T271_1

Toys and engineering materials

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Contents

Introduction

Engineers need to have a sound understanding of materials and their properties in order to select an appropriate material for any particular design or purpose. This free course, *Toys and engineering materials*, develops your understanding of the impact of new engineering materials on the changing design of toys and motor vehicles.

Often, the development of an engineering product, such as a motor vehicle, is taken for granted and the link to the development of the component parts that allow these developments to occur is missed. For example, the impact of carbon fibre on the development of high performance vehicles, or the impact of battery technology on the development of electrically powered vehicles.

The availability of more sophisticated materials has driven the evolution of motor vehicles, and this is well captured by examining the evolving design and performance of the vehicles at the motor museum, as shown in the introductory trailer of this course.

This OpenLearn course is an adapted extract from the Open University courses T271 *Core engineering A* and T272 *Core engineering B*.

Learning outcomes

After studying this course, you should be able to:

- understand how the development of engineering materials can drive the design process
- understand how the introduction of semiconductors made a huge impact on the future of design
- read real examples of the impact of material developments on toy manufacture.

1 Engineering: a holistic approach

Often in an engineering project you will need to incorporate knowledge and skills from all areas of your experience: skills learned on the job, from your studies or, indeed, life skills. In this course, you are going to look at a short case study that considers material use in the manufacture of toys.

In this course, 'toy' is used to describe a range of items, including traditional toys, such as dolls and LEGO®, sports equipment, such as cricket bats, and leisure equipment, like drones and hoverboards. The case study will concentrate primarily on materials use and development.

The main types of materials considered in this section are wood, synthetic polymers, composites and metals.

1.1 Materials use in the manufacture of toys

There have been impressive advances in the design and manufacture of toys over the past few decades. These advances have been driven by the rapid development of material science and electricity storage systems, such as lithium ion batteries.

If you were born a few hundred years ago, your childhood toys would not have been dissimilar to those used by children thousands of years ago. For tens of thousands of years, children played with the objects they could find in nature, such as twigs, stones or animal parts like bones, skins or internal organs of animals. For example, dice may have originated from throwing sheep's knucklebones (Figure 1), and an inflated pig's bladder was used as a playing ball.

Figure 1 A statue from the Roman era of women playing with knucklebones

Today, toys are far more sophisticated, and many of the toys available now could not have been envisioned by previous generations. One example is shown in Figure 2. Most of these advances in toy manufacture have occurred within the last century.

Figure 2 Sophisticated remote-controlled flying toys have become commercially available in the last decade

Recent technological advances in materials engineering and mass production have made toys more affordable. Prior to the invention of synthetic plastics, toys such as dolls and other play figures were handmade using porcelain, wood and bone, or mass-produced using tin and lead. These toys were relatively expensive and therefore less readily available. Modern materials have allowed toys to be mass-produced at vastly reduced cost, such as the play figures shown in Figure 3.

Figure 3 Mass-produced plastic play figures

In this course, inventions and developments leading to the evolution of toy design are used as examples to highlight the effect of materials engineering on modern life.

1.2 The longevity of wood

Start by looking at the three charts in Figure 4. Known as Ashby charts, these visual representations compare two different properties of materials; in this case, strength against density. The differently coloured 'ovals' indicate the range of values of these properties that are found for a particular material or class of material.

