LECTURE 2

Structure and Properties of Polymer Composite Materials

Microstructural Architecture, Reinforcement Physics, and Advanced Performance Dynamics

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Lecture Overview: Plan, Aim & Key Tasks

Lecture Plan

1. Classification: Matrices & reinforcement geometry

2. Interphase: Stress transfer & interfacial shear

3. Mechanics: Micromechanics & anisotropy

4. Processing: Autoclave, RTM & 3D printing

5. Degradation: Environmental & fatigue behavior

Lecture Aim

To examine the relationships between polymer matrix molecular architecture, reinforcement phase morphology, and resultant mechanical, thermal, and electrical properties in advanced engineered composite systems.

Key Learning Tasks

Classify: Polymer matrices & fibrous fillers

Evaluate: Interfacial adhesion mechanisms

Calculate: Composite elastic moduli

Correlate: Microstructure with fracture modes

Core Principle: Composite performance is governed not just by component properties, but by the synergy created across the interphase region.

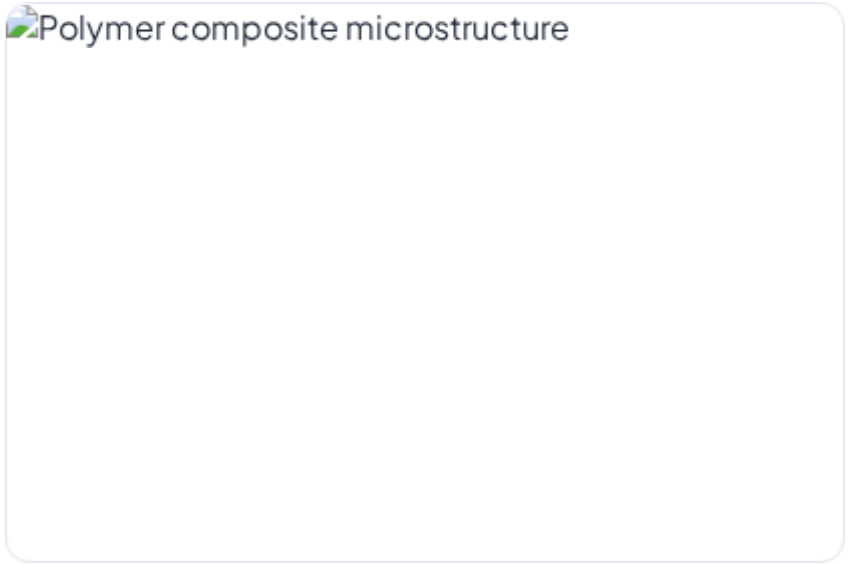
Fundamentals of Polymer Composites

Multi-phase material systems produced by combining a continuous polymer matrix with a discontinuous reinforcing phase.

The polymer matrix transfers load and protects fiber surfaces, while the high-modulus reinforcement provides stiffness, load-bearing capacity, and directional strength.

Continuous Matrix
Thermoset or Thermoplastic Resin

Reinforcing Phase
Particles, Whiskers, Fibers, or Fabrics



Key Advantage: High specific strength (strength-to-weight ratio)

Designability: Tailorable anisotropic mechanical profiles

Polymer Matrix Classification

Thermosetting Resins

Epoxy, Polyester, Vinyl Ester, Polyimide

- Permanent 3D cross-linked covalent network upon curing.
- Exceptional dimensional stability and high creep resistance.
- Low melt viscosity facilitates easy fiber wet-out.

Thermoplastic Resins

PEEK, PEI, PPS, Polyamide (Nylon)

- Linear or branched polymer chains bound by Van der Waals forces.
- Reversible thermal re-melting permits rapid thermoforming.
- High fracture toughness and recyclability potential.

Performance Threshold: High-temperature thermoplastics (e.g., PEEK) retain stiffness up to 250°C.

Reinforcement Phase Morphology

Morphological Taxonomy

Particulate Filled

Aspect Ratio ≈ 1

Spheres, silica, calcium carbonate. Provides isotropic property enhancement and cost reduction.

