Background information

Different bonding:

Property/性質	Ionic Bonding （離子鍵）	Covalent Bonding （共價鍵）	Metallic Bonding （金屬鍵）
Structure (結構)	Crystal lattice of positive and negative ions （正負離子組成的晶格結構）	Discrete molecules or network structures （獨立分子或網狀結構）	Array of positive metal ions with a "sea" of delocalized electrons （金屬陽離子與自由電子海的結構）
Properties (性質)	- High melting and boiling points （高熔點和沸點） - Conducts electricity when molten or dissolved （熔融或溶解時導電）	- Low to high melting points, depending on the strength of the bond （熔點因鍵的強度而異） - Generally non-conductive （通常不導電）	- High melting and boiling points （高熔點和沸點） - Conducts electricity （具有延展性和可塑性）
Characteristics (特徵)	- Strong electrostatic attraction between ions （離子間強烈的靜電吸引力）	- Shared electron pairs between atoms （原子間共用電子對）	- Delocalized electrons move freely among positive ions （自由電子在金屬陽離子間自由移動）
Examples (範例)	Sodium chloride (NaCl), Magnesium oxide (MgO) （氯化鈉、氧化鎂）	Water (H_2O), Diamond (C) （水、鑽石）	Copper (Cu), Iron (Fe) （銅、鐵）

Biocompatibility, Properties, Biomaterials

Biocompatibility refers to the ability of a material to perform with an appropriate host response in specific situation.

Factors that impact determine biocompatibility	High Biocompatibility
1. Toxicology 2. Reactions 3. Mechanical effects 4. A broad range of interactions with surrounding proteins, and cells, inducing cell–biomaterials interactions (and tissue–biomaterials interactions)	1. stable and acceptable physiological response 2. Pharmacological(藥理) acceptability e.g. Non-toxic 3. chemically inert(惰性) 4. Adequate mechanical properties

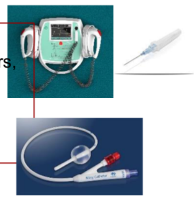
Question: Does the Food and Drug Administration (FDA), or Health Canada, regulate and approve the use of biomaterials? (老師 ppt 中的問題)
Ans: No materials are approved. The approval is granted for medical devices, not biomaterials themselves.

❋ **Classes of medical devices:**

classifies medical devices into three classes (Class I, II, III) based on **the level of risk**

- **Class I**: simple, low risk devices
  - *Examples*: surgery tools, toothbrush, wound dressing, contact lenses and ultrasound scanners
  - General controls (must be labelled, Good Manufacturing Practice, GMP, record keeping, etc) – most exempt from premarket submission

- **Class II**: more complex, higher risk
  - *Examples*: implanted devices such as catheters 導管, acupuncture needles, powered wheelchairs, infusion pumps
  - Special controls, 10-15% require clinical data, 90 days for FDA to review (based on 'substantial equivalence'
  - Labelling, guidance in use, tracking, design controls, performance standards



- **Class III**: most complex, highest risk
  - *Examples*: implantable pacemaker, HIV diagnostic tests, automated external defibrillators, and endosseous implants
  - Premarket application, to establish safety and effectiveness
  - Biomedical research to clinical testing: Bench – Animal – Human, many steps and very $$
  - 320 days for FDA to review

clinical testing

ISO10993 Biocompatibility Standards:

✸ The big 3 assays(檢測)：

1. Cytotoxicity 細胞毒性(最 common): This test evaluates whether a biomaterial releases any substances that are toxic to cells. It provides information about potential cell damage or cell death caused by the material, indicating acute toxicity.
2. Sensitization 敏化作用: This assay assesses whether a material can cause an allergic reaction (sensitization) after repeated exposure. It helps identify if the material could trigger immune responses in the body, such as skin rashes or inflammation.
3. Irritation or intracutaneous reactivity 刺激或皮內反應性: This test determines whether a biomaterial causes localized irritation when in contact with tissues. It measures the potential for causing swelling, redness, or inflammation in response to direct contact with skin or other tissues.

Test for biocompatibility:

	Advantages	Limitations
In vitro	• Quick to perform • Least expensive • Large-scale screening • Good experimental control • Can understand mechanisms of bio-interactions	• Relevance to *in vivo* or clinical use is sometimes (often) questionable
In vivo	• Allows complex, systemic interactions • Response is more comprehensive than *in vitro* testing • More relevant than *in vitro* testing	• Relevance to clinical use is sometimes (often) questionable • Expensive, time consuming • Legal/ethical issues • Difficult to control • Difficult to interpret and quantify
Clinical testing	• Relevance to the clinical use of materials is assured	• Very expensive • Very time consuming • Major legal/ethical concerns • Can be difficult to control • Difficult to interpret and quantify

In vitro test for cytotoxicity:

e.g. MTT assay: test cell metabolic activity (生物代謝活性), purple=cell growth

Challenges in sample preparation: (ppt 中提出在做醫療設備或材料測試，準備樣品時會遇到的問題)

(1) How to properly bring diverse material and device test samples into a standardized and appropriate level of contact with test systems

(2) How to treat composite materials and devices

(3) How to account for potential material interactions, for composite devices

(4) Other confounding factors (i.e. device size, supplier variability, tissue contact differences, etc.

1. **Bioinert (生物惰性): Minimal interaction with the biological environment, non-reactive.** These materials do not trigger(觸發) a biological response or interact with surrounding tissues when implanted in the body. They remain stable without causing a reaction, though a fibrous capsule may form around them. Examples include titanium-aluminum-vanadium alloys and polyethylene oxide polymers.
2. **Bioactive (生物活性): Promotes positive interactions and integration with biological tissues.** These materials actively interact with surrounding tissues, often promoting tissue bonding or integration. They undergo(接受) surface modifications, such as the formation of a biologically active layer. Examples include synthetic hydroxyapatite and bioglass.
3. **Bioresorbable(生物相容性、生物可吸收性)** refers to a material starts to dissociate(離解) and degrade(降解) (ie; hydrolysis 水解), and slowly become replaced by advancing tissue (such as bone). Common examples of bioresorbable materials are tricalcium phosphate [$Ca_3(PO_4)_2$], polylactic–polyglycolic acid copolymers, and certain hydrogels.

Foreign body response 排異反應 is a reaction of the body's immune system to a foreign material, typically characterized by inflammation, the formation of foreign body giant cells, and encapsulation of the material with fibrous tissue, which can interfere with the material's intended function.

- **Mutability(可變性)** refers to the ability of something to change or be changed
- **Adaptation(適應性)** is the process through which an organism or system adjusts to changes in its environment or conditions, improving its ability to survive or function.

Biomaterial

- is a nonviable(無法生存的) material used in a medical device (implanted or external), intended to interact with biological systems.
- is used to make devices to replace a part of a function of the body in a way that is physiologically(生理) acceptable
- is any substance (other than a drug), natural or synthetic(合成), that treats, augments(增強), or replaces any tissue, organ, and body function.

