Composite Materials
(복합재료특론)

03 – Matrix Materials

Wonoh Lee

School of Mechanical Engineering, Chonnam National University

3-1. Role of Matrix in Composite Materials

1. To transfer stress into the reinforcements
2. To provide a barrier against environment
3. To distribute and protect the reinforcements
4. Control the electrical and chemical properties
5. Carry interlaminar shear stress

Desired Properties as Matrix in Composite Materials

1. Good wetting or bonding with reinforcements
2. High temperature capabilities
3. Excellent chemical resistance
4. Reasonable strength, modulus and elongation (elongation should be greater than that of fibers)
5. Low shrinkage
6. Low coefficient of thermal expansion
7. Low density
8. Low moisture absorption

3-2. Classification of Matrices

Matrix determines the maximum temperature limit

1)Metal Matrix	MMC	1093℃(2000°F)
2)Ceramic Matrix	CMC	1647℃(3000°F)
3)Polymer Matrix	PMC	429℃(800°F)
4)Intermetallic Matrix	IMC	

TABLE 2.8. Matrix Materials

Polymeric

- Thermoset polymers (resins)
  - Epoxies: principally used in aerospace and aircraft applications
  - Polyester, vinyl esters: commonly used in automotive, marine, chemical, and electrical applications
  - Phenolics: used in bulk molding compounds
  - Polyimides, polybenzimidazoles (PBI), polyphenylquinoxaline (PPQ): for high-temperature aerospace applications (temperature range 250–400°C)
- Thermoplastic polymers
  - Nylons (such as nylon 6, nylon 6,6), thermoplastic polyesters [such as polyethylene terephthalate (PET), PBT], polycarbonate (PC), polyacetals: used with discontinuous fibers in injection-molded articles
  - Polyamide-imide (PAI), polyether ether ketone (PEEK), polysulfone (PSUL), polyphenylene sulfide (PPS), polyether imide (PEI): suitable for moderately high-temperature applications with continuous fibers

Metallic

- Aluminum and its alloys, titanium alloys, magnesium alloys, copper-based alloys, nickel-based superalloys, stainless steel: suitable for high-temperature applications (temperature range 300–500°C)

Ceramic

- Aluminum oxide (Al_2O_3), carbon, silicon carbide (SiC), silicon nitride (Si_3N_4): suitable for high-temperature applications

3-3. Metal Matrices

1. General Properties : Good strength & modulus
   Excellent toughness
   Low-to-high density
   (Mg: 1.7 g/㎤ - W: 19.3 g/㎤)
   Good formability

Table 3.5. Mechanical properties of some common metals and alloys

	E (GPa)	σ_y (MPa)	σ_{max} (MPa)	K_{Ic} (MPa $m^{1/2}$)
Pure (ductile) metals				
Aluminum	70	40	200	100
Copper	120	60	400	to
Nickel	210	70	400	350
Ti-6A1-4V	110	900	1000	120
Aluminum alloys (high strength– low strength)	70	100–380	250–480	23–40
Plain carbon steel	210	250	420	140
Stainless steel (304)	195	240	365	200

Table 3.6. Density of some common metals

Metal	Density ($g\ cm^{-3}$)	Metal	Density ($g\ cm^{-3}$)
Aluminum	2.7	Lead	11.0
Beryllium	1.8	Nickel	8.9
Copper	8.9	Silver	10.5
Gold	19.3	Titanium	4.5
Iron	7.9	Tungsten	19.3

Metal : Work Hardening
Precipitation Hardening
Grain Size Strengthening
Solid Solution Strengthening

→ Increase in strength (Extrinic Property)
No change in modulus & density (Intrinsic Property)

