Taxonomy of Materiality

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Contents

Introduction

This taxonomy of materiality summarises important information regarding certain materials and manufacturing processes to provide the reader with a detailed understanding of how they work, their uses, and a summary of their advantages and disadvantages. The images included will help the reader to visualise the processes and uses of materials described, encouraging an analytical and creative mindset when reading this text.

The materials explored in this book intentionally cover various categories including metals, woods, polymers, synthetic materials, smart materials, and composites. They also span across history from the use of cork to seal containers during the Egyptian Empire to the development of aerogels designed to be lighter than the volume of air they displace.

Similarly, the industrial processes detailed in this taxonomy date as far back as the use of lampworking in Africa thousand of years ago all the way up to recent experimentation with contour crafting, a way to 3D print entire houses in just 24 hours. The selected manufacturing processes also cover a variety of materials to broaden the array of information supplied in this text.

A case study into Lego's eco journey towards producing 100% sustainable bricks is also included at the back. This provides an example of the importance of carefully selecting materials and manufacturing processes at an industrial scale in a step towards circular design.

JELUTONG

Jelutong is a hardwood that comes from **tropical evergreen** trees. It is primarily grown in **South East Asia**, and is therefore slightly more expensive due to its rarity. It is initially a white colour but gradually becomes yellowy brown over time. It has been overharvested and is therefore becoming a threatened species.

Jelutong was originally tapped for latex to make chewing gum but is now exploited for its ease of carving. It is commonly used for **patternmaking and carving** detailed wooden ornaments.

Abstract wooden sculpture by Mark Sasaki to exhibit the creative freedom of carving Jelutong

- Uniform grain lines – no distinct growth lines
- Softness – easy to carve
- Dimensional stability
- Low shrinkage levels prevent cracking after carving

- Poor decay and insect resistance
- Sawdust can cause skin irritation and dermatitis
- Easy to dent surface

PIEZOELECTRIC MATERIALS

Piezoelectric materials **generate an electric current in response to mechanical pressure**. In the 1880's, the piezoelectric effect was proved through studying the pyroelectricity of underlying crystalline structures. It has since been discovered that this electric charge accumulates in **certain crystals, ceramics, proteins, and biological matter like DNA and bone**.

These unique types of smart materials are now being used in various everyday electronic appliances like **mobile phones, speakers, and grill igniters** to generate an electric current as a result of a single touch.

Piezoelectric show power generator to charge the user's phone/music device

- Instantaneous responses
- No maintenance – generate their own electricity
- Generators are environmentally friendly, compact, and lightweight

- Only works for dynamic pressure measurement
- High output impedance – frequency anomalies
- Sensitive to temperature and humidity

KEVLAR

Kevlar is an **aramid fibre woven into textile materials** due to its **unparallel strength-to-weight** ratio that is **quintuple that of steel**. Chemical giant **DuPont** was searching for a lightweight material for tyres, leading to the invention of Kevlar. Whilst experimenting with polymers, they discovered that some of them formed liquid crystals whilst in solution, creating an uniquely strong structure.

The unique properties of Kevlar have led to it being used in **car tyres, aeroplane bodies, and cut-resistant gloves**. This become revolutionary due to its strength despite being so light.

Kevlar police armour designed to protect the wearer from bullets and knives

- Extremely high impact resistance
- Heat resistance – prevents wearer overheating
- Durable yet lightweight
- High tensile strength

- Moisture absorbent – affected by environment
- Poor compressive strength – stiff to wear
- Expensive and non-sustainable production - needs concentrated sulfuric acid

CARBON FIBRE

Carbon fibre is an **organic polymer containing chains of crystalline carbon filaments**. It gains its strength when **twisted and then woven into cloth**. It can then be **moulded and coated in resin** for additional strength and structure.

It has been exploited in the **motorsport industry to maximise speed** whilst protecting the internal mechanisms of the car. It is also commonly used in **aircraft production and military machinery**. The sports industry has also recently adopted carbon fibre to produce lightweight but strong bicycle frames and tennis racquets.

Lightweight, carbon fibre aero bike

- Strong yet lightweight – superior to heavy steel
- Heat and chemical resistance
- Low thermal expansion
- Extremely high tensile strength

- Expensive manufacturing process
- Shorter lifetime than metals
- Brittle and low shear strength

PEWTER

Pewter is a metal alloy containing **mostly tin with some antimony and copper** for additional strength. Popular in **Roman household products**, Pewter is still being used today to create jewellery and tableware with a vintage aesthetic. It is **typically cast** and then sometimes detailed using hammering and engraving.

Due to its shiny aesthetic and castability, pewter is perfect for **jewellery and tableware**. It is also cheaper than metals like silver but can be polished to appear similar.

