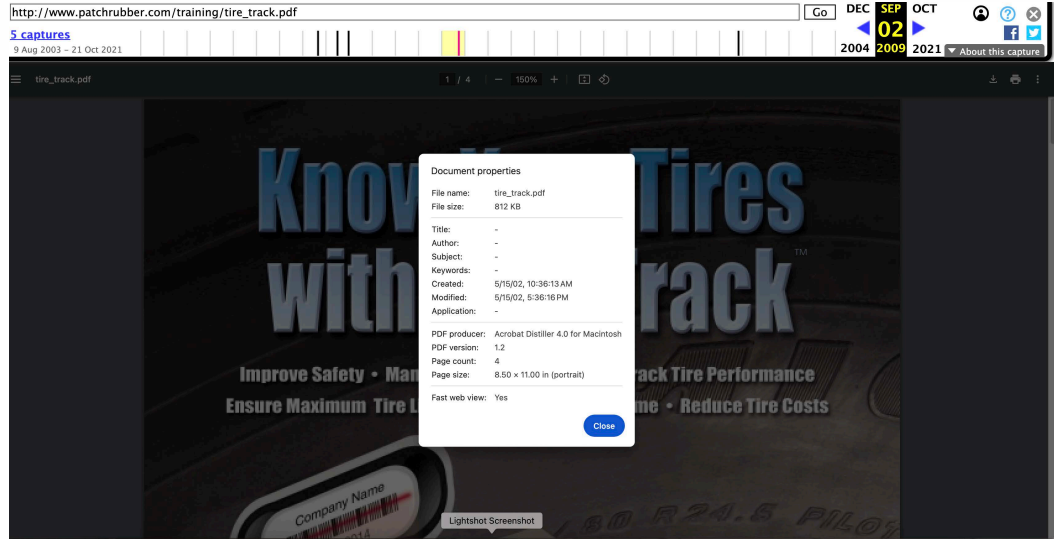
Tracking Systems LLC

Tire-Track – Know Your Tires!

Visit www.tire-track.com for more information.

The Tire-Track System is distributed by:

Attachment I



Attachment J

Reduce Your Tire Costs with the **TIRE-TRACK™ ID UNIT**

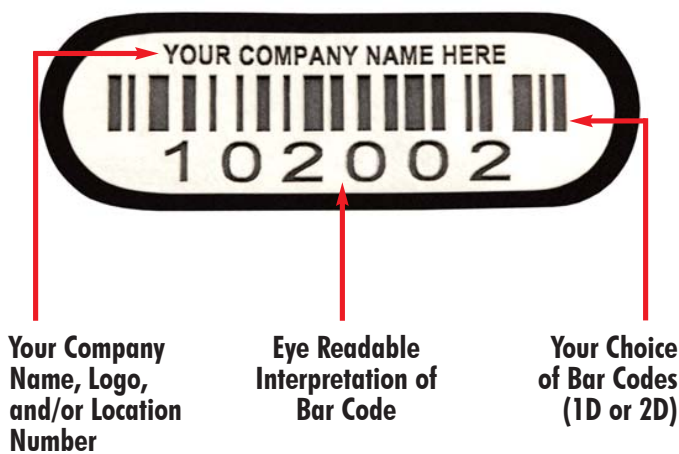
**Track Tire Performance • Track Cost per Mile / 32nd • Improve Inventory Control
Improve Purchase & Maintenance Decisions • Ensure Maximum Tire Life • Improve Safety
Avoid Vehicle Downtime • Improve Data Accuracy vs. Branding • Deter Theft**



Developed by
TIRE-TRACK, LLC



Actual Size



Your Company Name, Logo, and/or Location Number

Eye Readable Interpretation of Bar Code

Your Choice of Bar Codes (1D or 2D)

Whether you're hauling freight or a bus load of first graders... your cargo is valuable. However, that cargo won't reach its destination if your fleet's tires are not properly maintained and managed. Next to fuel, tires make up the single largest expense in a fleet's budget. It only makes good business sense to monitor these assets properly.

To help reduce your tire costs, TIRE-TRACK, LLC has developed the **TIRE-TRACK ID UNIT**™. The ID UNIT(S) are permanent, **all-rubber** bar code & RFID (optional) labels that serializes each tire

with a unique identification number to work with your fleet maintenance or tire program. Each ID UNIT contains a bar code with the corresponding human readable number, as well as your company's name and/or "unique identifier" for quick identification and to help deter theft or substitutions.