MMC : Composite Strengthening Mechanism

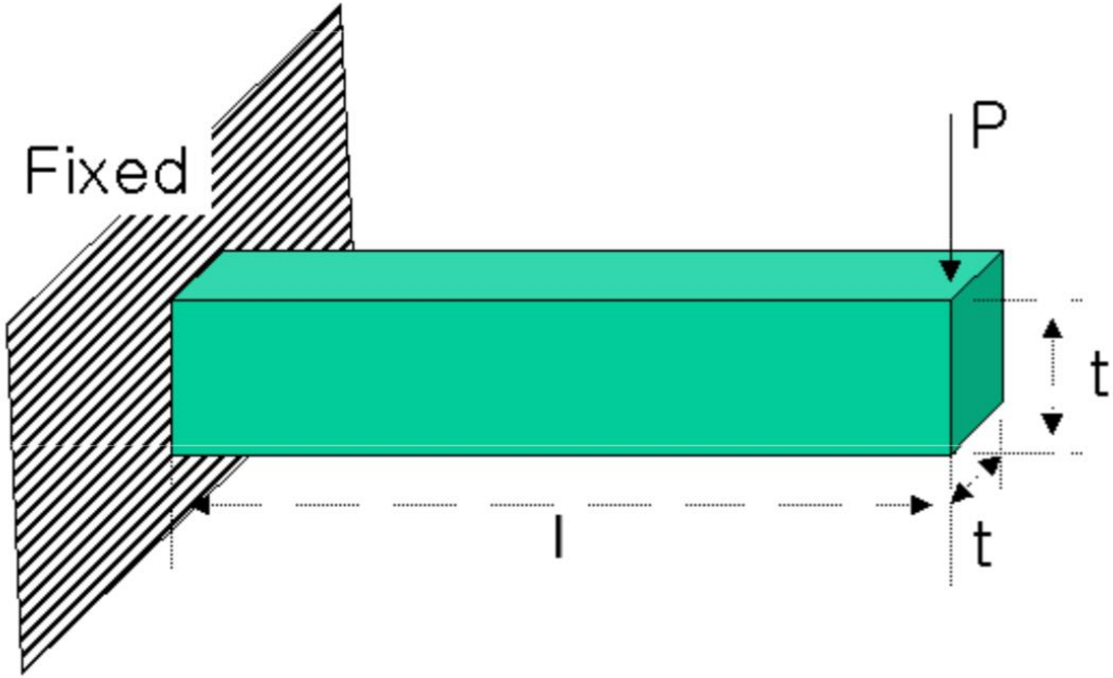
High strength
High modulus
Low density

fiber → Increase in specific strength & specific modulus at the same time

Structural Application

Needs to increase specific strength & specific modulus at the same time !

Elastic Deformation of Cantilever Beam



Elastic Deflection

$$\delta = \frac{Pl^3}{3EI} = \frac{4Pl^3}{Et^4}$$

Moment of Intertia

$$I = \frac{t^4}{12}$$

Mass $\quad M = lt^2\rho$

$$t = \left(\frac{M}{l\rho}\right)^{1/2}$$

$$\delta = \left(\frac{4\rho l^3}{E}\right)\left(\frac{l\rho}{M}\right)^2$$

$$M = \left(\frac{4Pl^5}{\delta}\right)\left(\frac{\rho^2}{E}\right)^{1/2}$$

For a given stiffness , P/δ, mass can be minimum when

$$\left(\frac{\rho^2}{E}\right)_{min} \quad \text{or} \quad \left(\frac{E}{\rho^2}\right)_{max}$$

$\Rightarrow$ High modulus & low density are needed !

(High specific modulus)

2. Important Metal Matrices

1) Al Alloys

B/Al, SiC/Al	
1100 Al (pure Al)	good impact resistance
2024 Al, 2124 Al, 7075 Al	good strength
6061 Al	good strength & corrosion resistance

2) Mg Alloys

Graphite/Mg, B/Mg	
AZ 91C	most popular sand and mold cast alloy
AZ 61A	

3) Lead Alloys

Graphite/Pb	to increase the strength of lead in chemical, battery, building application

4) Ti Alloys

Borsic/Ti, SiC/Ti	good strength up to ~600℃
Ti-3Al-2.5V	
Ti-6Al-4V	
Ti-13V-10Mo-5Zr-2.5Al	

5) Cu alloys

Graphite/Cu, W/Cu, Nb/Cu

High thermal conductivity - skin structure of space shuttle

electrical contact materials

6) Superalloys

W/Superalloy increase the high temp. stability

turbine blade

3-3. Ceramic Matrices

1. General Properties

Advantages : excellent strength & modulus
excellent high temp. stability
high corrosion resistance
low density