Question: Common functions of biomaterials? (列出常見的幾個而已，還有很多) (老師 ppt 中的問題)

Ans: - Repair-damaged tissue
- Substitute(代替;取代) for missing tissue
- Improving existing / inadequate(不足) function
- Implanted device (e.g. pacemaker)
- drug release

Question: Fixation using an orthopedic(骨外科) implant. What could go wrong? (老師 ppt 中的問題)

Ans: - Infection
- Inflammatory response
- Mechanical failure
- Screw failure
- Movement limitation
- Corrosion

Classes of Biomaterials:

Class (English)	Class (中文，繁體)	Example Materials (English)	Example Materials (中文，繁體)	Examples as Biomaterials (生物材料範例)	Common Applications (English)	Common Applications (中文，繁體)	Advantages (English)	Advantages (中文，繁體)	Disadvantages (English)	Disadvantages (中文，繁體)
Metals	金屬材料	Titanium, Stainless Steel	鈦, 不鏽鋼	Orthopedic implants and repair, joint replacement, dental root implants, suture wires, bone plates, and screws	Joint Replacements, Dental Implants	關節置換物, 牙科植入物	High strength, Durable	高強度, 耐用性好	Corrosion, High stiffness	可能腐蝕, 剛性高
Ceramics	陶瓷材料	Alumina, Hydroxyapatite	氧化鋁, 羥基磷灰石	Hydroxyapatite as bone graft material, Alumina in dental crowns	Bone Implants, Dental Crowns	骨植入物, 牙冠	Hard, Biocompatible	硬, 生物相容性好	Brittle, Difficult to process	脆, 難加工
Polymers	高分子材料	Polyethylene, Polylactic Acid	聚乙烯, 聚乳酸	UV-curable dental composites, Ultra high molecular weight polyethylene (UHMWPE), Polypropylene fiber woven mesh, Artificial heart	Sutures, Drug Delivery Systems	縫合線, 藥物傳遞系統	Flexible, Biocompatible	柔韌, 生物相容性好	Lower strength, Can degrade	強度低, 可能降解

Summary of Advantages and Disadvantages:

- Polymers (高分子材料): Polymers are flexible and biocompatible, making them suitable for soft tissue applications, but they often have lower strength and may degrade over time.

- Metals (金屬材料): Metals like titanium are highly durable and strong, which is useful for load-bearing implants(負重植入物), but they can suffer from corrosion(腐蝕)and may be too stiff(僵硬) for certain applications.

- Ceramics (陶瓷材料): Ceramics are biocompatible and very hard, making them ideal for dental and bone implants. However, they are brittle(脆) and difficult to process..

Mechanical Properties

Youngs Modulus： (Stress, Strain)

$$E = \frac{Stress(應力)}{Strain(應變)} = \frac{\sigma}{\epsilon} \quad (GPa)$$

E higher → stiffer(僵硬), High resistance to pressure and wear(耐高壓和耐磨)很大力才能有一點形變量

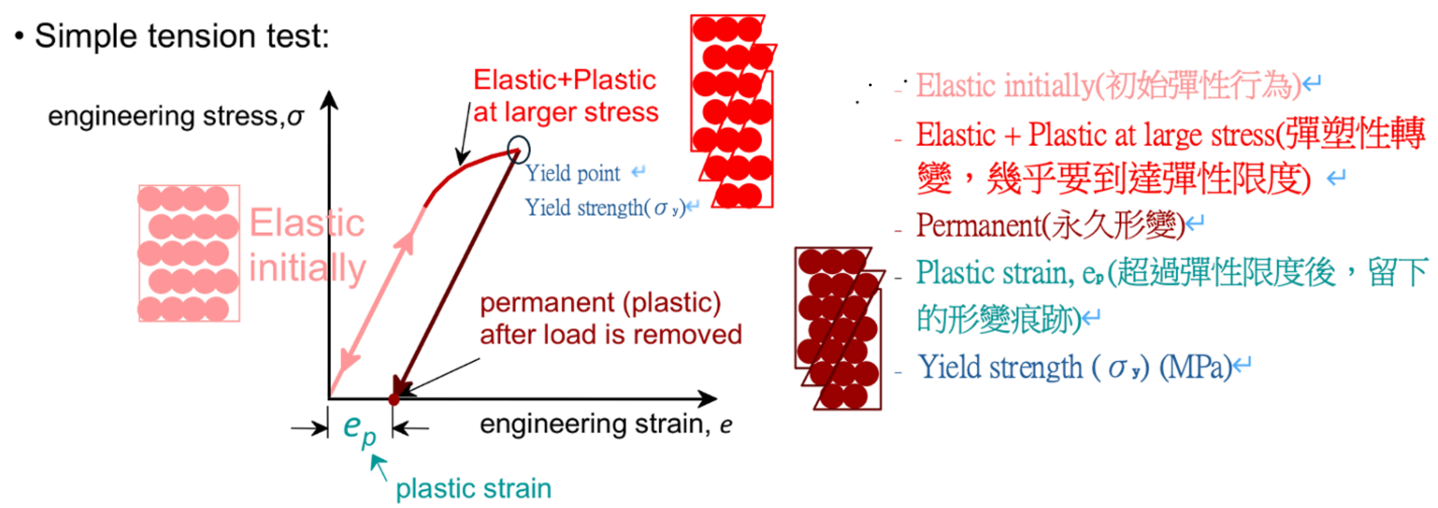
→高負載, 形狀穩定性 e.g.骨科植入物（如金屬或陶瓷）

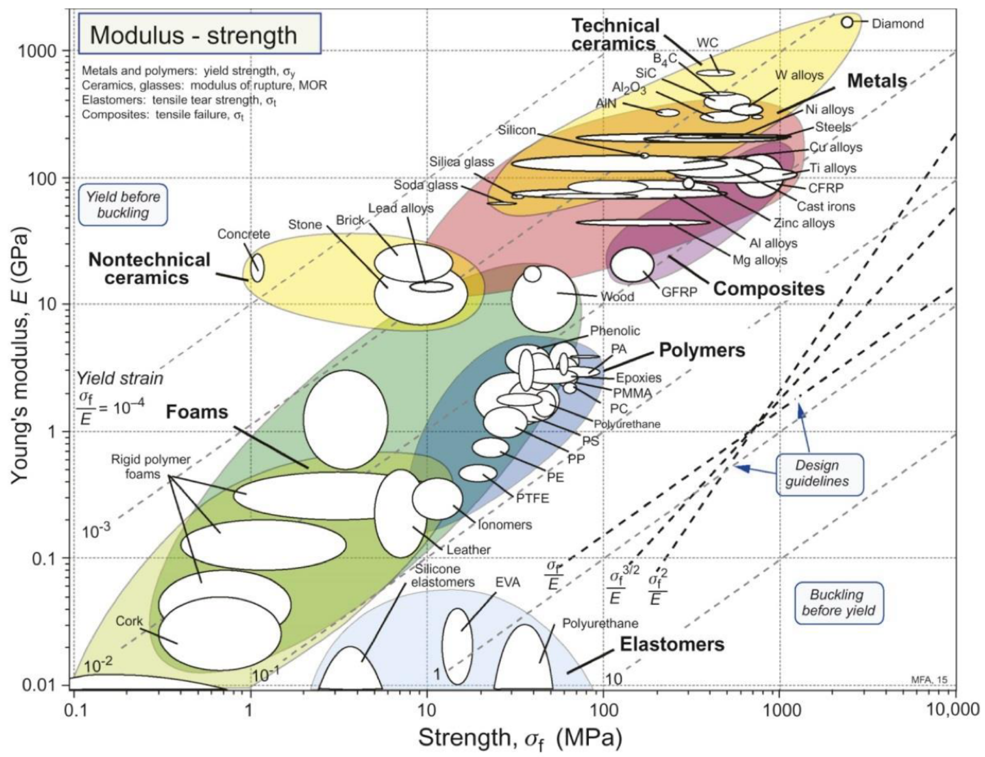
E lower → flexible(有彈性), bendable(易於彎曲) 小小力就能產生很大的形變量