A selection of old-fashioned pewter tableware

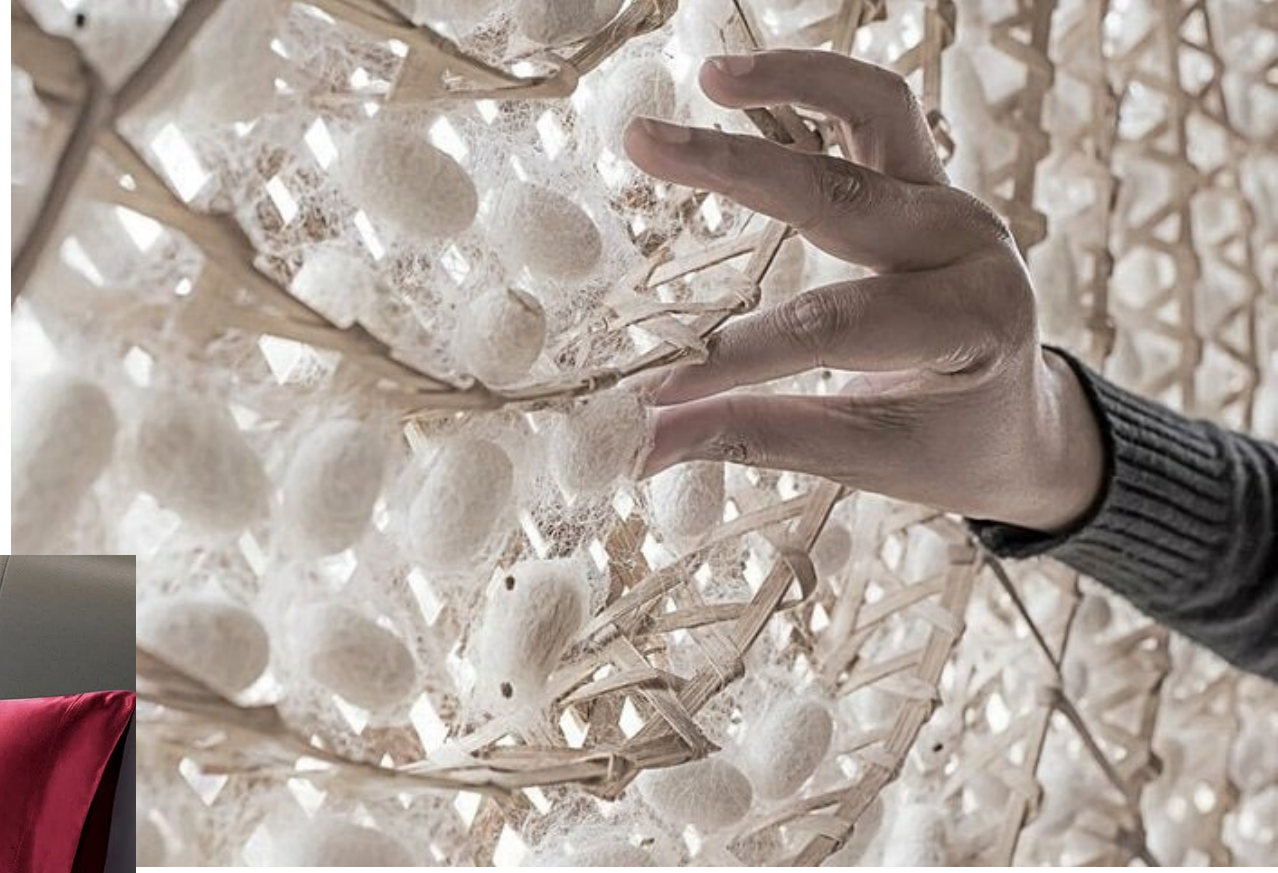
- Low melting point – easy to cast
- Easy to polish or leave with a vintage satin finish
- Malleable and ductile

- Tarnishes over time
- Low durability
- Lead content can poison if absorbed

SILK

Silk is **a natural protein fibre with a reflective, triangular prism structure produced by silkworms** that is woven into cloth. The use of silk traces back to **ancient times**, and has historically been used most by the Chinese.

Silk's absorbency and thermoregulation makes it a suitable material for lots of clothing, however, it is very expensive and therefore mainly used for **formal wear and wedding dresses**. It is also used for **upholstery, bedding, and other furnishings**.



Crimson silk bedsheets and pillowcases

- Naturally sourced, recyclable, and biodegradable
- Thermoregulatory – maintains room temperature
- Soft and comfortable
- Smooth and wrinkle-free

- Unethical – requires killing silkworms
- Unique properties make it very expensive
- Requires special care to prevent damage
- Stains easily

GRAPHENE

Graphene is **a layer of interconnected carbon atoms in a hexagonal structure** that is considered to be a revolutionary modern material. It is **extracted from graphite after corrosion in molten salts** and can be **rolled into cylinders to make carbon nanotubes**.