Discontinuous Short Fibers

Aspect Ratio 10 - 100

Chopped glass/carbon strands. Suitable for high-speed injection molding processing.

Continuous Long Fibers

Aspect Ratio > 1000

Unidirectional tows and woven fabrics. Maximum structural efficiency along fiber axes.

Critical Dimension Rule: Fiber length must exceed critical length (lc) for efficient stress transfer.

High-Performance Reinforcing Fibers

Carbon / Graphite Fibers

PAN-based: High tensile strength (3.5 – 7.0 GPa).

Pitch-based: Ultra-high elastic modulus (up to 900 GPa).

Turbostratic Structure: Graphitic basal planes aligned along axis.

Glass & Aramid Fibers

E-Glass: Low cost, general electrical insulation.

S-Glass: High strength magnesium-alumino-silicate formula.

Aramid (Kevlar): Para-aramid chains with extreme impact energy absorption.

Structural Parameter: Fiber diameter (5–15 μm) dictates matrix-to-fiber surface area contact ratio.

The Interphase Region

3D Gradient Transition Zone

The interphase is a distinct 3D region surrounding the fiber with physical, chemical, and mechanical gradient properties differing from both bulk matrix and bulk fiber.

Sizing Agents: Chemical couplings applied to fiber surface.

Interfacial Shear Strength (IFSS): Primary indicator of load transfer capability.

Transcrystallinity: Preferential matrix crystallization at fiber boundaries.

Key Mechanism: Interfacial debonding precedes ultimate composite tensile fracture.

Interfacial Adhesion Mechanisms

Covalent Coupling

Silane agents (e.g., γ-MPS) bridge inorganic glass fiber silanols to polymer matrix.

Physical Wetting

Low contact angle liquid polymer spreads completely over fiber surface micro-cavities.

Mechanical Friction

Surface etching or plasma oxidation creates micro-roughness for mechanical keying.

Failure Boundary: Weak adhesion causes fiber pull-out; excessively strong adhesion yields brittle crack propagation.

Micromechanics: Rule of Mixtures

Longitudinal Modulus (Iso-Strain Model)

$$E_1 = E_f \cdot V_f + E_m \cdot V_m$$

Transverse Modulus (Iso-Stress Model)

$$E_2 = (E_f \cdot E_m) / (E_f \cdot V_m + E_m \cdot V_f)$$

Variable Definitions

E1, E2: Composite longitudinal and transverse tensile moduli.

Ef, Em: Moduli of fiber and matrix phases.

Vf, Vm: Volume fractions of fiber and matrix (Vf + Vm = 1).

Limitation: Halpin-Tsai semi-empirical equations are required for short aligned fibers.

Anisotropy & Laminate Mechanics

Isotropic

Properties identical in all directions (unreinforced polymers, spherical particulate fillers).

Orthotropic

Three mutually perpendicular planes of material symmetry (unidirectional fiber lamina).

Quasi-Isotropic

Multi-angle laminate stacking sequence [0°/±45°/90°]s yielding isotropic in-plane stiffness.

Classical Laminate Theory (CLT)

Relates membrane forces and bending moments to mid-plane strains and curvatures via the [ABD] stiffness matrix.

Critical Fiber Length (lc) Dynamics

The minimum fiber length needed for axial stress build-up to reach ultimate fiber tensile strength (σf*).

Critical Length Formula

$$l_c = (\sigma_f^* \cdot d) / (2 \cdot \tau_c)$$

Where **d** is fiber diameter and **τc** is interfacial shear yield strength.

Fiber Length Regimes

1. **l < lc:** Matrix shears; fiber matrix debonds before fiber fractures.
2. **l = lc:** Peak fiber stress exactly equals tensile strength at center.
3. **l >> lc:** Efficient continuous-like load reinforcement.

Processing Impact: Extrusion screw shear breaks fibers below lc if improperly controlled.

Fracture Mechanics & Toughening

Mechanism 01

Crack Deflection

Impeded crack paths twist around rigid particles/fibers, increasing total crack surface energy dissipation.