→吸收衝擊或變形能力 e.g. 聚合物（如聚乙烯、聚丙烯）

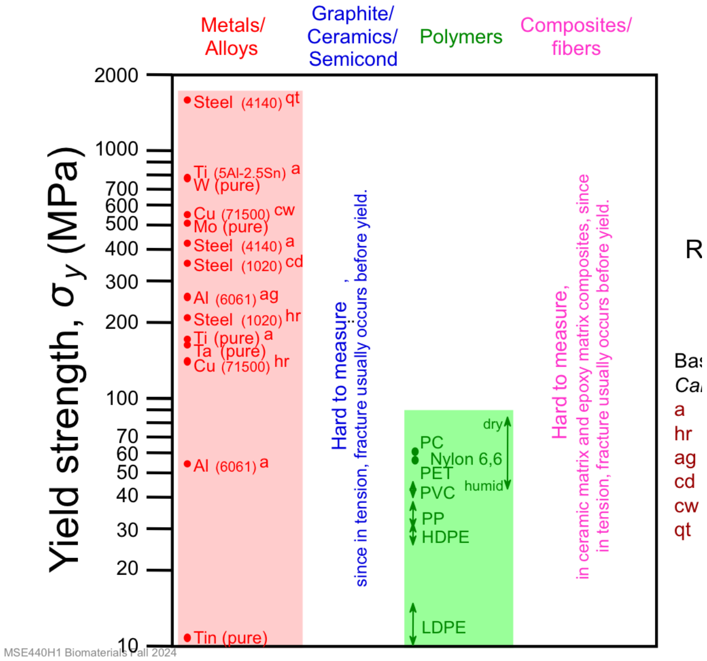
e.g. E high---> E low

ceramics and metal　　　composites　　　polymers





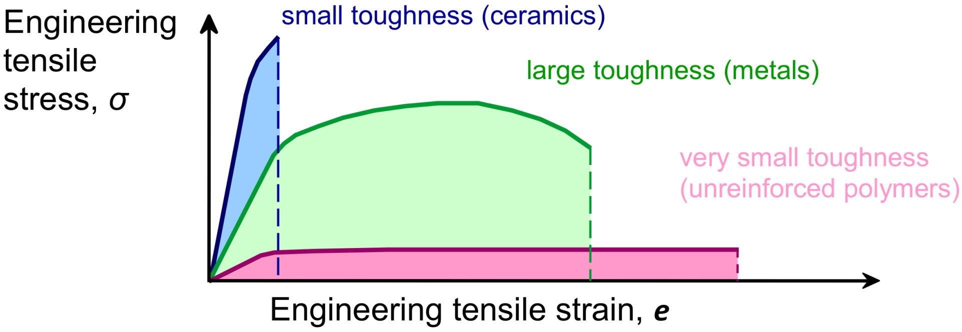
Yield strength(彈性限度):

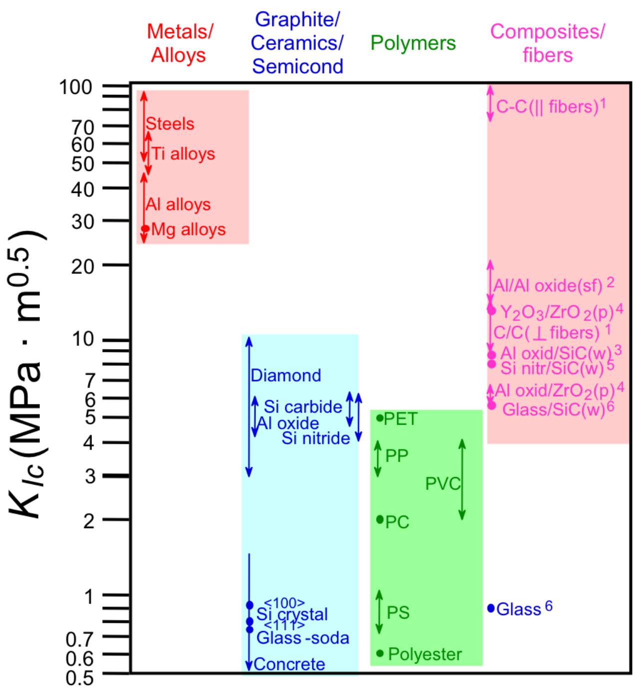


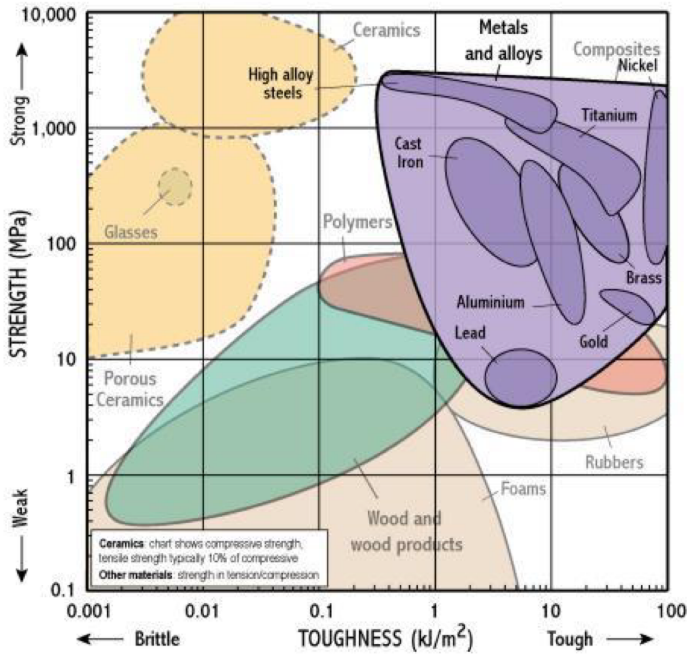
Tension(張力): 拉伸或牽引材料的力量

Toughness(韌性): 材料在斷裂前能承受多少能量，可以透過應力-應變曲線下的面積來表示

A measure of a material's ability to absorb energy and deform without breaking. It represents the total energy absorbed by a material up to the point of fracture(斷裂)