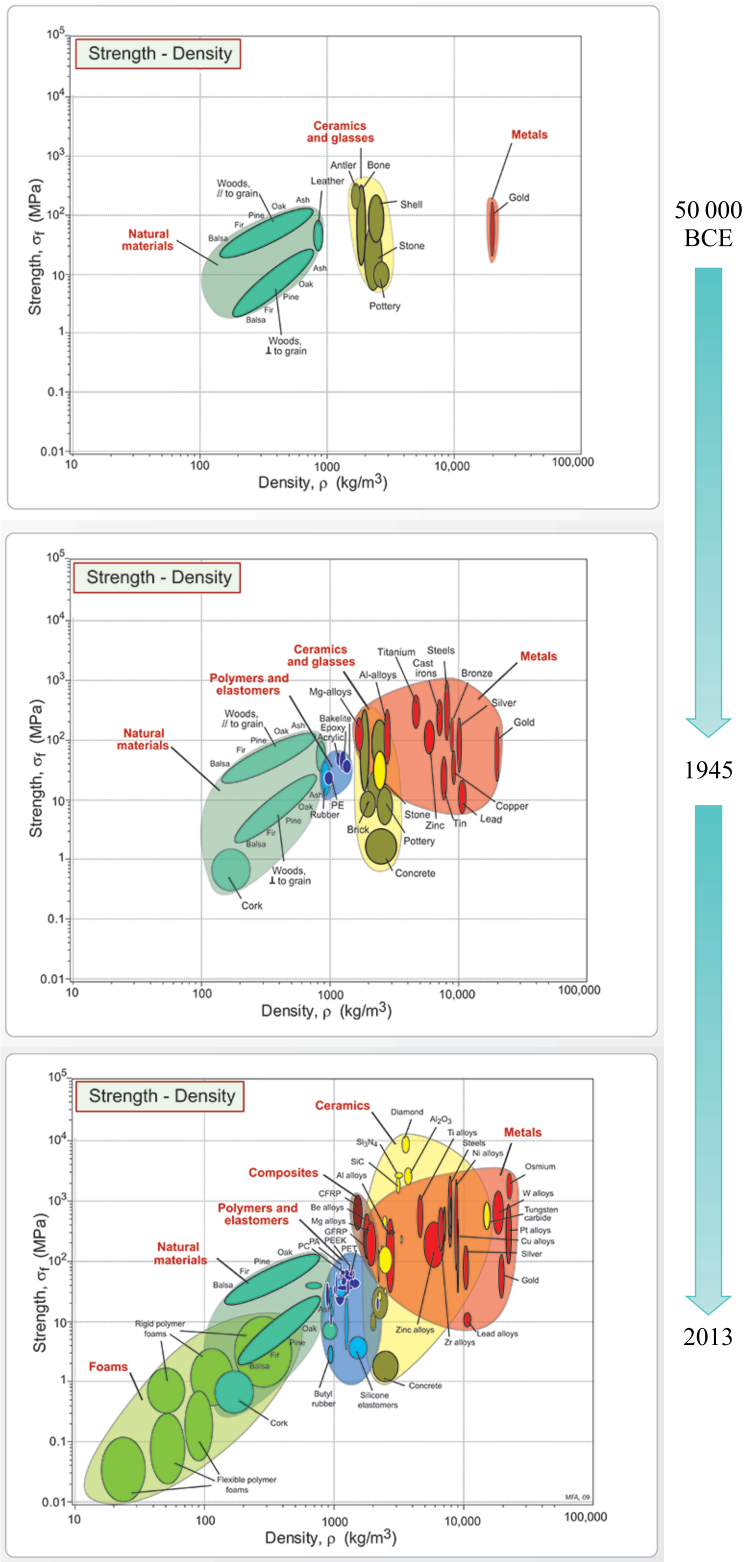

Figure 4 The use of various materials for manufacturing and construction over time

Each chart is a snapshot of a time in history and represents the materials available at that time. Look first at the blue-green ovals (on the left of the charts). These represent wood, which is still used widely today. In the centre of the middle chart, the blue ovals represent polymers and elastomers. These materials didn't appear until the early twentieth century. Finally, in the bottom chart representing the present day, there are the additions of composites, denoted by a small dark brown oval in the centre, and foams, the large section of light green ovals starting at the bottom left-hand corner. These charts highlight both the continued use of materials like wood and the emergence of new materials such as composites.

In Figure 4, look at the top chart, dated 50 000 BCE. Here, the combinations of strength and density offered by wood cover a greater range than those of other materials. Also, within each type of wood there is a large variation both in density and strength. For example, there are many naturally occurring forms of cork, and each variety exhibits very different values of both strength and density. This difference is less marked for the other materials shown on the charts.

In contrast to wood, look at the orange ovals on the right of the middle and bottom charts. These represent types of steel, and they all exhibit a wide variation in strength, but show more consistency in the densities.

It is this variation in both density and strength that makes wood useful. A single type of wood can be adopted for a wide array of uses, as exemplified by oak, which has a density that varies from around 850–1130kgm^{-3}. Lower density oak is extensively used in the construction of ships, while higher density Japanese oak is used to make drums, as it produces a brighter and louder tone. Such differences are also exploited in the manufacture of toys.

In Figure 5, hardwoods such as maple have been used for higher strength components, but their use is kept to a minimum as they add weight and are expensive. Meanwhile, cheaper soft woods, such as spruce or fir, are used for large parts, saving money and weight.