Commonly used for technological applications such as **rechargeable batteries, touchscreens, headphones, and solar panels**. It is also being adopted in the medical sector for products involving **biotechnology, drug delivery, and disease detectors**.

Flexible organic LED graphene phone screens

- Tough yet flexible
- Considerably stronger than steel
- Lighter than aluminium and transparent
- High thermal and electrical conductivity

- Requires toxic chemicals to be produced
- Can be affected by oxidated environments
- Toxic properties if it enters the cell membrane
- High production costs

CELLULOSE

Cellulose is a **polysaccharide found in plant cell walls** and the **most abundant organic polymer worldwide**. It is used in materials like wood and cotton. It was first isolated in the 1830's and was put into industrial use a few decades after for products like cling film. It is extracted from plants through **pulping**.

It is primarily used in the production of **papers and boards**. However, it has expanded into various other industries to make products such as **clothing and food packaging**.

Biodegradable cellulose food packaging

- Odourless and tasteless
- Recyclable and biodegradable
- Strong and durable

- Requires the destruction of plants to be extracted
- High water absorption

CORK

Cork is another term for the **bark layer of cork oak trees** found in parts of **Europe and Africa**. It is completely organic and sustainable as **the tree can remain standing whilst the cork is harvested**. It has been used for thousand of years, originally used to **seal containers** during the Egyptian Empire and used for **sandals** in Ancient Greece.

It is now famous for its use as wine **bottle stoppers**. Its versatility makes it suitable for other products too such as **badminton shuttlecocks, coasters, and even some furniture**.

Vintage aesthetic, cork wine bottle stoppers

- Impermeability and elasticity due to cell structure
- Sustainable and renewable material
- Cork trees are not endangered
- Thermal insulation

- Scratches easily
- Dents under heavy weight
- Discoloured by light over time

AEROGELS

Aerogels are **solid, synthetic, ultralight** materials produced by **combining silica with a solvent before extracting the liquid and replacing it with air**. They were invented in the 1930's but are now being developed by NASA. Despite being lighter than air, they do not levitate as they are **microporous** and therefore fill up with air which weighs them down.

NASA uses aerogels to keep rocket fuels at cryogenic temperature. It is also being used for **insulation** (including insulated clothing) and experimenting with products such as **phone cases and cooler bags**.

Aerogel insulating a flower from the heat of a Bunsen burner

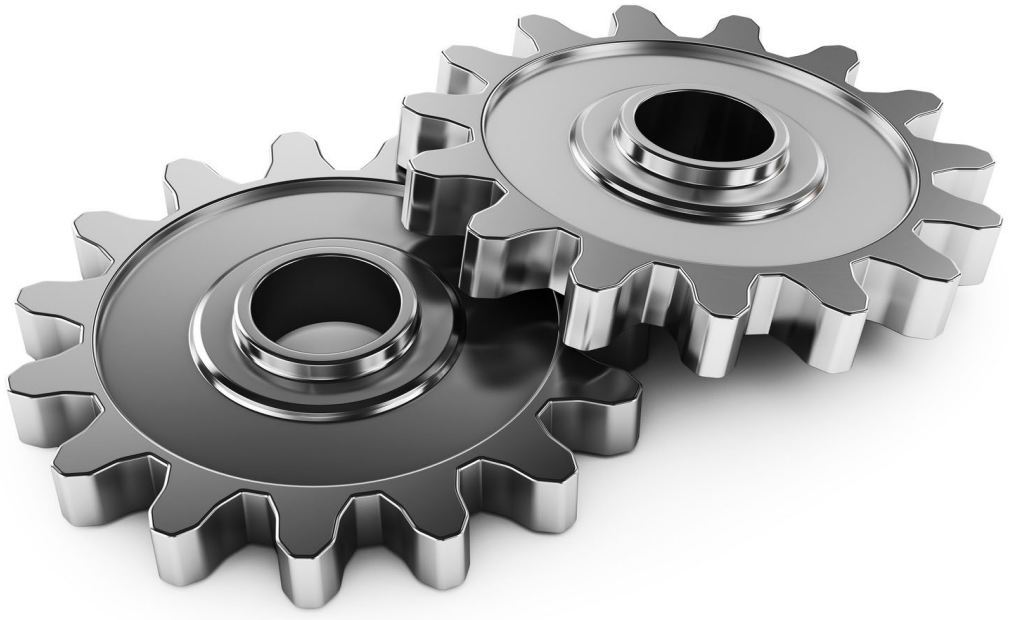
- Fire resistant and thermal insulation
- Lighter than air it displaces
- Designed to be water repellent

- Dents or shatters under pressure
- Expensive production
- Some added substances are difficult to dispose of

PLASMA-ARC CUTTING

A subtractive industrial process that uses an accelerated, ionised gas beam capable of melting through metal. It was developed in the 1980's, and **CNC was incorporated** the following decade to guide the nozzle for complex cuts. The plasma can exceed **20,000 degrees Celsius**, thus requiring lots of PPE including a welding mask, ear guards, and leather gloves. Good ventilation or a respirator is also recommended.