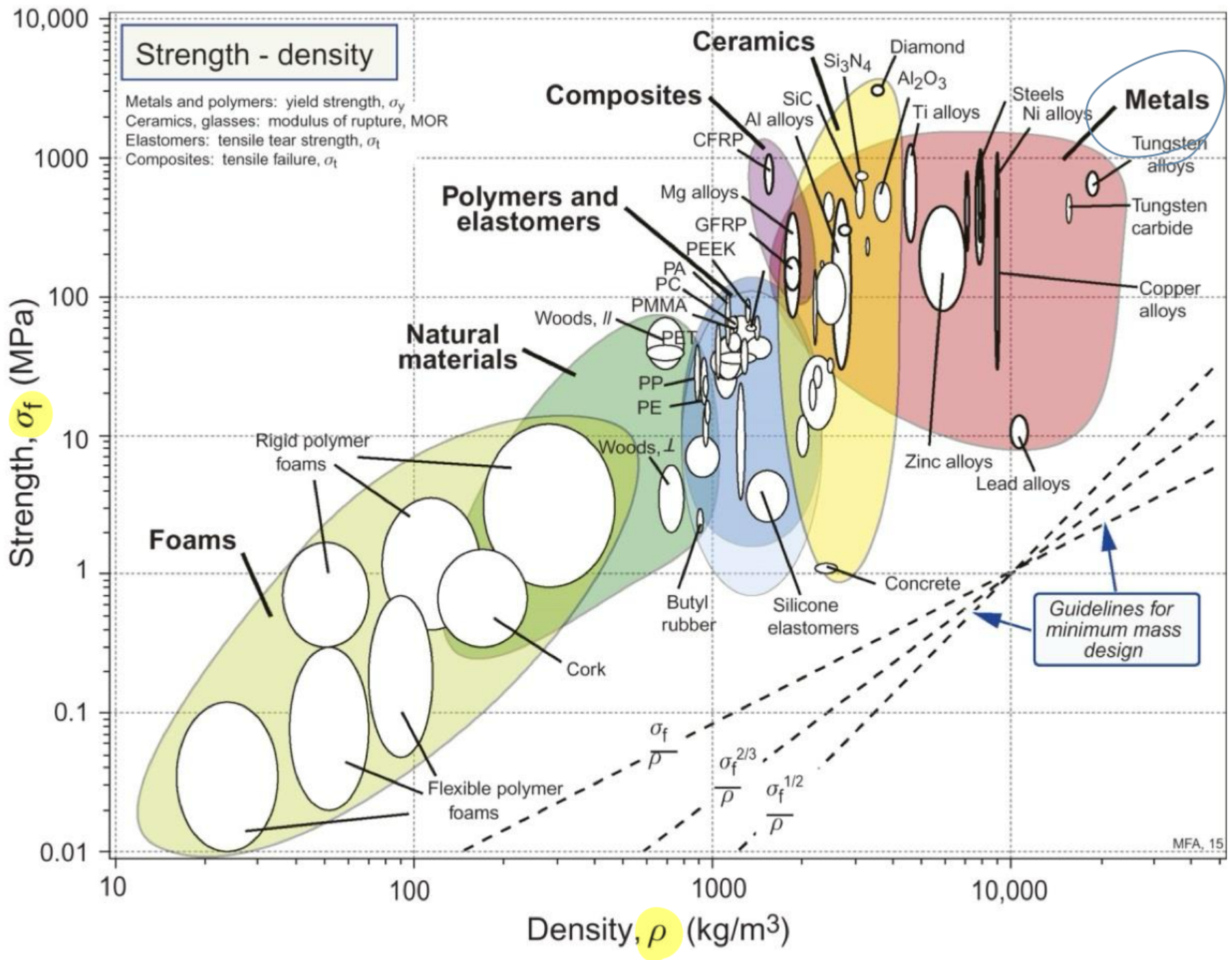






Densities of different material classes:

1. **Metals/Alloys:**
   large atomic masses(原子量大)
   metallic bonding (金屬鍵)→close-packing structures(緊密堆積結構)
   → higher density
2. **Ceramics/Semiconductors**
   covalent bonding(共價鍵)→less dense packing(堆積密度低)
   lighter elements
   → still high density, but lower than metal
3. **Composites/Fibers:**
   fiber reinforcements like glass fibers or carbon fibers in a polymer matrix
   → intermediate densities
4. **Polymers:**
   amorphous regions (disordered molecular arrangement 分子排列不規則)→poor packing
   lighter elements like carbon (C), hydrogen (H), and oxygen (O)



Applications of Biomaterials - Hip joint

e.g. Hip joint replacement (不同材料的 hip joint replacement 的優缺點)

Question: Why? debris from wear associated with metal-metal contact–causing chronic inflammation

Ans: only test it in the lab→no human test→real motion hasn't been tested

Question: Consider normal walking –what are the peak forces acting on a hip or knee joint? (老師 ppt 上)

Ans: During normal walking, the ratio of joint force relative to body weight can exceed 5-6 times. These forces occur primarily when the foot strikes the ground and during the stance phase of walking, as the body shifts weight onto the leg. They must withstand such loads without deforming. Therefore, the yield strength (彈性限度) is a crucial consideration in ensuring the durability and safety of prosthetic implants.

材料/Material	Advantages (優點)	Disadvantages (缺點)
Metals (金屬材料) e.g., Titanium Alloys, Stainless Steel (例如：鈦合金、不鏽鋼)	- Strong, durable (強度高，耐用) - Good wear resistance (耐磨性良好) - Biocompatible, especially titanium (生物相容性好，特別是鈦合金)	- Fatigue over time (金屬疲勞) - Wear particles may cause inflammation (磨損顆粒可能引發炎症)
Ceramics (陶瓷材料) e.g., Zirconia, Alumina (例如：氧化鋯、氧化鋁)	- Very hard, minimal wear (非常硬，磨損少) - Chemically inert, good compatibility (化學惰性，相容性好) - Low friction (低摩擦)	- Brittle, can crack under stress (脆性高，受力易裂)
Polymers (高分子材料) e.g., UHMWPE (例如：超高分子量聚乙烯)	- Good cushion, absorbs impact (良好緩衝，吸收衝擊) - Lightweight (重量輕) - Low friction (低摩擦)	- Wear particles can cause inflammation (磨損顆粒可能引發炎症)

Metals/Alloys

Characteristics:

1. Properties:

– Mechanical properties:

Metals are known for their high yield strength, tensile strength, and fatigue resistance(耐疲勞), making them ideal for load-bearing applications such as orthopedic implants (e.g., hip and knee replacements) and bone plates. low modulus(低模量)(flexible 柔韌性高 and less stiff 不僵硬)

– Fracture Toughness（斷裂韌性）:

Metals generally possess high fracture toughness, which means they can absorb energy and resist crack propagation. This is critical in implants that are exposed to repetitive loads and potential impact forces.

– Formability(可加工性):

Metals can be processed and shaped through various manufacturing methods like forging, casting, and machining, allowing the creation of complex geometries required for implants.

– Biocompatibility:

Many metals, such as titanium and its alloys, exhibit good biocompatibility, meaning they do not cause adverse reactions in the body, like inflammation or rejection.

– Cost-effectiveness:

Metals like stainless steel and cobalt-chromium alloys are relatively more cost-effective compared to advanced materials like ceramics and some polymers, making them widely accessible for various medical applications.

The ideal recipe for an implanted alloy includes excellent biocompatibility with no adverse tissue reactions, excellent corrosion resistance in body fluid, high mechanical strength and fatigue resistance, low modulus, low density, and good wear resistance.

2. Disadvantages and Limitations:

– Limited Biocompatibility (有限的生物相容性): Many metals can cause adverse reactions when in contact with biological tissues

– High Thermal Conductivity (高導熱性): It is a limitation when thermal insulation(絕緣) is required.

– High Density (高密度):Most metals have high density, making them relatively heavy.

Why Low Modulus and Low Density Are Important for Implanted Alloys:

Low modulus helps to match the stiffness of the implant with that of natural bone, reducing stress shielding and promoting healthy bone growth.

Low density ensures that the implant remains lightweight, improving patient comfort and ease of movement, which is especially important in load-bearing applications like joint replacements.

Corrosion in Metals: Why It's Not a Contradiction

Metals can corrode when exposed to certain environments, especially when in contact with electrolytes like body fluids. This is because metals, in general, can undergo oxidation reactions, leading to corrosion. For example, untreated iron will rust in the presence of moisture and oxygen. However, many metals and alloys used in biomedical applications (e.g., stainless steel, titanium, cobalt-chromium alloys) are designed or selected specifically for their resistance to corrosion

Topic	Details
Introduction	Developed in large scales in the 1920s (20世紀20年代). 316L stainless steel (316L不銹鋼) is the most common type for biomaterial implants.
Chromium Content (鉻含量)	Chromium is a major component in stainless steel, with a minimum of 11 wt % (重量百分比) needed for effective oxide passivation (氧化鈍化).
Corrosion Resistance (耐腐蝕性)	Generally resistant to corrosion, except in low-oxygen (低氧), high-salinity (高鹽度), or poor-circulation environments (循環不良的環境).
Passive Layer (鈍化層)	Forms a chromium oxide layer (鉻氧化物層, Cr_2O_3) that blocks oxygen diffusion (氧擴散) to the steel surface, preventing further corrosion (防止進一步腐蝕).
316L Stainless Steel Properties	Austenitic (奧氏體): Non-magnetic (非磁性), FCC structure (面心立方結構). High modulus (高模量) of 200 GPa. Work hardens (加工硬化) rapidly.
Work Hardening & Heat Treatment	Cannot be cold-worked (冷加工) without intermediate heat treatments (中間熱處理). Excessive heat treatment (過度熱處理) or welding can cause carbide precipitation (碳化物沉澱), leading to corrosion.
Manufacturing Methods (製造方法)	Can be hot forged (熱鍛), investment cast (精密鑄造), or formed by powder metallurgy (粉末冶金).
Clinical Use (臨床使用)	316L stainless steel was the most common orthopedic implant alloy until the 1970s and is still used today. High modulus is considered a drawback for orthopedic implants due to stress shielding (應力屏蔽 fects.

