Using FT-IR Spectroscopy to Elucidate the Structures of Ablative Polymers

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The composition and structure of an ablative polymer has a multifaceted influence on its thermal, mechanical and ablative properties. Understanding the molecular level information is critical to the optimization of material performance because it helps to establish correlations with the macroscopic properties of the material, the so-called structure-property relationship. Moreover, accurate information of molecular structures is also essential to predict the thermal decomposition pathways as well as to identify decomposition species that are fundamentally important to modeling work. In this presentation, I will describe the use of infrared transmission spectroscopy (FT-IR) as a convenient tool to aid the discovery and development of thermal protection system materials.
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Outline

1. Introduction
   • Importance of polymer structure (Motivation)
   • FT-IR principle and technique

2. Applications
   • Detailed structural analysis of a phenolic polymer
   • Correlation among cure condition - crosslinking - thermal stability/char yield
   • Correlation between crosslinking - thermal oxidative decomposition mechanism
   • Diagnostic of a thermal decomposition product

3. Conclusion
Structure of Hemoglobin – How Nature Designs Its Materials

Unique sequence of amino acids

Held together by hydrogen bonding

Held together by hydrogen, ionic, sulfide bonding

Several peptide chains joined together

http://alevelnotes.com
Polymer Structure and Morphology

...influence key thermal, mechanical and ablative properties

Polymer matrix

Interface

Reinforcing fiber

Polymer structure and morphology (shape of a polymer)

How the polymer distributes around the fiber

Good morphology

Poor morphology
Techniques to Identify Polymer Structures

1. Nuclear Magnetic Resonance (NMR, both liquid and solid state)
   • Precise information of how atoms are bonded

2. FT-IR (Fourier Transform Infrared) transmission spectroscopy
   • Identify polymer structures, in particular polar functional groups, crosslink degree, crystalline region

3. Raman spectroscopy
   • Identify non-polar groups, such as olefinic groups (as in graphitic species)

4. Mass spectrometry
   • Information about fragments/groups, fragmentation modes

5. XPS (x-ray Photoelectron Spectroscopy)
   • Information about elements and functional groups on a surface
Main advantages of FT-IR
- Speed
- Sensitivity
- High spectral accuracy and resolution
- Internally calibrated
- Mechanical simplicity
- Easy sample preparation and operation
FT-IR spectroscopy: Theory

Vibrational modes of a -CH2 group

Symmetrical stretching
Twisting
Wagging
Scissoring
Rocking
Asymmetric stretching

Vibrational transitions absorb discrete energy levels unique to a molecule

http://en.wikipedia.org/wiki/Fourier_transform_infrared_spectroscopy
To chemists, a FT-IR spectrum is like a pair of eyes looking into a molecule.

The intensity, shape, width and location of a peak all reflect the specific local environment the group is in.
Curing Chemistry of Phenolic Resin

Phenolic resin (resole)  Phenolic Network polymer

A typical reaction in network formation
Textbook example and extremely informative
Absorption peaks can be easily assigned to corresponding groups
Quantitative estimation of the degree of crosslinking is possible.
Region 1: 4000cm\(^{-1}\) - 2700cm\(^{-1}\)

3500cm\(^{-1}\): Phenolic OH
3040cm\(^{-1}\): aromatic \(sp^2\) C-H
2940cm\(^{-1}\): Aliphatic \(sp^3\) CH\(_2\) asym. Stretch
2860cm\(^{-1}\): Aliphatic \(sp^3\) CH\(_2\) sym. stretch
Region 2: 1700cm\(^{-1}\)- 1000cm\(^{-1}\)

\[ \text{I}_{\text{CH}_2}/ \text{I}_{\text{C=C}} \text{ can be used to semi-quantitatively measure the crosslinking degree} \]
Region 3: 900cm\(^{-1}\) - 700cm\(^{-1}\)

Most highly crosslinked

1,2-ortho-
1,6-para
1,2,4-ortho, para, 1,2,6-ortho, ortho-

1,2,4,6-ortho, para, ortho-
Experiments: phenolic resin was cured under three different conditions, each with increasing temperature and cure time.

Condition 1, Condition 2, Condition 3

Temperature and cure time increases
FT-IR of Cured Phenolic Polymers

Change of intensity in multiple peaks indicates the progress of curing (more crosslinking).
Thermogravimetric Analysis (TGA) (in Nitrogen, 20°C/min.)

Char yield correlates with degree of polymer crosslinking
Weight% increases with increased crosslinking
Decomposition of Phenolic – Char Forming Mechanism

Virgin polymer structure dictates the decomposition pathways and char yield

Char structures were characterized by solid state $^{13}$C NMR

Substructures of graphitic/carbon char

Amorphous carbon char
Application 2: Identifying a Decomposition Process

-CH₃ group formed
- Lower degree of crosslinking

Yellow “cake” below
Dark surface “crust”
Thermal Decomposition in Vacuum

Likely Pathway

- Lower degree of crosslinking
- –CH₃ group formed

Model polymer was cured in nitrogen and at an elevated temperature (close to the oven condition)
A Bottom Up Approach to TPS Materials Discovery

- A thorough understanding of chemistry/molecular structure is key
- Most of these correlations have been obtained by experiments
Advantages and Limitations

Advantages:
1. Convenient, low cost, speedy
2. Excellent tool for first screening of polymer structures and identification of unknowns
3. Useful for predicting reactivity and physicochemical properties, as well as interpreting decomposition mechanisms and products
4. Routinely used at Ames for qualitative determination of new polymer structures as well as analyzing curing products
5. Can be coupled with TGA to study thermal decomposition products (TGA-IR)

Limitations:
1. Mostly qualitative, does not provide precise molecular structures
2. Can be semi-quantitative with the right software
3. Not all polymers have well-resolved absorption peaks in the IR region (overlaps, weak absorptions)
Using TGA-FT IR to Monitor Gas Phase Products

- TGA-IR allows the gas phase products to be collected continuously as a function of temperature.
- Gas phase infrared spectra are much sharper than condensed phase spectra, and recognition of the individual molecules is possible.

http://www.uclan.ac.uk/schools/forensic_investigative/fire_hazards_science/equipment_tests/tga_ftir_magna.php

http://cnx.org/content/m23038/latest/
Contributors

Tane Boghozian, Ehson Ghandehari, Firouzeh Mohadjerani, Jeremy Thornton

Acknowledgement

Hypersonics group of
Thermal Protection Materials branch,
NASA Ames Research Center

Funding

Hypersonics
EDL-TDP