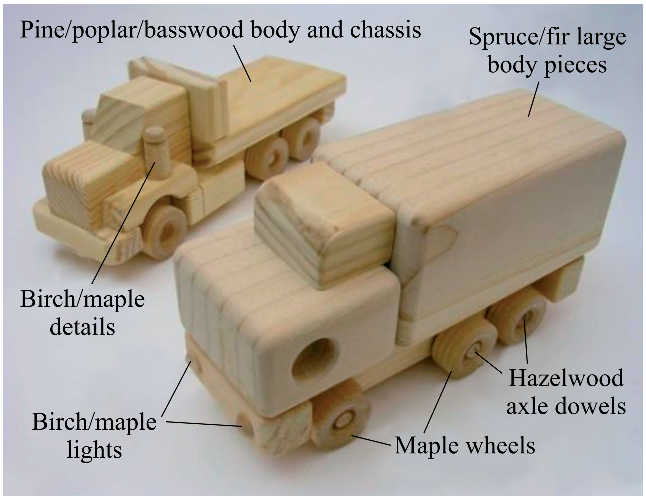

Figure 5 Toys utilising different woods for different parts

Notice that the Ashby charts give different values for the strength of wood depending on whether it is measured parallel or perpendicular to the grain. This is an example of **anisotropic behaviour**, meaning that values of individual properties vary depending on the direction in which a force is applied.

This fact is well known to lumberjacks, wood loggers, and carpenters, who know that it is far easier to split wood parallel to the wood grain than across the grain. This is an important attribute when designers and engineers use wood for toys. For instance, when making a toy that needs to withstand high loads, such as a cricket bat, it is important how the wood is cut out of the tree.

Cricket bats are manufactured out of willow. Willow has an average tensile strength of 59MPa along the grain, but 2.4MPa across the grain. Consequently, for cricket bats, the willow must be cut so that the ball will impact the bat perpendicularly to the grain, to ensure the bat exhibits its greatest strength. This grain direction is clearly visible in Figure 6.

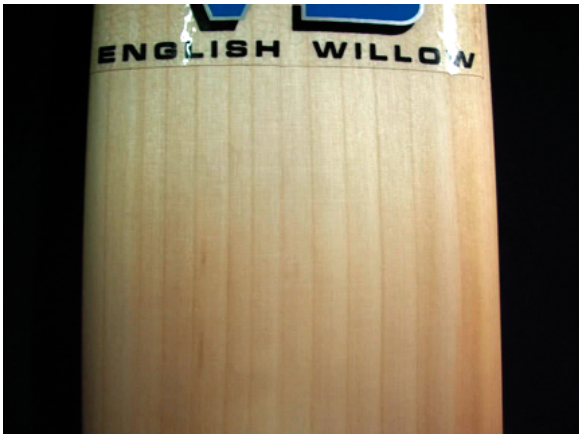

Figure 6 The grain in a willow cricket bat

Apart from its useful engineering properties, people have a natural affinity to wood, mostly owing to its appealing texture, colour, feel and even its smell. All these desirable properties, alongside its ready availability, low cost, inertness and (generally) non-poisonous composition, make wood an ideal material for making toys (Figure 7).

Figure 7 Wooden blocks and a modern train set that are safe for young children

However, wood does not just excel as a material for toys. Wood can also be considered as an engineering construction material.

1.3 Versatile plastic

The first viable and economic methods for producing the synthetic materials now commonly described collectively as ‘plastics’ were developed in 1907, by Leo Hendrik Baekeland, a Belgian-born American living in New York State who invented ‘Bakelite’. In the decades that followed, a wide range of similar materials were developed, and ‘plastic’ became a household name. The most evident property of the new materials was their formability: most plastic materials can be moulded into virtually any desired shape. Most plastics have a much lower strength than metals, but this disadvantage is often outweighed by plastics having a much lower density and cost when compared to metals.

Polymer is a collective name for all materials that are formed from long chain molecules. There are naturally occurring materials that are polymers, such as silk, wool, cellulose and proteins. Plastics is a collective term often used for synthetic polymers, whether or not they exhibit plasticity.

The mass production of plastics in the late 1950s saw the development of many plastic toys, including construction-based plastic toys such as LEGO®, which used plastics tough enough to be assembled and disassembled many times. Figure 8 shows some of the best-selling toys that are made of plastic.