Material (材料)	Properties (特性)	Advantages (優點)	Disadvantages (缺點)	Biomedical Examples (生物醫學應用範例)
Stainless Steels (不銹鋼)	- High strength (高強度) - Corrosion resistant due to Cr content (因含鉻具抗腐蝕性)	- Cost-effective (成本低) - Good mechanical properties (良好的機械性質)	- Potential release of Ni, causing allergic reactions (可能釋放鎳，導致過敏反應)	Orthopedic implants, surgical instruments (骨科植入物, 手術器械)
Co-based Alloys (鈷基合金)	- High wear resistance (高耐磨性) - Good corrosion resistance (良好抗腐蝕性)	- High strength and toughness (高強度和韌性) - Biocompatible (生物相容性好)	- High cost (成本高) - Difficult to machine (難以加工)	Dental prosthetics, joint replacements (牙科假體, 關節置換)
Ti and Ti-based Alloys (鈦及鈦基合金)	- Low density, high strength-to-weight ratio (低密度，高強度重量比) - Excellent biocompatibility (極佳的生物相容性)	- Corrosion-resistant (抗腐蝕) - Forms stable oxide layer (形成穩定的氧化層)	- High cost (成本高) - Poor wear resistance (耐磨性差)	Hip implants, dental implants (髖關節植入物, 牙科植入物)
Dental Metals (牙科金屬, Au, Ni-Ti alloys)	- High corrosion resistance (高抗腐蝕性) - Shape memory (形狀記憶) for Ni-Ti	- Au: Biocompatible, non-reactive (生物相容性好, 不反應) - Ni-Ti: Shape memory for orthodontics (形狀記憶，適用於牙齒矯正)	- Au: High cost (成本高) - Ni-Ti: Ni release risk (有鎳釋放風險)	Dental crowns, braces, wires (牙冠, 牙齒矯正器, 牙科鋼絲)
Mg Alloys (鎂合金)	- Lightweight (輕量) - Biodegradable (生物可降解)	- Promotes bone growth (促進骨骼生長) - Degradable without surgery (可降解 需二次手術)	- Rapid corrosion rate (腐蝕速率快) - Gas release during degradation (降解時釋放氣體)	Temporary implants, bone screws (暫時性植入物, 骨螺釘)

"L" = low carbon content, improving corrosion resistance

Table 5-1. Compositions of 316L Stainless Steel Surgical Implants (ASTM, 2000)

Element	Composition (w/o)
Carbon	0.030 max
Manganese	2.00 max
Phosphorus	0.025 max
Sulfur	0.010 max
Silicon	0.75 max
Chromium 鉻 → forms a protective oxide layer on the surface, protecting further oxidation.	17.00–19.00
Nickel	13.00–15.00
Molybdenum 鉬 → enhance its corrosion resistance in seawater	2.25–3.00
Nitrogen	0.10 max
Copper	0.50 max
Fe	Balance

⁕ **Question:** What will happen if we heat up stainless steel too much?
Ans: Loss of Corrosion Resistance, start to oxidize, Changes in Mechanical Properties- more brittle and reducing its tensile strength

3. Common metals and alloys:
   (1) 316L stainless steel:

– Advantages: corrosion resistance, austenitic (面心立方, FCC, Provides high toughness and ductility, making it easy to shape into medical devices and resistant to corrosion in the body.) and nonmagnetic (Safe for use in MRI environments)
– Disadvantages: High modulus
–

⁕ **Question:** 為什麼 316L stainless steel 的 high modulus 是缺點？
Ans: 316L stainless steel's high modulus means it is very stiff compared to bone. The implant absorbs most of the stress, leading to bone weakening around it.

(2) Co-based alloys:
Advantages: excellent corrosion resistance, wear resistance, and fatigue strength, Add Ni to improve corrosion resistance
Disadvantages: High modulus

(3) Ti and Ti-based alloys:
Advantages: Excellent specific strength, lower modulus, superior tissue compatibility, and high corrosion resistance, its oxide (titanium in atmosphere readily forms a nascent oxide layer) had excellent osseointegration properties, very low density (4.5 g/cm3), very good mechanical and corrosion resistance
e.g. Ti-6Al-4V (common):
   Advantages: lightweight, strong, high strength-to-weight ratio, excellent corrosion resistance, high biocompatibility, high temperatures 耐高溫, resists fatigue,
   Disadvantages: expensive, challenging to machine
   e.g. aircraft components, hip replacements, and dental implants

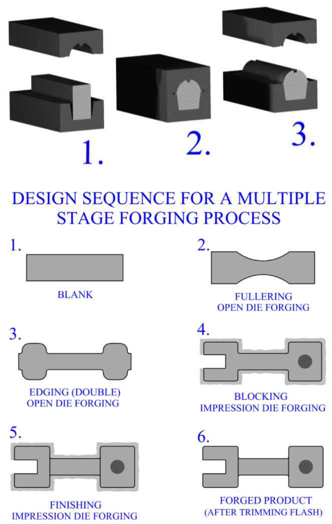
(4) Dental metals: e.g. Au, Ni-Ti alloys

(5) Mg alloys:

⁕ **Question:** Mg Alloys? Why use Mg?
Ans: Mg is biodegradable(bioresorbable)
Lightweight(weight reduction is critical, such as in orthopedic(骨科)devices
Magnesium is biocompatible, Mg^{2+} are essential for various biological functions and are naturally found in the body, helping to enhance bone growth and healing,
Mechanical Properties Similar to Bone (機械性質與骨相近)
The elastic modulus of Mg alloys is closer to that of natural bone compared to other metals
Application Flexibility: Magnesium alloys can be customized through alloying

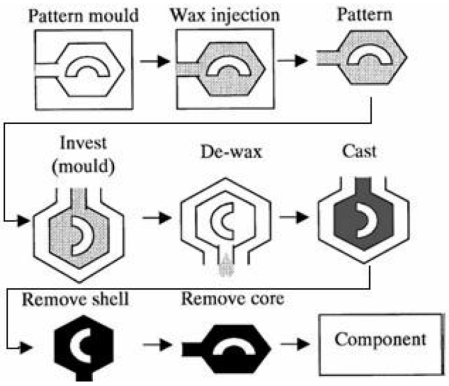
4. Metal processing methods:

(1) Forging(鍛造): large hydraulic(水力) presses exert the compressive(壓縮) forces, at different temperatures. E.g. cold, warm or hot (iron, steel) forging



Advantages	Disadvantages
- Generally low cost - high production rates	Cannot be used for complex forms – significant capital expenditure, costs associated with forming die (for identical parts), so only economical for large production runs

(2) Investment Casting (熔模鑄造): lost-wax casting



Pattern Mold 製作模具 Wax Injection 注入蠟 Pattern Formation (形成蠟模型) Invest (Mould Formation) (製作陶瓷模具) De-waxing (除蠟) Casting (澆鑄) Removing Shell and Core (去除陶瓷殼和內芯) Final Component (最終成品)

(3) Milling(研磨): Uses CNC for precise shaping, suitable for custom implants.