Disadvantages: hard and brittle ($\because$ ionic bonding - few slip systems)
low fracture toughness
low thermal shock & mechanical shock resistance

CMC SiC/Si_3N_4
increases in toughness → toughening mechanism

2. Important Ceramic Matrices

4-Types

1) Si_3N_4

SiC/Si_3N_4 strong, tough and oxidation resistant
low thermal shock resistance
→ advanced heat engine application

2) SiC

SiC_f/SiC strong, tough and oxidation resistant
high thermal conductivity
structural application up to ~1400℃
→ gas turbine engine for supersonic aircraft

3) Oxide

Al_2O_3 excellent high temperature stability
mulite
ZrO_2

4) Glass Ceramics

Lithium Aluminosilicate (LAS)
low thermal expansion coef. $\sim 1.5 \times 10^{-6}/K$

Table 3.7. Properties of some ceramic matrix materials

	Young's modulus (GPa)	Tensile strength (MPa)	Coefficient of thermal expansion (10^{-6} K^{-1})	Density ($g\ cm^{-3}$)
Borosilicate glass	60	100	3.5	2.3
Soda glass	60	100	8.9	2.5
Lithium aluminosilicate glass-ceramic	100	100–150	1.5	2.0
Magnesium aluminosilicate glass-ceramic	120	110–170	2.5–5.5	2.6–2.8
Mullite	143	83	5.3	
MgO	210–300	97–130	13.8	3.6
Si_3N_4	310	410	2.25–2.87	3.2
Al_2O_3	360–400	250–300	8.5	3.9–4.0
SiC	400–440	310	4.8	3.2

Source: Adapted with permission from Ref. 27.

3-4. Polymer Matrices

1. General Properties

Advantages: Low density (< 1.5 g/cm^3)
High corrosion resistance
Easy processing
Cheap cost

Disadvantages: Low strength (< 120MPa)
Low modulus
Low service temperature (< 400 ℃)
Moisture absorption → degradation, swelling
"Hygroscopy"
High CTE ($50\text{-}200 \times 10^{-6}$/K) → thermal expansion mismatch, internal stress
Poor electrical conductivity

2. Types of Polymers

1) Thermoset Polymers : cross-linked polymer structure

Become hard and rigid by heating

Decrease in stiffness and decompose above certain temperature

Brittle, failure strain 1-3%

Cannot reshaped by subsequent heating.

ex)epoxy, phenolic, polyester, polyurethane, silicon, rubber

2) Thermoplastic Polymers : linear polymer structure

Become soft and melt by heating

Can repeatedly softened or hardened by heating or cooling

Better high temerature capability and fracture toughness than thermoset polymers.

Ductile, failure strain 30-100%

ex)polyethylene, polystyrene, polymethyl methacrylate (PMMA), polyetherether ketone(PEEK)

3. Important Polymer Matrices

1) Thermoset Matrices

Epoxy

Advantages : service temperature up to ～180℃
better moisture resistance
lower shrinkage (～3%) than polyester on curing
good bonding with glass fibers

Disadvantages : brittle
low fracture toughness
more expensive than polyester

Polyester

Advantages : good corrosion and moisture resistance
very low cost
good bonding with glass fibers

Disadvantages : limit to applications up to 80℃
larger shrinkage (4～8%) than epoxy on curing

Polyimide

higher service temperature up to ～300℃
low fracture energy 15-70 J/m^2

Bismaleimide

service temperature ranged 180-200℃
good resistance to hygrothermal effect

Table 3.1. Some important characteristics of epoxy

Density, ρ ($g\ cm^{-3}$)	Strength, σ (MPa)	Modulus, E (GPa)	Poisson's ratio, ν	CTE α ($10^{-6}\ K^{-1}$)	Cure Shrinkage (%)	Use Temp. (°C)
1.2–1.3	50–125	2.5–4	0.2–0.33	50–100	1–5	150

Table 3.2. Some important characteristics of polyester

Density, ρ ($g\ cm^{-3}$)	Strength, σ (MPa)	Modulus, E (GPa)	Poisson's ratio, ν	CTE α ($10^{-6}\ K^{-1}$)	Cure Shrinkage (%)	Use Temp. (°C)
1.1–1.4	30–100	2–4	0.2–0.33	50–100	5–12	80

2) Thermoplastic Matrices

PEEK(Polyetherether ketone)

Max. continuous use temperature ～250℃ (short use temp. ~ 300℃)

High fracture energy ～500 J/m^2 (50-100 times higher than epoxy)

Low moisture absorption 0.5% at R.T. (4-5% for epoxy)

replaces epoxy in many aerospace applications.