Mechanism 02

Fiber Bridging

Intact fibers span crack wakes, exerting compressive closing forces on propagating crack tips.

Mechanism 03

Fiber Pull-Out

Frictional work done withdrawing broken fiber ends from matrix sockets absorbs high impact energy.

Toughening Additives: Core-shell rubber (CSR) particles induce localized matrix shear yielding in brittle epoxies.

Thermal Properties & Glass Transition (Tg)

Polymer Chain Mobility Restriction

Strong attractive interactions between nanofillers and matrix chains immobilize segment rotation, elevating the effective glass transition temperature (Tg).

CTE Reduction: Low-expansion inorganic fillers decrease coefficient of thermal expansion.

Thermal Conductivity: AlN, BN, or graphene networks improve heat dissipation.

HDT Elevation: Heat Deflection Temperature shifts closer to polymer melting point.



Tg Elevation Range

+10°C to +35°C

Observed in well-dispersed polymer nanocomposites.

Analytical Tool: Dynamic Mechanical Analysis (DMA) measures storage modulus loss peak for Tg.

Electrical Properties & Percolation Theory

Percolation Threshold (ϕc)

The critical filler volume fraction where conductive particles (carbon black, CNTs, graphene) touch to form a continuous electrical transport path through insulating polymer.

Power-Law Conductivity Equation

$$\sigma = \sigma_0 \cdot (\phi - \phi_c)^t$$

Conductive Filler Aspect Ratios

Spherical Carbon Black: High threshold (ϕc ≈ 10–15 vol%).

Carbon Nanotubes (CNTs): Ultra-low threshold (ϕc < 0.1 vol%).

Applications: EMI shielding, antistatic coatings, piezoresistive sensors.

Transport Mode: Electron tunneling across thin (<2 nm) polymer interparticle barriers.

Processing: Autoclave Prepreg Curing

1. Prepreg Layup

Pre-impregnated fiber plies stacked manually or via Automated Fiber Placement (AFP).

2. Vacuum Bagging

Sealed flexible bag evacuates trapped air and volatile byproducts prior to heating.

3. Pressure Curing

Autoclave applies 3–7 bar gas pressure and 120–180°C heat profile for void consolidation.

Quality Metric: Void content maintained strictly below **1.0 vol%** for primary aerospace structural components.

Processing: Resin Transfer Molding (RTM)

RTM Process Steps

1. Preform Loading: Dry textile fiber preform placed inside matched rigid mold cavity.

2. Resin Injection: Low-viscosity thermoset resin pumped under controlled pressure (1–10 bar).

3. In-Mold Curing: Heat accelerates cross-linking followed by part ejection.

Darcy's Law Permeability Flow

Governs resin front velocity (v) through porous preform reinforcement:

$$v = - (K / \mu) \cdot (dP / dx)$$

K = Preform Permeability, μ = Resin Viscosity, dP/dx = Pressure Gradient

Advantage: Rapid cycle times suited for medium-volume automotive structural manufacturing.

3D Printing & Additive Manufacturing

Continuous Fiber 3D Printing (CFF)

In-Situ Co-Extrusion

Continuous carbon/glass fiber tow coated with molten thermoplastic (PA, PEEK) at print nozzle.

Toolpath Optimization

Algorithmic alignment of continuous fiber trajectories along principal stress vectors.

Inter-Layer Voids Challenge

Requires thermal compaction rollers to eliminate intra-filament gaps.



Strength Comparison

Continuous carbon printed parts exhibit **10x higher tensile strength** than unreinforced 3D printed polymers.

Future Direction: Multi-material robotic 6-axis spatial printing without support structures.

Non-Destructive Inspection (NDI/NDT)

Ultrasonic C-Scan

Reflected echo acoustic impedance shifts map defect depth.

High-frequency acoustic waves (1–10 MHz) detect internal delaminations, foreign object inclusions, and void clusters.

X-Ray Micro-CT

3D Volumetric Resolution: Resolves sub-micron micro-cracks.