Advantages: one step machining, from a single block – can work from 3D model/design for custom, complex designs

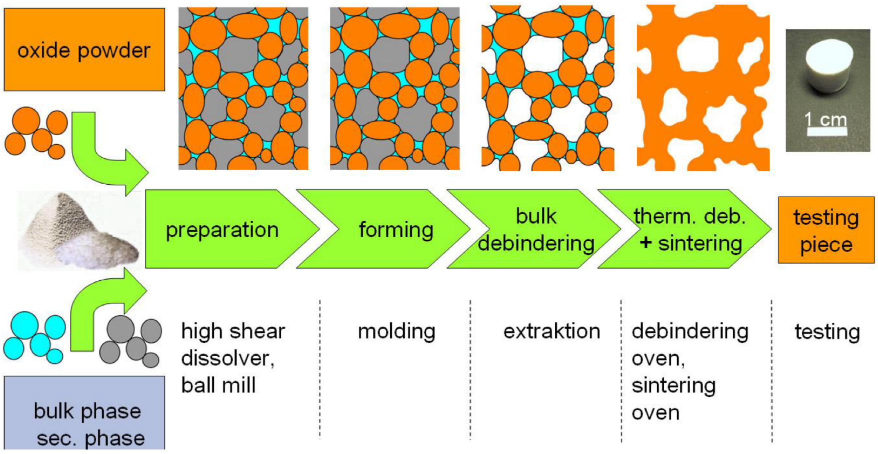
Disadvantages: slow, expensive – can have trouble with undercuts or complex designs – hard materials such as Ti, or Co-alloys can be slow to machine

(4) Powder metallurgy(冶金術)+ Selective Laser Sintering (選擇性激光燒結, SLS): Use in 3D printing

Ceramics

Characteristics:

1. Ionic Bonding(離子鍵):
   (1) hard (2) no free charges→insulator(絕緣體) (3) large band gap→transparent(透明)
2. Mechanical properties:
   (1) Almost no plastic deformation(幾乎沒有塑形變形)
   (2) Brittle fracture(因脆性而斷裂)
3. Ceramic processing methods
   (1) Press Forming(壓製成形): dry powder pressing (pressure or pressure and heat)
   (2) Extrusion Forming (擠出成形): suitable for symmetric(對稱)parts, such us tubes or pipes
   (3) Slip Casting(注漿成形): 將陶瓷顆粒漿料澆注到多孔模具中，然後進行燒結
   (4) Sintering(燒結): heat and/or pressure→Atoms diffuse across grain(結晶顆粒) boundaries→reducing porosity



4. Common ceramic biomaterials:

	Characteristics	Structure
Aluminum oxide (alumina, Al_2O_3)	- High hardness(可作為磨料) - High T_m(可作為耐火材料) - Very stable and nonreactive →highly biocompatible(生物惰性高) - Fracture toughness is very low(斷裂韌性低, brittle)	
Zirconium oxide (zirconia, ZrO_2)	- Fracture toughness is very high - Good wear resistance (耐磨性好) - High T_m(可作為耐火材料) - Biocompatible (生物相容性好) - Low thermal conductivity (低熱導率)	
Calcium phosphate (hydroxyapatite, HAp)	- Similar composition to bone (Hap→strength and hardness) - Low mechanical strength (more brittle) - Highly biocompatible (HAp)	

	- Bioactive (生物活性高) hydroxyapatite(HAp) can stimulate bone formation and bond directly with bone tissue - Degradable in physiological conditions (it can dissolve and be replaced by new bone, making it suitable for resorbable bone grafts.)	
Bio-glass	- Highly bioactive - Amorphous structure (無定形結構) - Low mechanical strength (brittle and not suitable for load-bearing applications) - Used for bone regeneration - Most well -developed: SiO_2+CaO+NaO_2+P_2O_5	

Zirconium oxide (zirconia, ZrO_2)

Fracture toughness about 3 times higher than most ceramic oxides – why? (老師 ppt)

Due to **transformation toughening** (轉變增韌). When stressed, its crystal structure shifts from **tetragonal** (四方晶相) to **monoclinic** (單斜晶相), causing a **volume expansion** (體積膨脹) near cracks. This expansion generates **compressive stresses** (壓縮應力) around the crack, which **hinders crack propagation** (阻止裂縫擴展). This unique mechanism effectively resists crack growth, giving zirconia greater toughness compared to other brittle ceramics like alumina (氧化鋁), which do not exhibit such phase changes.

5. Coating:

(1) Plasma-Sprayed Coatings: e.g. HAp coating→improve bioactivity

(2) Coating Techniques:

- Electrophoretic Deposition, EPD(電泳沉積): e.g. TiO_2
- Sol-Gel Process(溶膠-凝膠法):

Pros: low temperature, solution-based

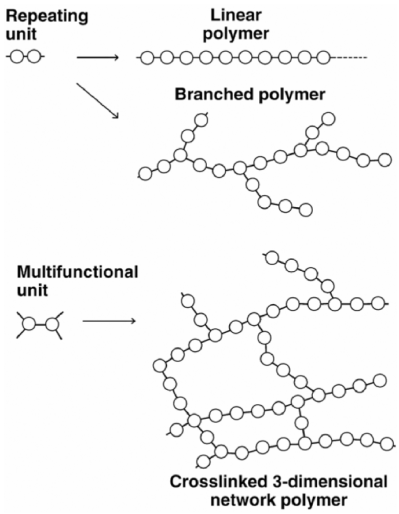
Cons: a lot of volume change, cracking and adhesion

e.g. oxides of silicon and titanium. e.g. porous structure of bioactive glass

6. The creation of **porous ceramics** is aimed at taking advantage of their **high surface area**(高表面積), **permeability**(滲透性), and **biocompatibility**, making them **versatile**(多用途) for medical implants, insulation materials(隔熱材料), and filtration applications (過濾應用)

Polymers

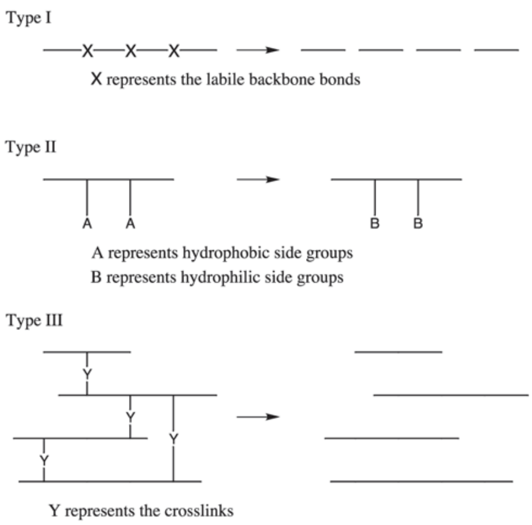
1. Structure:
   (1) Degree of polymerization(DP，聚合度) increases: chain length increases(鍊長)→ High Molecular Weight (MW，分子量)→ Chain mobility decreases(流動性)→ High strength and greater thermal and chemical stability
   (2) Chain(是 polymers 很重要且有影響力的指標): linear, branched(支鍊), cross-linked
   (3) Linear chain (e.g. polyvinyl 聚乙烯, polyesters 聚酯)→crystallize more→improve resistance to degradation(改善降解性) by hydrolysis(水解)