The gas consists of **oxygen, nitrogen, and** argon, which makes contact with the electrode and ionises to create pressure, forcing out a plasma beam constricted by the cutting tip. This creates an **electric arc between the electrode (cathode) in the gas nozzle and the workpiece (anode).** Upon contact with the workpiece surface, the gas reverts to its original state and produces immense heat which melts the metal. The gas flow then blows away any hot molten metal.



"An accelerated, ionised gas beam capable of melting through metal"

This process can be performed on almost any electrically conductive metal such as steels, aluminium, brass, and copper. It is typically used for **on-site construction and signage**. It is also a common process in automotive repair and restoration.

- Fast and accurate on thin sheets of material
- Produces no metal chips
- inert gases - safer than oxygen-based gases which risk explosion
- CNC or portable handheld cutters

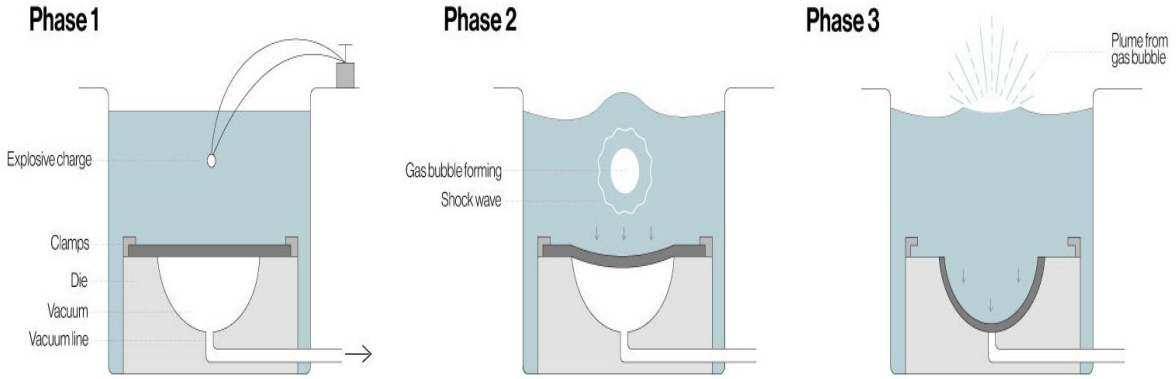
- Larger heat-affected zone (HAZ) around cut
- Expensive CNC equipment
- Unable to cut thicker sheets or coated materials

EXPLOSIVE FORMING

A sheet metalwork production that uses a controlled explosion to generate force, **moulding the metal into the die**. This process developed in America in the 1950's, although the shaped charge effect of explosions had been exploited previously in 1890's to engrave thick iron plates. The explosion occurs underwater, creating a **shockwave that can travel up to 400ft per second**.

The explosion is typically performed underwater to control the shockwave speed and prevent damage to the surroundings. This blasting pool or container is the main safety regulator. Gases frequently used the generate the explosion include; **hydrogen, oxygen, methane, and acetylene**. Suitable PPE must be worn for the handling of toxic chemicals.

Most metals can be used such as aluminium, steels, titanium, and copper. It is frequently used to create aerospace components such as aircraft panelling due to its accuracy for complex pieces. It is often used for **corrugated parts such as radiators** because of the work hardening strength the process inevitably increases.



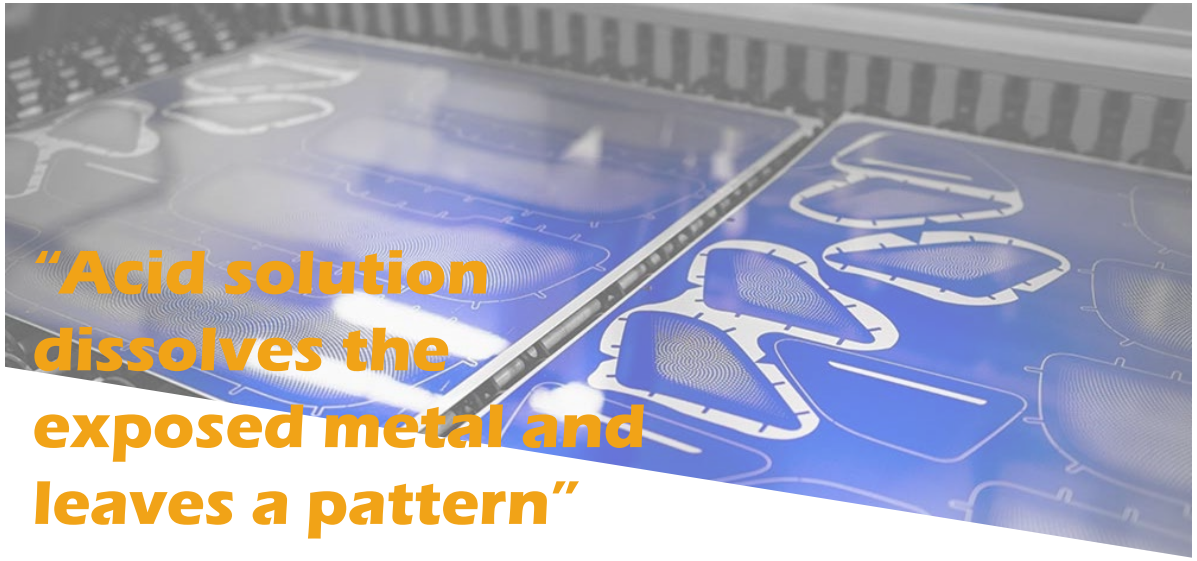
- Cheaper than building presses for mass production
- Results in work hardening – stronger finished product
- High accuracy for complex shapes
- Good surface finish – pre-coated in protective layer