PPS(Polyphenylene Sulfide)

Max. continuous use temperature ～240℃

Outstanding resistance to heat, frame and chemicals.

Excellent electrical insulation.

Good matrix for carbon fibers

PMMA(Polymethyl Methacrylate)

High fracture energy ~1KJ/m^2

Polysulphone

Outstanding heat resistance and creep resistance.

Good resistance to solvents and chemicals.

Excellent fracture energy ～5 KJ/m^2 (7075Al ～ 8 KJ/m^2)

Thermoplastic Polymide

K-polymer	Du Pont
PEI(polyetherimide)	GE Plastics

TABLE 2.10. High-Performance Thermoplastic Matrix Polymers[48]

Polymer Composition	Acronym	Morphology	Glass Transition	Melting Temperature	Processing Temperature (°C)	Manufacturer	Trade Name
Polyether ether ketone	PEEK	Semicrystalline	143	343	360–400	ICI	Victrex PEEK
Polyphenylene sulfide	PPS	Semicrystalline	138	288	340–370	Phillips 66	Ryton PPS
Polyether ketone	PEK	Semicrystalline	165	365	400–450	BASF	Ultrapek PEK
Polyether ketone ether ketone ketone	PEKEKK	Semicrystalline	173	370	420–450	BASF	Ultrapek
Polyether sulfone	PES	Amorphous	260	—	400–450	ICI	Victrex HTA
Polyether imide	PEI	Amorphous	217	—	350–400	GE Plastics	Ultem PEI
		Semicrystalline	270	380	380–420	Mitsui Toatsu	P-IP
Pseudothermoplastics							
Polyimide	LARC-TPI	Amorphous	250	—	330–350	Rogers, Mitsui Toatsu	
	PI	Amorphous	265	—	350	CIBA-Geigy	Matrimide 9725

Table 3.1. Representative properties of some polymeric matrix materials

	Epoxy	Polyimide	PEEK	Polyamide-imide	Polyether-imide	Polysulfone	Polyphenylene sulfide	Phenolics
Tensile strength (MPa)	35–85	120	92	95	105	75	70	50–55
Flexural modulus (MPa)	15–35	35	40	50	35	28	40	—
Density (g cm^{-3})	1.38	1.46	1.30	1.38	—	1.25	1.32	1.30
Continuous-service temperature (°C)	25–85	260–425	310	—	170	175–190	260	150–175
Coefficient of thermal expansion (10^{-5}°C^{-1})	8–11	9	—	6.3	5.6	9.4–10	9.9	4.5–11
Water absorption (24 h%)	0.1	0.3	0.1	0.3	0.25	0.2	0.2	0.1–0.2

Source: Adapted with permission from Ref. 3.