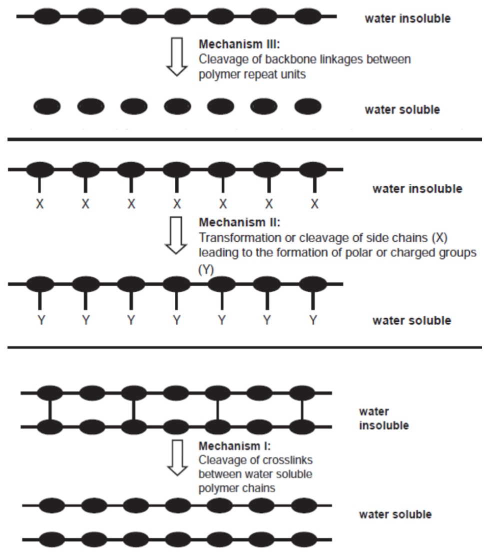


2. Pros and cons of polymers:
   Pros:
      I. Chemical and compositional can be controlled, leading to different properties: change MW, cross-linking, functional groups, crystallinity→ stiffness, strength, biodegradation/resorption can also be changed
      II. Mechanical properties (and chemistry) is much closer to natural materials and tissue

   Cons:
      I. More complicated issues of biocompatibility and toxicity compared to metals and ceramics
      III. Certain polymers are susceptible to gradual hydrolysis (容易逐漸水解)
      IV. Mechanical properties: lower strength and more problems of time-dependent deformation (creep, environmental stress fracture)
3. Degradation (是材料隨著時間或在特定環境下逐漸分解成較小的分子或簡單化合物的過程):
   Aim of degradation: Improve the chemical stability, change the mechanical properties and gain the byproducts during degradation
   - Type I - Scission of the Polymer Backbone (聚合物主鏈的斷裂):
     Breaking the polymer backbone through hydrolysis or enzyme action. Polymers with a C-C backbone tend to be non-biodegradable.
   - Type II - Conversion of Hydrophobic Side Groups to Hydrophilic (疏水側基轉變為親水): This process involves changing hydrophobic side groups into hydrophilic (often anionic) groups as an initial step in the degradation process, and cells can attach more easily.

- Type III - Loss in Crosslinking (類型 III - 交聯鍵的喪失): Reduce crosslinking (Because it cause hydrogels change from water-soluble(溶於水) to insoluble(不溶).)

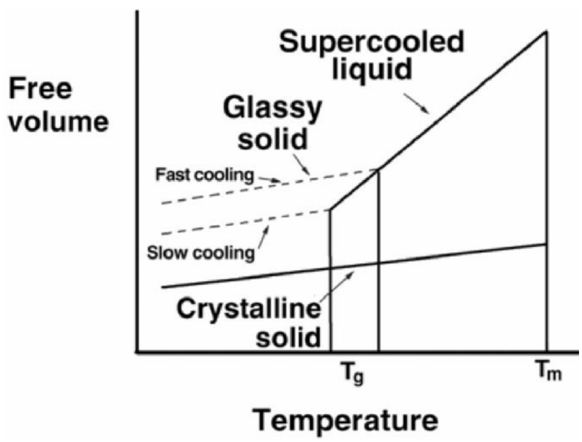


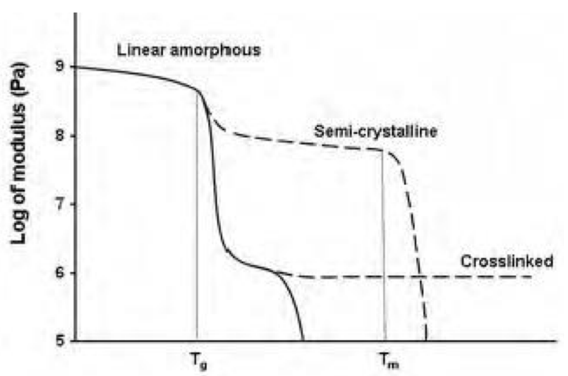


⁕ **Question:** Why design biodegradable polymers?

Ans: Temporary scaffolds for engineered tissue replacement or for drug release

4. Characteristic (polymer's behavior):





Glass Transition Temperature (Tg): Tg marks the temperature where a polymer transitions from a hard, brittle state (glassy) to a soft, rubbery state.
- Below Tg, glassy state, limit mobility(流動性).
- Above Tg, more flexible.

Melting Temperature (Tm): Tm represents the temperature at which a crystalline polymer melts and becomes a liquid. Above Tm, the polymer loses all ordered structure and flows as a melted liquid.

Effect of Cooling Rate:
- Fast cooling favors the formation of a glassy solid because the polymer does not have enough time to crystallize.
- Slow cooling allows the polymer chains to arrange themselves into a more ordered, crystalline structure.

(1) Crystalline Solid (結晶固體):

- At lower temperatures, polymers can form a crystalline structure (the polymer chains are arranged in a highly ordered, regular pattern 有序的結晶結構) if cooled slowly.
- Crystalline solids have low free volume, meaning the polymer chains are tightly packed together.

(2) Glassy Solid (玻璃態固體):

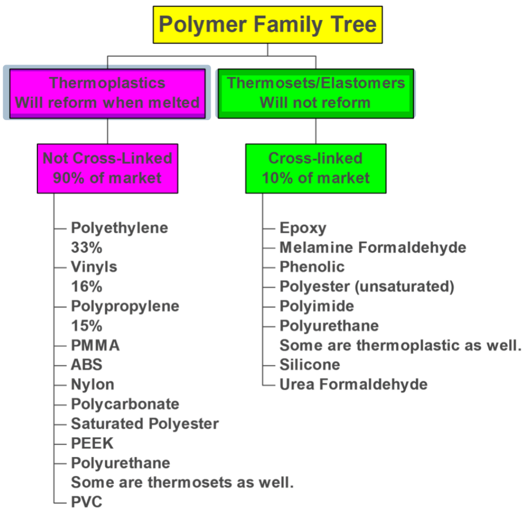
- When a polymer is cooled quickly (fast cooling) from above Tg, it may not have time to organize into a crystalline structure, so it becomes a glassy solid.

- A glassy solid is rigid(剛硬) but lacks the ordered structure of a crystalline solid, retaining more free volume between polymer chains.

(3) Supercooled Liquid (過冷液體):

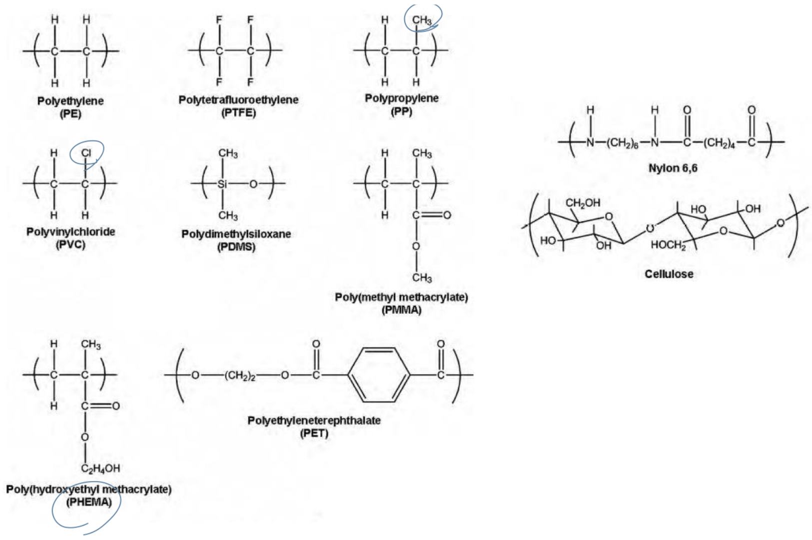
- When cooling is very fast, the polymer can remain in a supercooled liquid state, which is less ordered than the crystalline state but has more free volume than the glassy state.