- Produces lots of C02 and uses toxic chemicals
- Long set-up time
- Not widely available

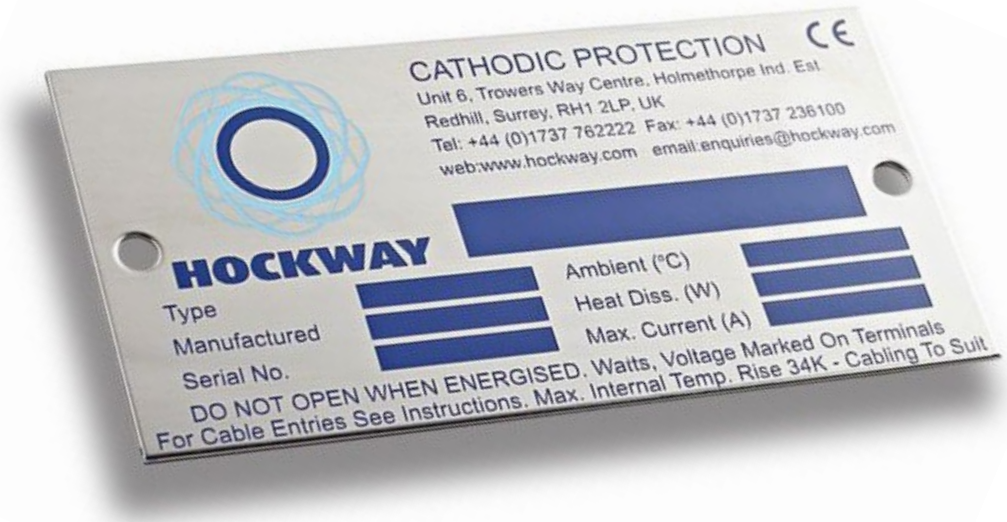
CHEMICAL ETCHING

A subtractive process that **uses chemicals and corrosive metals to etch a design into a metal sheet**. Due to the use of chemicals, valves must remain firmly shut when not in use. Operators should also wear an apron, rubber gloves and safety goggles. Good ventilation is recommended to prevent long-term health problems due to the inhalation of hazardous acids.

A **photoresist polymer stencil is applied to a metal sheet** by roller, wet dip, or dry lamination. The metal is then sandwiched between photo tools and **exposed to UV light**, hardening selected laminate areas into an acid resistant surface. Unexposed laminate is washed clear. Acid solution dissolves the exposed metal and leaves a pattern. Holes are created by exposing the metal to chemicals from both photo tools.



"Acid solution dissolves the exposed metal and leaves a pattern"



Practically all metals can undergo photochemical etching such as nickel, titanium, steel and copper. It is often used for **nameplates, trophies, and circuit boards** due to high levels of detail and repeatability.

- Micron accuracy for limitless parts – all sprayed at once
- Smooth and burr-free edges
- Cost effective tooling
- No loss of material properties – no heat or force used

- Needs lots of surface preparation for etching
- Controlled clean environment to prevent dirt or dust particles disrupting connection between polymer and metal

LAMPWORKING

A glass forming process that uses air blasts and tools to create abstract ornamental forms. This technique has **thousands of years of history** across various continents from Africa to Asia to Europe, experiencing a modern resurgence. Due to the intense height and light, it is necessary to wear safety glasses and have a good extraction/ventilation system. Remove flammable items from the nearby are.

Its main difference to glassblowing is that it **uses a handheld torch** instead of a furnace to melt the glass. This allows **greater control to form unique shapes** and create bespoke products. The molten glass is the worked into any desired shape with hand movements and blasts of air. This is usually performed on a graphite work surface due to its heat resistance

“uses air blasts and tools to create abstract ornamental forms”

This process is exclusive to glass and is used to create Christmas tree decorations, marbles, figurines, and ornaments. It was also used to create **beads from as early as 5th Century BC**, a practice that became popular in Italy.