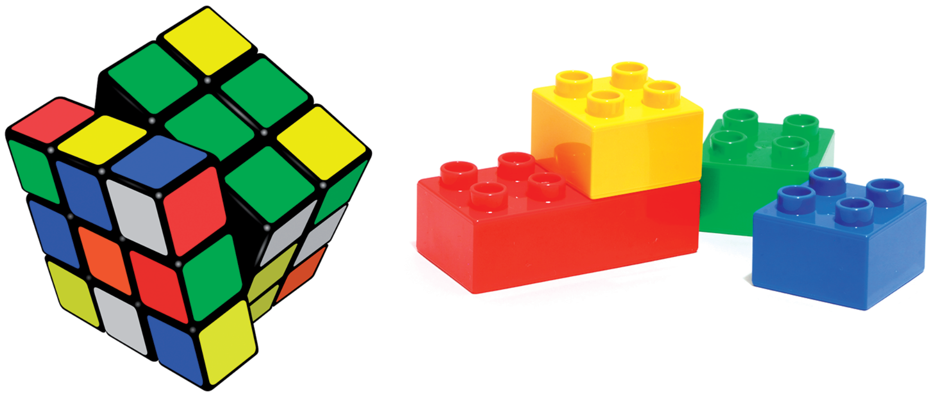

Figure 8 Rubik's cube and LEGO® are still in demand after their first appearance over 40 years ago

1.3.1 Injection moulding

In this activity, you are asked questions on the following video, which shows how injection moulding of plastics to manufacture LEGO® pieces is done industrially.

Activity 1 Lego and injection moulding

Allow about 15 minutes

Consider the following questions as you watch the video and note down your answers.

a. How do the manufacturers ensure that the LEGO® brick is coloured throughout the whole piece?

b. What is the pressure of injection moulding in pascals?

   Use the conversion factor 1 psi = 6894.8 Pa (to 1 d.p.) and give your answer to one significant figure.

Video content is not available in this format.

Answer

a. Colour is added to the particulate material, mixed, and then heated to between 230 °C and 310 °C and 'cooked' in an oven to form a coloured paste.

b. In the video, you are told that the pressure of injection is 29 000 psi. This can be converted to pascals using the conversion factor 1 psi = 6894.8 Pa (to 1 d. p.), so

$$\begin{aligned} 29\,000 \times 6894.8 &= 199\,949\,200 \\ &= 0.1999\ldots \times 10^{9}\ \mathrm{Pa} \\ &= 0.2\,\mathrm{GPa}\ (\text{to 1 s.f.}). \end{aligned}$$

Therefore the pressure of injection is 200 000 000 Pa or 0.2 GPa (to 1 s.f.).

Note: As an engineer, you may be required to define or interpret values from the very small scale (individual atoms) to the very large (the Voyager 1 probe has covered billions of kilometres on its travels to the outer reaches of the Solar System). To accommodate this range of values, there is an additional unit extension, the SI prefix, which gives standard multipliers to the SI units. You may already be familiar with using prefixes like giga (G), mega (M), kilo (k), milli (m), micro (μ) and nano (n), but if not, here are a few examples:

1 Tm = 10^{12}m (or 1 000 000 000 000 m)

1 GN = 10^{9}N (or 1 000 000 000 N)

1 MW = 10^{6}W (or 1 000 000 W)

1 ms = 10^{-3}s (or 0.001s)

The SI prefixes allow you to present information in a format that is easier to interpret. So, at the small scale, the diameter of a hydrogen atom is 1.06 × 10 −10 m, or 106 pm (picometres) and, at the other extreme, Voyager 1 is approximately 20 859 million km from the sun, which is 20.859 × 10 12 m or 20.869 Tm (terametres).

1.3.2 Building a tower

To gain an understanding of the strength of a LEGO® brick made out of a polymer called acrylonitrile butadiene styrene (ABS), consider how high a tower made of 2 × 2 LEGO® bricks could theoretically reach.

When designing a tower, there is a theoretical limit to the height that can be achieved before it is crushed under its own weight. Plastic is an excellent choice of material for toy manufacture because of its toughness and its high strength-to-weight ratio, but is it really strong enough to build a skyscraper with?

Activity 2 How tall can you build a LEGO® tower?

Allow about 15 minutes

Engineers have determined that a 2 × 2 LEGO® brick could withstand a force of just under 4220 N before failing. A single 2 × 2 LEGO® brick has a mass of 1.15 g and a height of 9.6 mm (excluding the connecting dimples on the top side).

Assuming g = 9.81 m s^{-2}, calculate the following:

a. What mass of LEGO® would provide a force of 4220 N?

b. To the nearest brick, how many 2 × 2 LEGO® bricks would constitute the mass of LEGO® calculated in part (a)?

c. How high would the tower reach before exceeding the structural strength of a 2 × 2 LEGO® brick?