Why the **TIRE-TRACK ID UNIT**™ vs. tire branding or other bar code labels?

Tire branding is slow, expensive, dangerous and can damage the tire. In addition, it relies upon manual data collection/entry which is prone to error. Bar code data collection has proven itself for the past 20 years to be a more accurate, speedier process.

Silk-screened or ink printed tire identification labels have been available for some time. They are similar in that both products place "paint" or ink on the surface of the rubber. Their initial appearance is very good, however the image wears off easily.

The **TIRE-TRACK ID UNIT**™ is a **multi-layered** black & white rubber label specifically designed for tires & other harsh environments. The bar code and other information is engraved through the white rubber to expose the contrasting black rubber, so there's no "paint" or ink to rub-off. In addition, it resists UV light and won't "brown-out" like other bar code labels.

	BRANDING	INK or SILK-SCREEN PRINTED LABELS	TIRE-TRACK ID UNIT™
DOES IT PERMANENTLY SERIALIZE YOUR TIRES?	Yes	No	Yes
IS IT EASY TO READ?	No	Yes, providing the bar code has not worn-off	Yes
CAN INFORMATION BE READ ELECTRONICALLY?	No	Yes, providing the bar code has not worn-off	Yes
CAN IT SURVIVE RETREADING?	Yes	No	Yes
CAN IT WORK WITH YOUR EXISTING SOFTWARE PROGRAM?	Yes, information must be entered manually	Yes, providing the bar code has not worn-off	Yes
CAN IT DAMAGE THE TIRE?	Yes, if you brand too deep	No	No



WHICH ID UNIT IS RIGHT FOR YOU?



CVL-ID UNIT:

The **CVL-ID UNIT** is specifically designed for tires and is constructed similar to a repair patch. It is vulcanized to the tire "just like a patch" with cold-cure vulcanizing cement, or can be installed during the retread process. **The CVL-ID UNIT is intended for those fleets that retread their tires.**



SI-ID UNIT:

The **SI-ID UNIT** is designed for tires and many other surfaces (i.e. metal, wood, plastic, etc). It is bonded with industrial "superglue." The bond is incredibly strong, quick and easy to apply. **The SI-ID UNIT does not withstand the retread process; therefore it is intended for those fleets that do not retread their tires.**



DEMO KITS:

Demo Kits are available for both the CVL and SI Product(s). Each kit includes 15 samples and everything you need to properly apply them. (Contents may vary).

OPTIONAL



SAS:

For those customers who are interested in RFID technology, TIRE-TRACK, LLC offers the option of including an industry approved RFID chip in either ID Unit. The RFID chip is Gen2 compliant.



HARDWARE & SOFTWARE

If you do not currently have a Tire Tracking or Fleet Maintenance Program but are still interested, **TIRE-TRACK, LLC** has developed strategic partnerships with other leaders in the Fleet Software business that can provide you with both the appropriate hardware and software.

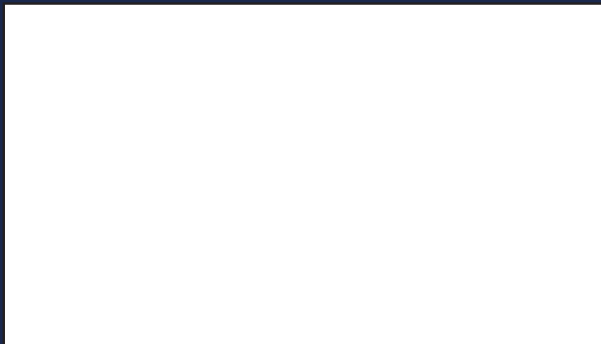
"FAMOUS QUOTES" FROM OUR CUSTOMERS

- *"I was able to show my boss that the more expensive tire to buy, was less expensive to own" . . . Laredo, TX*
- *"We tried every label possible, nothing works except the ID UNIT" . . . NYC, NY*
- *"You're inexpensive, easy and you work with what I already own" . . . Brooklyn, NY*
- *"So for about \$3, I can track my tires from cradle-to-grave using my existing program. What am I missing?" . . . Houston, TX*
- *"Tracking tires shouldn't have to be rocket science" . . . PB, FL*
- *"I never realized how many tires were being stolen" . . . Dover, DE*
- *"I've been able to reduce my inventory by almost 20%" . . . Allentown, PA*