- Cost effective tooling
- Bespoke items and opportunity for expression
- Develops hand working skills

- Time-consuming to get well-finished products
- Difficult to mass produce identical pieces

PRESSING PLYWOOD

This process involves fusing plywood panels together using platens of immense pressure and heat to help them reach **maximum mechanical strength**. The **hot press machine uses pressure and heat to process wood**. Operators must wear safety goggles and heat-resistant gloves. Platens must be perfectly aligned to prevent an uneven pressure distribution. Temperature must be monitored and the machine must be cooled after pressing.

Firstly, plywood veneers are **loaded onto a room temperature lay-up rack with opposing grain direction** for additional strength. Next, they are pressed using hot platens exceeding **100 degrees Celsius**, curing the glue between the panels. Pressure is slowly released to prevent delamination or other defects. Cold pressing is a similar process which offers a lower risk of deformation but requires a longer bonding time.

"fusing plywood panels together using platens of immense pressure and heat"

Hot pressing is a process that is now used in the ceramics, glass, and even metal industries. However, for plywood, it is used to create **stock form sheets** that can then be bulk bought by companies to make various products.

- Finished panels have maximum mechanical strength
- Produces large sheets of stock size plywood
- Requires few operators – mostly automated process

- Produces high amounts of CO_2 to heat the platens
- Time consuming – curing time and platens cooldown
- Expensive machinery

SLIP CASTING

Liquid clay is poured into plaster moulds to create complex forms. This technique was **developed over a thousand years ago in China** and reinvented in the 18th Century in Europe. Slip casting is a relatively safe production process. The most safety concerns revolve around using the kiln such as wearing safety gloves. Hands should be washed regularly to prevent slip drying onto hands or accidental consumption.

Once the **plaster mould** is secured with elastic bands to prevent leaks, the slip (ceramic particles suspended in water) is poured into it. It is then left inside with **longer times leading to a thicker wall**. Excess slip is then poured out of the mould. This should be left for an hour or longer, enabling it to shrink before release from the mould. Trim any excess clay for the finished piece which should then be kiln dried.

Slip casting is used to create ceramic vessels of various forms and wall thicknesses. These can include **vases, chimneys, bowls, and ornaments**. It has been a popular process for creating complex shapes for over a thousand years.

- Clay can be reused as slip – minimal waste
- Controlled wall thickness
- Produces identical, complex shapes that cannot be accurately hand-formed

- Slow process for batch production without multiple moulds
- Time-consuming to make new moulds
- Dimensional precision – shrinks within the mould

ANODISING

An electrochemical process that fortifies the oxide layer of a metal. It **developed large-scale during the 1920's for the protection of military machinery**. It has since inspired the development of sulfuric acid and oxalic acid anodising. Protective clothing should be worn throughout the process due to the use of acidic electrolyte. All operators should stay clear from the electrolyte whilst an electrical current is being passed through.

The metal is **immersed in a bath of electrolyte with a cathode**. When an electric current is passed through, the **metal becomes an anode and attracts the oxygen ions of the electrolyte to form an aluminium oxide wall**. A dye can be added after removal as the metal is porous.

"An electrochemical process that fortifies the oxide layer of a metal"

Anodising is most commonly performed on aluminium, but also works for magnesium and titanium. It **does not work on steels because the oxide layer (rust) flakes off** and allows the metal to corrode anyway. It is usually used for electronic appliances like **microwaves, pans, and fridges**.