Answer

a. The mass required to create a force of 4220 N is

$$\frac{4220\,\mathrm{N}}{9.81\,\mathrm{N\,kg^{-1}}} = 430.173\ldots\,\mathrm{kg}.$$

b. The number of LEGO® bricks in 430.173… kg of LEGO® is therefore

$$\frac{430\,173\ldots\,\mathrm{g}}{1.15\,\mathrm{g}} = 374\,063.73\ldots$$

so there are 374 064 bricks to the nearest brick.

c. The height of the LEGO® tower is

$$\begin{aligned}374\,064 \times 9.6\,\mathrm{mm} &= 3\,591\,014.4\,\mathrm{mm}\\ &= 3.591\ldots \times 10^{6}\,\mathrm{mm}\\ &= 3.6\,\mathrm{km}\ (\text{to 2 s.f.}).\end{aligned}$$

Further developments in material performance allowed the introduction of the first sustainable LEGO® bricks in 2018. You can read about these developments in this article.

To sum up, plastics are an incredibly versatile and often very cheap material that is put to a vast array of uses in toy manufacture. But, like many other synthetic materials, plastics are not really sustainable, and are the cause of significant environmental harm if not correctly disposed of.

2 The application of metal

Arguably metals, including steel, are the most important structural materials in modern life. Metals have several properties which have made them extremely popular with toy manufacturers. For instance, due to their high formability, metals can be rolled into thin plates and then pressed to make tubular or hollow components. The vintage toys in Figure 9 are made from thin steel sheets which, very often, are pressed **tinplate** (a thin sheet of steel coated in tin). Tinplate has some desirable properties for toy manufacturers such as its lustre, corrosion resistance, solderability, weldability and formability.

Figure 9 1950s vintage tinplate toy car

2.1 Advantages and disadvantages

Typically, metals have a much higher strength than plastics and woods, meaning that a plastic toy with a wall thickness the same as the tinplate toy would be insubstantial to handle. But perhaps the most attractive property of a tinplate toy is its similarity to the real items.

However, older metallic toys had a number of significant disadvantages over plastic toys. One was their tendency, when they break, to present razor-sharp cutting edges to small fingers. Also, they rapidly became unattractive as the paint was lost through wear and tear. Small children ingesting the paint of such toys was identified as a serious health risk due to the use of lead-based paints. Indeed, they were banned from use in the UK in 1978. These issues are removed by the use of coloured plastics.

Finally, due to the development of high strength aluminium and zinc alloys (used in the die-casting process discussed next), as well as a new generation of plastics and composites, the popularity of using steel as a toy material has plummeted.

These days, although metals are less popular for toy making, they remain a key material used in engineering design.

2.2 The introduction of die-cast toys

Die-casting is a mass production process often used for metal processing. Typically, a molten metal is injected under high pressure into the cavity of a steel mould where it solidifies into its final shape. The steel mould is made of at least two parts which can be separated to release the cast product as shown in Figure 10. In many ways, die-casting is similar to the plastic injection moulding that was used to manufacture the LEGO®.

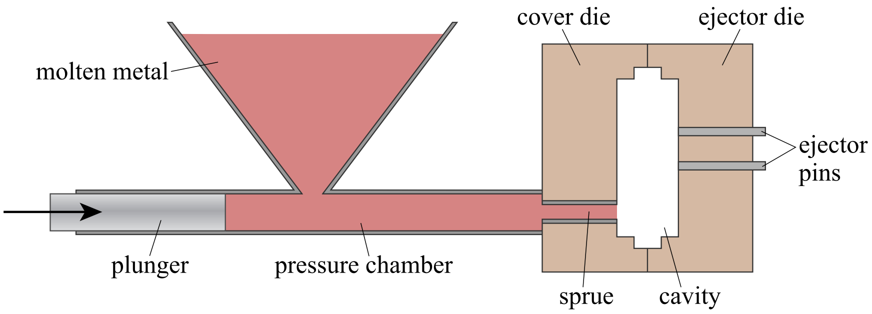

Figure 10 Die-casting machine consisting of a plunger to push the molten metal into a two-piece die made from tool steel

As the injection system and the die (mould) are both made of steel, most die-cast products are made from metals with lower melting points such as zinc, copper, aluminium, magnesium, lead and their alloys. Production of die-cast toys started early in the twentieth century. The majority of die-cast toys are made from zamak, which is a zinc alloy containing small amounts of aluminium and copper.

An attractive feature of die-cast toy production is the ability to produce highly detailed precision models, as compared to those made from wood, plastic and sheet steel. Figure 11 shows the level of detail that can be integrated into metallic die-cast models, especially when several different cast components are assembled together. Regardless of the level of detail and precision, die-cast toys are more durable than hollow-structure toys made of steel sheets or plastic.