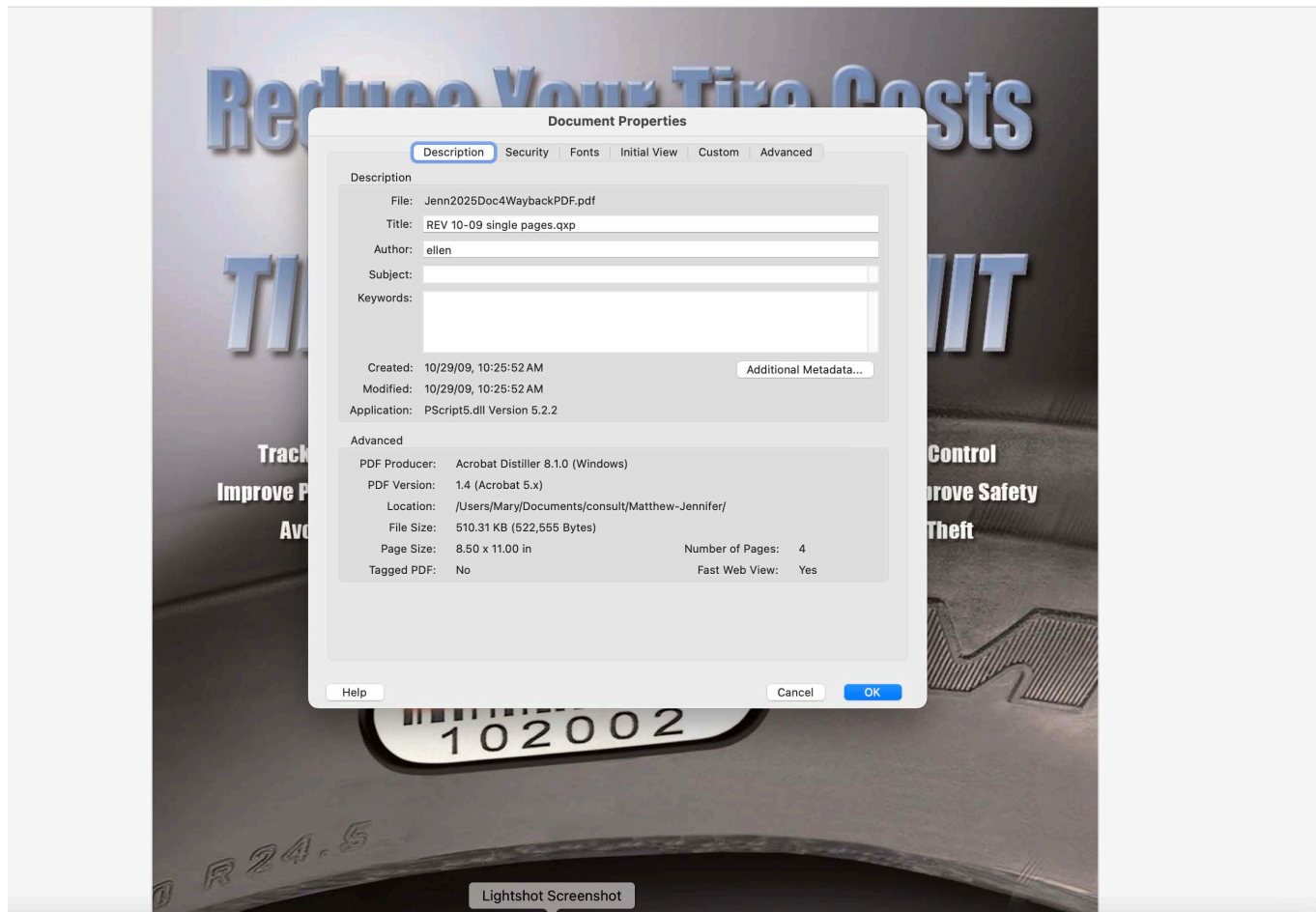
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For more information, please call:



Attachment K



Attachment L

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FAST-DRY CEMENT

Fast-Dry Self-Vulcanizing Cement eliminates the most common cause of failed repairs - lack of proper drying time. Fast-Dry Cement activates the chemical vulcanization process to bond repair units to the tire casing. **Flammable. Flash point -4° F. Shelf life 1 year.**

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16-450	1 Qt.	.94	11	5	6
16-451	8 Oz.	.25	7	3	12
16-452	1 Gal.	3.8	32	15	4



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