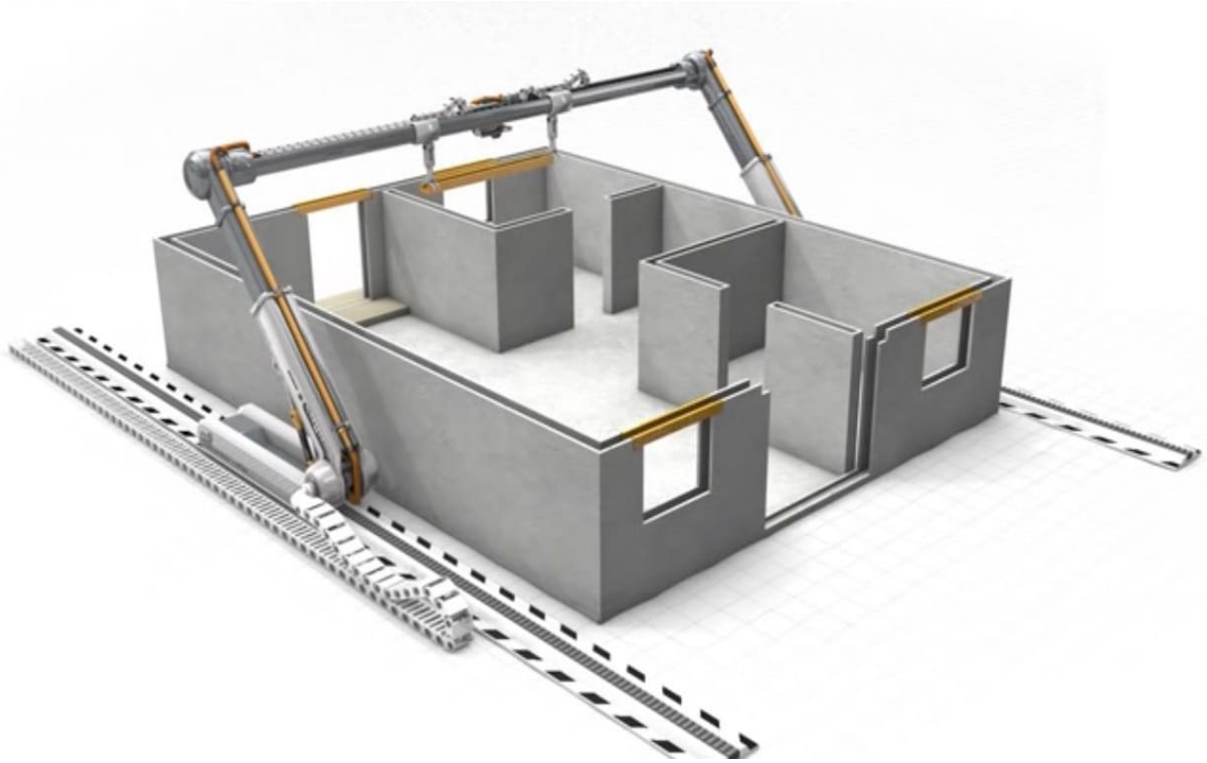
- High quality finish of various colours
- Good durability and resistance to surface damage
- UV stability makes it ideal for outdoor products
- Better surface adhesion than paints

- Expensive equipment unless batch produced
- Affects dimensions due to thickened oxide layer
- Harmful byproducts like aluminium hydroxide

CONTOUR CRAFTING

A recently developed process of 3D printing large architectural structures to minimise waste. This is a new technology founded by **Behrokh Khoshnevis**, who designed the process for **home construction after natural disasters** plagued his home country Iran. He is now CEO of the Contour Crafting Corporation.

The construction fundamentals are near-identical to rapid prototyping. A **CNC-controlled crane** of gantry builds structures layer by layer, stopping occasionally to allow the insertion of plumbing, wiring, and other systems. The process is **capable of building a home in one day**.



"3D printing large architectural structures to minimise waste"

This new construction process uses 3D prints concrete into any desired form. It has been **considered by NASA for the creation of structures on Mars and the Moon**. It has the potential to make structures from 90% lunar material which means transporting less materials from Earth.

- Additive process – no waste production
- Efficient and accurate process
- Architectural freedom to design unique forms
- Cheaper materials

- Replaces role of construction workers
- Very expensive machinery
- High CO_2 production from machinery

PULTRUSION

A continuous fibre lamination process that creates reinforced plastic components using liquid resin. This process was developed in the USA shortly after WWII, with the main difference to extrusion being that the fibres are **pulled through rollers**, not pushed through dies.

Woven fibres are pulled through a series of rollers and **impregnated with resin** in the form of a bath or resin injection chamber. It is then passed through a **heated die** to initiate **polymerisation** and create a continuous roll of hardened fibre.

"A continuous fibre lamination process that creates reinforced plastic components"

Pultrusion commonly uses fibreglass and polyester resin. It is used to create products with a single cross section like tool handles, structural beams, and fridge components.

- Continuous process – high output for machinery costs
- Requires little monitoring
- Uniform output
- Produces UV and corrosion resistance

- Generally limited to one cross section
- Expensive heated dies
- Most used materials are not recyclable

SANDBLASTING

Sandblasting involves firing tiny sand particles at a material to change the surface texture. It can be **smoothed, roughened, or cleaned** of any imperfections. **Respiratory equipment and good ventilation** is crucial to prevent inhalation of sand particles. A blast helmet and a sandblasting suit or some other protective clothing should also be worn.

There are various types of sandblasting with different pressure levels. In general, a **pressurised fluid or gas is used to propel sand through a nozzle** at the material suspended on hooks or secured in place. This is performed in a blast room with good ventilation.

Sandblasting has been used for over 100 years to re-texture materials. It can be used on a variety of materials including **glass, metal, plastic, and ceramic**. Its most common use is cleaning **patios and brickwork** or rust from **boat hulls and other large structures**.