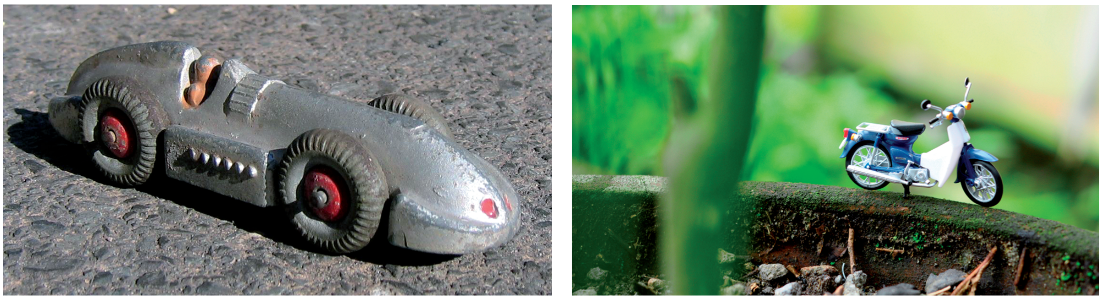

Figure 11 A model of George Eyston's land record car 'Speed of the Wind' made between 1936 and 1940 (left) and a modern highly accurate scale model of a moped assembled from die-cast parts (right)

2.3 Composite materials

A composite material is made from more than one material component combined together to achieve mechanical properties more desirable than those of either material when used alone. Composites are usually formed by embedding small pieces of one material (reinforcement) into a matrix formed of another material. For example, fibreglass is a composite material consisting of glass fibres embedded in a matrix of polymer resin. Other common fabricated composites are concrete – stone particles in a cement matrix – and plywood – wooden layers in a glue matrix with the grain of the wood in alternating layers crossed.

The reinforcing component in a composite material is often fibrous and is typically used to improve the strength and toughness of the composite. Incorporating the fibres into the matrix in sheets allows the orientations of the fibres within the matrix to be controlled and, coupled with the availability of many different types of fibre, this means that the final product can have a wide range of properties.

However, recent developments in the mass manufacture of composites based on carbon fibres, known collectively as Carbon Fibre Reinforced Polymers (CFRP), have had a massive impact in the aerospace, automotive, marine and sports goods industries as well as the toy industry. This is mainly due to the exceptionally high strength-to-weight ratio of CFRP of around 2457 $kN\,m\,kg^{-1}$, while that for steel is typically 254 $kN\,m\,kg^{-1}$.

The evolution of ultra high-strength sports goods (see Figure 12) and airborne toys, such as drones, is partly due to the recent development of extremely light and yet very strong composite materials like CFRP.

Figure 12 A tennis racket made using CFRP

2.3.1 The manufacture of tennis racquets

In this activity you are asked questions on the following video, which shows one method of manufacturing modern composite tennis racquets.

Activity 3 Tennis racquet

Allow about 10 minutes

Consider the following questions as you watch the video and note down your answers.

a. How many layers of CFRP are added to the frame at the start?
b. How and why do they keep the core hollow during the heating process?
c. What material is added to the inside of the frame, and why?

Video content is not available in this format.

Answer

a. Between 7 and 12 layers of CFRP are added to manufacture the frame.
b. Pressurised air is pumped into the frame, to ensure space is available for it to be filled with a suitable material.
c. Foam is pumped into the frame to add strength and stability to the finished product.

2.3.2 Manufacturing composites

This activity asks you to locate a product and analyse its properties.

Activity 4 Composites

Allow about 15 minutes

Do some online research to try and identify a toy or game that includes CFRP or other composite parts. Write a couple of sentences about the product, stating which part of the game or toy uses the composite.

Answer

As an example answer, roller skate wheels are often manufactured from composites. Composites can be very strong to carry the mass of the user, but are light and durable.

In addition, roller skates use a composite material to allow braking without the use of brake pads. Each composite wheel includes a centre section formed of hard material, such as high-density polyethylene. This has a low rolling friction that promotes efficient rolling. On either side of the central section the wheels comprise a soft material, such as polyurethane, that will form a high friction contact with the ground. To brake, the skater rotates the skates creating an angle to the direction of travel. This allows the softer material to interact with the ground, slowing the motion.

3 The introduction of semiconductors

Following the development of semiconductor materials in the 1950s, toys have become more interactive through the inclusion of electronic circuitry. Semiconductors led to the development of transistors and then on to the creation of printed circuit boards, which had a huge impact on the toy industry.

3.1 Transisters, circuits and batteries

Through the careful addition of traces of certain impurities to semiconductors such as silicon, and the careful juxtaposition of semiconductors treated with different impurities, it is possible to create devices in which the ability to conduct electricity can be controlled by the application of a small voltage. These devices, known as transistors, can operate at very fast rates (switching on and off millions of times per second) in response to an externally applied voltage.