5. Forming structure: (3D bioprinting can do both)
   (1) Thermoplastics(TPs, 熱塑型塑膠): Increase temperature→ intermolecular forces decrease(分子間作用力減小)→viscous liquid→ become deformable and moldable→Cooled(Solidifies)→high molecular weight
   e.g. polyethylene (PE), polyvinylchloride, polypropylene (PP), polystyrene (PS), and nylon
   (2) Thermosets(熱固性聚合物): cross-link between polymer chains→curing(固化) a prepolymer
   Prepolymer(預聚物)- initially heated→soften and flow, but the high temperatures produce a chemical reaction that hardens the material into an infusible(不熔化) solid→this process can't repeat e.g. epoxy, silicone; toaster parts, automotive engine parts, electrical outlet parts, handles on pots and pans, ash trays



Category (分類)	Thermoplastics (熱塑性聚合物)	Thermosets (熱固性聚合物)	Elastomers (彈性體/橡膠)
Cross-linking (交聯程度)	**No cross-linking** (無交聯)	**Highly cross-linked** (高交聯)	**Moderately cross-linked** (中等交聯)
Reheating	**Can be reheated and reshaped** (可重複加熱和重塑)	**Cannot be reheated or remolded** (不可重複加熱或重塑)	**Cannot be remolded once cured**, but retains elasticity (固化後不可重塑，但保持彈性)
Curing Process (固化過程)	Softens upon heating, **solidifies upon cooling** (加熱時變軟，冷卻時變硬)	Cures **irreversibly** through a **chemical reaction** (透過化學反應不可逆固化)	Forms through **cross-linking**, providing **elastic properties** (透過交聯形成，提供彈性)
Mechanical Properties (機械性質)	Can be **flexible** or **rigid**, depending on formulation (可柔軟也可剛性，取決於配方)	**Hard, rigid, brittle** after curing (固化後硬且剛性高，易脆)	**Highly elastic** and can **stretch significantly** (高度彈性，可大幅拉伸)
Examples (範例)	**Polyethylene (PE), Polypropylene (PP), Polystyrene (PS)** (聚乙烯, 聚丙烯, 聚苯乙烯)	**Epoxy, Silicone** (環氧樹脂, 矽膠)	**Natural rubber, Silicone rubber** (天然橡膠, 矽橡膠)
Applications (應用)	**Plastic bottles, toys, packaging** (塑膠瓶, 玩具, 包裝)	**High-temperature parts**, e.g., toaster parts, engine parts (高溫部件，如烤麵包機部件、引擎部件)	**Rubber bands, seals, tires** (橡皮筋, 密封件, 輪胎)

6. Common polymers in biomaterial applications:



(1) Polyethylene (PE)聚乙烯：

I. Linear polymers(提示：Linear chain →crystallize more→improve resistance to degradation(改善降解性) by hydrolysis(水解))

II. Easily crystallized

III. 3 types: low density (LDPE), high density (HDPE), and UHMWPE

IV. UHMWPE (ultra-high molecular weight PE):
- load bearing, high wear, high strength, hardness and stiffness
- long chain (提示：chain length increases(鍊長)→ High Molecular Weight→ Chain mobility decreases(流動性)→ High strength and greater thermal and chemical stability)

V. Highly crosslinked (stiff strength) UHMWPE(提示：cross-link between polymer chains→hardens the material into an infusible(不熔化) solid(hard, rigid, brittle)→this process can't repeat): Use in hip replacement

(2) Polyacrylates:

I. Common:
Polymethyl acrylate (PMA)-R_2 is CH_3
Polymethyl methacrylate (PMMA)-R_1 and R_2 are CH_3

II. Highly transparent→ Used for optical implants e.g. intraocular lenses

III. PMMA-hard contact lens, bone cement, dental resins

IV. Poly-HEMA: Hydrogel polymer – absorbs water→common for soft contact lenses

(3) Fluorocarbon polymers:

I. Common: Polytetrafluoroethylene (PTFE, Teflon 特氟龍)
If is fragmented into pieces, irritation will occur. (我筆記寫老師說 this sentence 很重要 IDK why??)

II. High electronegativity→ Highly chemically inert

III. Highly crystalline (提示：the polymer chains are arranged in a highly ordered and tightly packed together)→Can't be molded or melted easily - usually sintered under pressure

IV. often used as a vascular graft material

(4) Polypropylene (PP):

I. High tensile strength→surgical materials

II. Very high flexural fatigue life (彎曲壽命高) – useful for finger joint

III. High chemical stability

(5) Polyamides (PA):

I. Strong interchain hydrogen bonding, high degree of crystallization

II. Hygroscopic (吸濕的)(提示: high water absorption) - lose their strength when implanted, amide group becomes hydrolyzed(水解) by enzymes in body

III. E.g. Nylons 尼龍, wool, silk 蠶絲

對抗形變的能力

$\frac{\text{斷裂時的變形長度}}{\text{原始長度}} \times 100\%$

低吸水率⇒適合用於潮溼環境，且仍維持stable

Material (材料)	Tensile Modulus (拉伸模量, GPa)	Tensile Strength (抗拉強度, MPa)	Elongation at Break (斷裂伸長率, %)	Water Absorption (吸水率, %)	Relevant Characteristics (影響力特性)	Applications (應用)	Examples as Biomaterials (生物材料範例)
Polyethylene (PE)	0.8-2.2	30-40	130-500 高延展性	0.001-0.02	High strength, hardness, stiffness, low creep (高強度, 硬度高, 剛性高, 低蠕變性)	Medical tubing, joint replacements (醫療管材, 關節置換)	Hip liners, prosthetic components (髖關節襯墊, 假肢部件)
Poly(methyl methacrylate) (PMMA)	3-4.8 形變↓，難變形	38-80 形狀stable 可承受高應力	2.5-6	0.1-0.4	Rigid, transparent (剛性高, 透明性)	Intraocular lenses, bone cement (眼內鏡片, 骨水泥)	Dental fillings, bone replacement (牙科填充, 骨替換材料)
Polytetrafluoroethylene (PTFE)	1-2	15-40	250-550	0.1-0.5	High flexibility, chemical resistance (高柔韌性, 抗化學性)	Vascular grafts, catheters (血管移植物, 導管)	Coating for medical devices (醫療器械塗層)
Polylactide (PLA)	3.4	53	4.1	<0.5	Biodegradable, moderate strength (可降解, 中等強度)	Sutures, 3D-printed scaffolds (縫合線, 3D列印支架)	Biodegradable implants (可降解植入物)
Poly(hydroxyethyl methacrylate) (PHEMA)	0.29 柔軟	0.15	71	40	High water absorption, soft (高吸水性, 柔軟)	Soft contact lenses, hydrogels (軟性隱形眼鏡, 水凝膠)	Drug delivery systems (藥物釋放系統)
Polypropylene (PP)	1.6-2.5	28-36	400-900	0.01-0.035	Low water absorption, moderate flexibility (低吸水性, 中等柔韌性)	Surgical sutures, hernia meshes (手術縫線, 疝氣補片)	Nonwoven medical fabrics (醫用無紡布)
Poly(ethylene terephthalate) (PET)	3-4.9	42-80	50-500	0.06-0.3	High strength, durable (高強度, 耐用性)	Vascular grafts, heart valves (血管移植物, 心臟瓣膜)	Surgical sutures (手術縫線)

Hydrogels:
Hydrophilic polymer
(1) covalent cross-links
(2) ionic forces
(3) hydrogen bonds
(4) physical entanglement
→High water absorption
e.g. PHEMA