- Quick and efficient process
- Easy to coat complex geometric shapes
- Removes corrosion and smooths surface
- Helps paint attach afterwards due to small scratches

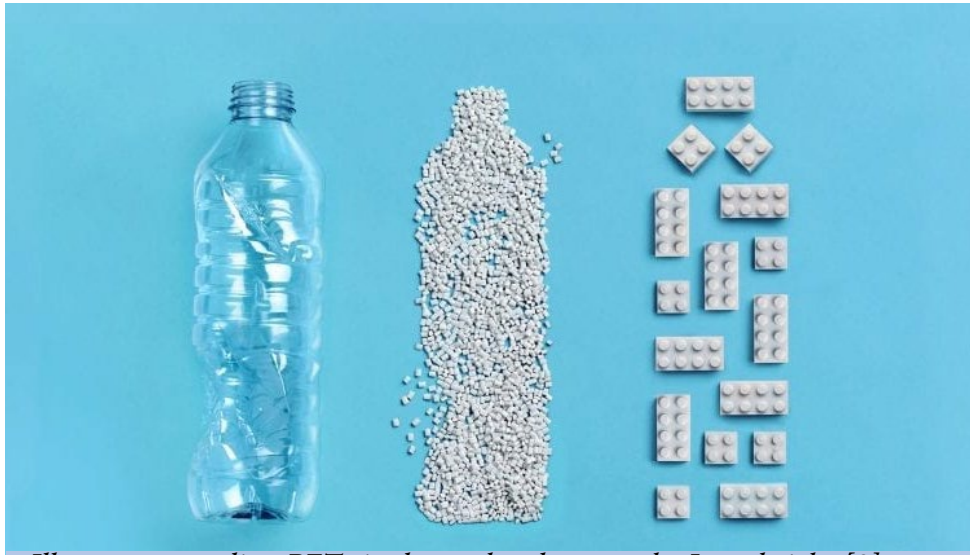
- Can scratch very smooth surfaces
- Produces toxic and polluting byproducts
- Sandblasting with sand has been outlawed in the UK due to cases of lung diseases

SUSTAINABLE BRICKS

Lego is a globally-renowned, Danish toymaking company that designs sets of interlocking, coloured bricks offering children imaginative freedom to create various structures. Amidst the growing awareness of climate change, Lego has launched plans for a more sustainable future in terms of materials, production lines, and packaging. Under Niels Christiansen's leadership, their advancements so far highlight the complexities of researching and introducing sustainability-based design changes into a firmly established production line, and the subsequent impact it can have on consumption levels.

Lego has been readdressing the environmental impact of the Lego brick for years, searching for long-lasting, sustainable material alternatives. They intend to use only sustainable materials by 2032. In 2018, Lego started making elements from bio-PE, derived from Brazilian sugarcane [1]. It is sourced sustainably using WWF guidance and possesses flexibility and durability comparable to ABS (used for 80% of Lego bricks at that time) [2]. This proves funded research can lead to sustainable solutions, a large investment many companies are reluctant to make. Furthermore, Lego boldly pledged to stop using petroleum-based materials within 2 years [3]. This proved too great a challenge, so instead attention has been directed towards improving ABS carbon footprint (which requires 2kg of petroleum for 1kg of plastic) by adding sustainable materials [2]. However, Lego's spending is scheduled to triple by 2026, foregrounding the issue of how much time and money investment is required.

Lego tested bio-PE on botanical-themed Lego elements [4]



Illustrates recycling PET single-use bottles to make Lego bricks [2]

Designing sustainably inevitably requires design changes for the product, packaging, and production process. This means eliminating single-use bags and, thus, a packaging redesign after consideration and testing. Currently, 75% of Lego boxes are recycled cardboard [1]. Additionally, materials possess different mechanical properties, hence why Lego has tested over 300 materials for the Lego brick. They recently ended an attempt at using recycled PET bottles [1] as the new brick material after discovering the machinery replacement and processing would cause a higher carbon footprint over product lifetime. This exhibits the difficulty of trying to simultaneously eliminate fossil fuels and reduce carbon emissions [3]. It also demonstrates the complexity of implementing design changes into an established production line that must meet consumption levels.

As the world's largest toymaker, Lego's mass-produced construction blocks have a huge environmental influence. With emerging companies like FabBrix, who have designed wooden Lego bricks, moving towards circular design is also a business decision [5]. Moreover, Lego blocks are injection moulded. This makes production changes expensive and time consuming, which could affect output levels and subsequently profit. Lego is therefore advertising their eco journey to attract consumers with an environmentalist ethos through public statements and branding. They also introduced a replay system in North America where people donate old bricks which are cleaned and donated to charity. This encourages a circular economy and strengthens the company-consumer relationship.

Lego's sustainable bricks display how companies can contribute to a sustainable future whilst maintains a connection with the client. By publicising the importance of circular design, Lego demonstrates the need to invest time and money into designing for the world we live in today.

Recyclable wooden construction blocks by FabBrix[5]

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