In the latter half of the twentieth century, battery-operated toys equipped with movement, sound and light effects became widely available. The introduction of logic boards allowed further evolutions to occur, from preset control (selecting from a small number of fixed movements, as in Figure 13, left), through corded controllers (allowing real-time control of the toy, as in Figure 13, centre), to using wireless remote controllers (enabling full remote control of all functions, as in Figure 13, right).

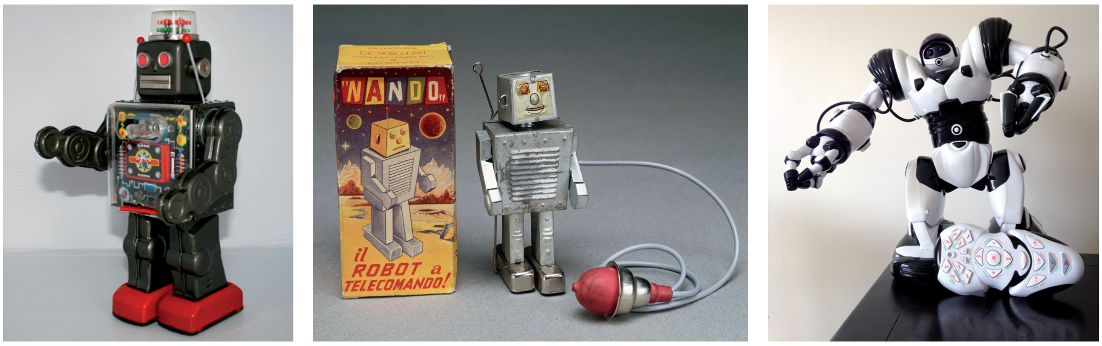

Figure 13 Toys with steel or aluminium casings without remote control (left) and with corded controller (centre) were swiftly replaced by more advanced toys equipped with cordless controllers (right)

The development of low-cost and versatile logic circuits was heralded as a breakthrough in toy design. However, the performance of battery-powered toys was frustratingly still limited by the capacity and weight of their power supplies. This all changed in 1991, when a revolution in battery design occurred, and the first commercial lithium ion battery was manufactured.

3.2 The lithium battery

For many years, the main obstacle in mass production of battery-operated airborne toys was the low power-to-weight ratio of conventional batteries. The energy stored in a conventional alkaline or lead acid battery is hardly enough to lift the battery itself for a reasonable amount of time.

The evolution of battery technology started around 1799 when the Italian physicist Alessandro Volta created the first electrical battery, called the voltaic pile. Almost exactly two hundred years later, the evolution continued with the introduction of the lithium ion battery.

The lithium ion battery has a much higher power-to-weight ratio than previous batteries, allowing smaller and lighter power supplies to be incorporated into toy designs.

The specific energy of a battery

Batteries are often described in terms of their specific energy (in $J\,kg^{-1}$), which is the ratio of the energy the battery is capable of releasing and the mass of the battery. Lithium batteries typically have specific energies ranging from $940\,kJ\,kg^{-1}$ to $2810\,kJ\,kg^{-1}$. This is up to 20 times higher than the specific energy of a lead acid battery used in a conventional car.

The lighter, more powerful lithium battery revolutionised many areas of engineering design, and toy manufacture was no exception. Toys were able to 'lift off' and stay airborne for significant periods of time, and toys such as hoverboards became viable (Figure 14). You will look at hoverboards in more detail after the next activity.

Figure 14 Substantial progress in energy storage systems, that is, high-capacity rechargeable lithium batteries, made the manufacture of flying toys and hoverboards possible

3.2.1 The manufacture of lithium ion batteries

In this activity, you are asked questions on the following video which explains why lithium ion batteries, now used in electric powered cars, are different from their predecessors.

Activity 5 Lithium ion batteries

Allow about 10 minutes

Consider the following questions as you watch the video, and note down your answers.

a. Why is it important to make the lithium metal alloy as pure as possible, and with as uniform a chemical composition as possible?
b. What is the role of the electrolyte (transport medium)?