Fiber Orientation Mapping: Quantifies 3D fiber spatial alignment vectors.

Void Density Quantification: Calculates precise volume fraction distribution.

Thermography Inspection: Active infrared thermography maps subsurface defects via differential heat dissipation rates.

Hygrothermal Degradation Mechanics

Moisture Absorption Pathways

Water molecules diffuse into polymer matrices via Fickian transport, disrupting hydrogen bonds between chain segments.

Plasticization & Debonding

Absorbed water causes matrix plasticization (reducing Tg by 20–50°C) and induces osmotic swelling stresses that rupture fiber-matrix interphase bonds.



Fickian Diffusion Model

$$M_t / M_\infty = 1 - \exp[-7.3(Dt/h^2)^{0.75}]$$

Predicts moisture mass uptake (Mt) over exposure time (t).

UV Degradation: Photo-oxidation degrades surface polymer layers, exposing reinforcing fibers to erosion.

Fatigue & Cyclic Damage Accumulation

4-Stage Fatigue Damage Progression

Stage 1: Matrix micro-cracking in off-axis plies (90° plies).

Stage 2: Crack coupling and inter-ply delamination initiation.

Stage 3: Interfacial debonding and localized fiber fracture.

Stage 4: Catastrophic fiber bundle rupture.

S-N Curve Behavior

Fatigue Limit: Up to 60–70% of ultimate static tensile strength.

Carbon fiber composites exhibit significantly flatter cyclic stress-life (S-N) curves than engineering metals (e.g., aluminum).

Stiffness Degradation Metric: In-situ elastic modulus monitoring tracks cumulative fatigue damage state.

Application: Aerospace & Automotive Structural Parts

Boeing 787 / A350

Over **50% composite weight fraction** (CFRP primary wing box, fuselage barrels) yielding 20% fuel efficiency gains.

Automotive Monocoque

Carbon fiber passenger safety cells in hypercars and EV battery enclosure trays for crash safety.

Wind Turbine Blades

Ultra-long (>100 m) hybrid glass/carbon Spar caps resisting aerodynamic flex fatigue.

Design Criterion: Replacing steel with CFRP achieves up to **60% mass reduction** while improving torsional rigidity.

Recycling & Circular Economy Challenges

Mechanical Recycling

Shredding & Milling

Grinds composite scrap into short fiber fillers for injection molding compounders.

Pyrolysis

Thermal Decomposition (500–700°C)

Burns off polymer matrix in inert atmosphere to recover clean carbon fibers with 90% strength retention.

Solvolysis

Supercritical Fluid Depolymerization

Chemical dissolution of polymer resin matrix to recover both intact fibers and virgin monomers.

Next-Gen Solution: Vitrimer thermoset resins containing dynamic covalent bonds that enable re-molding and chemical recycling.

Polymer Nanocomposites: CNTs & Graphene

Extreme Nanofiller Performance

Incorporating sub-100 nm carbon allotropes dramatically boosts mechanical, electrical, and barrier properties at ultra-low weight loadings (<1.0 wt%).

SWCNTs: Elastic modulus ~1 TPa, tensile strength 50–100 GPa.

Graphene Nanoplatelets (GNPs): 2D planar structure provides gas barrier tortuosity.

Dispersion Challenge: High surface area requires sonication or functionalization.

Key Barrier: Nanoparticle re-agglomeration via strong Van der Waals attractive forces.

Smart Composites & Autonomous Self-Healing

Auto

Microcapsule Self-Healing

Embedded dicyclopentadiene (DCPD) microcapsules rupture upon micro-crack propagation, contacting Grubbs catalyst to polymerize and seal damage autonomously.

Vascular

Vascular Healing Networks

Interconnected 3D microfluidic channels deliver liquid healing agents repeatedly to internal delamination sites.

Sense

In-Situ SHM Sensing

Embedded Fiber Bragg Grating (FBG) optical sensors monitor strain gradients and temperature in real-time.

Structural Health Monitoring (SHM): Real-time strain feedback eliminates costly scheduled teardown inspections.

Thank You for Your Attention

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