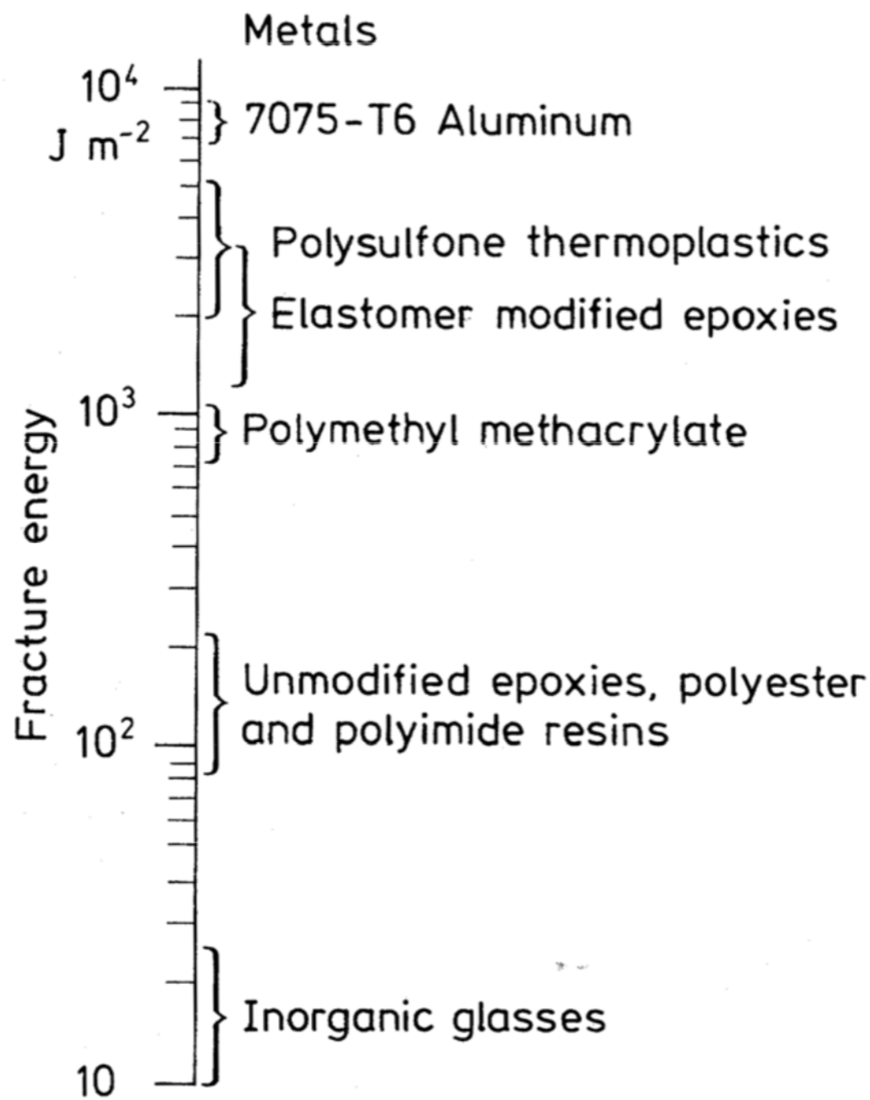


Fig. 3.11. Fracture energy for some common materials. [Adapted from Ting (1983), used with permission.]

3-5. Intermetallic Matrices

1. General Properties

High melting point > 1400℃
relatively low density
good strength & modulus
good oxidation & environmental resistance
low ductility at room temperature → alloy design, process modification
poor toughness at low temperature
low strength at high temperature
→ IMC

2. Aluminide, Silicide

TiAl, Ti_3Al, NiAl, Ni_3Al, FeAl, Nb_3Al …
$MoSi_2$

Intermetallic Compounds for High Temperature Structural Application

	Ni_3Al	NiAl	Ti_3Al	TiAl	$MoSi_2$	Nb_3Al
Structure	$L1_2$	B2	DO_{19}	$L1_0$	$C11_b$	A15
Melting Temp (°C)	1390	1640	1600	1460	2030	2060
Density(g/cm^3)	7.5	5.86	4.5	3.8	6.31	7.26
Modulus(GPa)	180-200	280-300	110-145	160-180	360-380	240-260
Yield Strength (MPa)	250-500	250-475	700-900	350-600	200-300 (1200°C)	100-200 (1200°C)
Tensile Strength (MPa)	1000-1200	300-500	800-1140	440-700	300-400 (1200°C)	200-300 (1200°C)
Elongation(%)	2-50	0-4	2-10	1-4	<0.5	<0.5
Oxidation Limit (°C)	1000	1200	650	800	1700	1200

Aerospace Industry

NASA, USA

National Aerospace Plane(NASP) : Supersonic Aircraft Mach 2-7

High Speed Civil Transport(HSCT) : Hypersonic Aircraft Mach 7-8

HITEMP(High Temperature Engine Materials Technology Program)

Japan

HPMSE(High Performance Materials for severe Environments)

↓

1)Higher engine operating temperature → H.T. Stability

2)Higher thrust-to-weight ratio → Light

⇒ Al_2O_3/NiAl, SiC/TiAl, Al_2O_3/FeAl, Al_2O_3/FeCrAlY

IMCs could be good candidate materials for gas turbine engine components such as turbine blade, disc, combustor.