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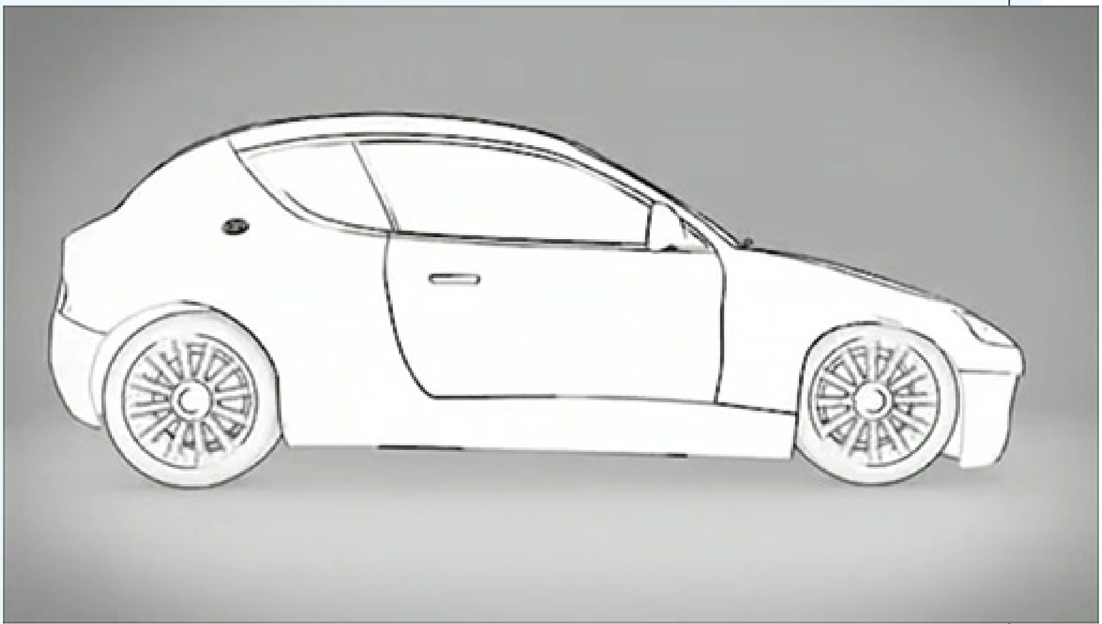

Answer

a. When the lithium metal alloy is purer and has a more uniform chemical composition, the battery performance and battery life increase.
b. It allows the lithium ions to flow freely between the anode and cathode through the micro-porous layer.

Lithium ion power supplies are not just used in toys; the technology features in mobile phones, handheld tools, electric cars and some household goods. Major advancements in high-capacity rechargeable batteries are expected in upcoming years, which will drive the proliferation of electric vehicles.

3.3 The hoverboard

You have seen examples of the influence of newly developed structural and functional materials on the 'creation' of new toys. As you approach the end of this course, consider the hoverboard shown in Figure 15.

A hoverboard is a self-balancing motor-driven personal transporter. Sophisticated electronic logic boards control the balance through **gyroscopes** (devices used to control stability), and the speed and direction of motion through pressure sensitive controllers.

The key components of the hoverboard, namely high-capacity energy storage systems, energy-efficient motors, sophisticated electronic logic boards, sensitive gyroscopes as well as high-strength structural alloys and polymers are shown in the following figure.

Interactive content is not available in this format.

Figure 15 The key components of a hoverboard. Click on the hotspots for more information.

Clearly, high-capacity batteries in combination with energy-efficient motors are needed to maximise the distance that can be travelled per charge. Similarly, high-precision gyroscopic systems and sensors are essential to ensure the stability and controllability of the hoverboard and hence the safety of the rider. Perhaps the least technologically demanding parts of a hoverboard seem to be its load-bearing components, such as the chassis, wheel bearings and drive shaft. However, optimum design and selection of materials for such components will require an insightful understanding of the loading mechanisms.

3.4 Designing a toy

You're reaching the end of the course now, and this is the final activity.

Activity 6 Innovation in design

Allow about 15 minutes

Find a toy that incorporates innovative materials, electrical features or structural design. This can be an item from around the house, or an image from somewhere on the internet. Write a couple of sentences to detail the innovative design features that prompted you to choose that toy.

Conclusion

Manufacturing of sophisticated toys requires an understanding of engineering materials, a solid grasp of the structural requirements of components such as the chassis, and the utilisation and integration of electrical/electronic engineering systems, including power storage.

As a consequence of such multidisciplinary projects, engineers need to have a working knowledge of a wide range of engineering fields before specialising in one particular discipline.

This OpenLearn course is an adapted extract from the Open University course T271 *Core engineering A*.

Images

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Figure 4: Ashby chart of strength vs density Chart created using CES EduPack 2018, Granta Design Ltd. http://www.grantadesign.com/education.

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Activity 3: How Tennis Racquets are made © GM Television.

Activity 5: Lithium-ion batteries: How do they work? © Courtesy of BASF.

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