Physics Education

Bending bad—testing caramel wafer bars (#TestATunnocks)

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PAPER
Phys. Educ. **56** (2021) 055002 (10pp)
iopscience.org/ped

Bending bad—testing caramel wafer bars (#TestATunnocks)

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Abstract
During the coronavirus pandemic, there have been significant challenges in the remote teaching and demonstration of experiments, especially those that require laboratory testing equipment. With a desire to give students a feel for our materials laboratory on open days and allow them to gain a deeper understanding of what materials science and engineering is about, we have designed an experiment focused on composite materials that can be performed remotely and without specialist equipment. This enabled students to experience a bend test sensorily through seeing, hearing and feeling it, creating a strong link to then being able to relate it to the pre-prepared experimental data taken in the laboratory. This fun, easy-to-run and engaging experiment allowed a shared experience and encouraged a discussion about students' observations, differences in results and implications of the bend strength of sandwich composites. We have found it not only works well universally by all ages but can be used with younger children to think about words such as 'stronger', 'stiffer' and 'flexible' and how materials can be different in different directions.

Keywords: mechanical testing, materials science, chocolate, outreach, STEM

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1. Composite materials

Composite materials are all around us. Nature has selected composite materials over the years for forming trees, plants, seashells and even the bones in our body. Each composite contains at least two materials with different physical and chemical properties, combining to create a structure that is typically stronger, lighter or stiffer than individual base materials.

One of the first composites documented was in Mesopotamia (modern Iraq) in 3400 BC. These early engineers found that if they glued wood strips on top of each other at different angles, it created a plywood that was stronger than just simply lining the pieces up in the same orientation. Combining materials like this is widely used in engineering applications from construction (wattle and daub, steel reinforced concrete) to aerospace and transportation applications (carbon fibre reinforced plastic).

One particular type is the sandwich composite. As the name suggests, a sandwich-structured composite is a special class of composite material. This is created by taking two thin, but stiff, 'skins' (commonly known as face sheets) and sandwiching them around a lightweight, thicker 'core'. The development of sandwich composites can be traced back to the Ancient Greeks in 1300 BC [1] but one of the first sandwich composites was patented in 1833 by civil engineer and locomotive designer, Robert Stephenson, using a wooden beam plated with wrought iron. This was to provide strength with a significant reduction to the weight of his Planet locomotive, a feature which contributed considerably to the commercial success of future locomotives. While the core material typically has a lower strength, its greater thickness provides the sandwich structure composite with a lower overall density but an increased bending stiffness. This combination of properties makes it ideal for use in lightweight, stiff structures such as the fuselage of an aircraft. Such materials were used in 1940, in WWII for the production of a British twin-engine multirole combat aircraft: the Mosquito, also known as the 'The Wooden Wonder' as it incorporated a plywood-balsa-plywood 'sandwich' giving the fuselage exceptional rigidity from the bonded structure.

2. Motivation

Due to the COVID-19 pandemic, significant challenges in remote teaching and the demonstration of science and engineering practicals have been felt, especially those that require laboratory testing equipment. While much work has gone into redesigning the teaching for remote delivery [2], it has also effected outreach and openday events. There has been quite a bit of use of measuring chocolate samples as a method of engaging students with Materials Science and Engineering events. This has included the testing of the toughness of chocolate at various temperatures [3, 4] which was further extended to examine the performance of a lightweight, stiff material, using high performance composite chocolates [5]. While breaking chocolate composites has been previously reported [6], our aim was to allow students a hands-on involvement of sandwich composites with how an engineer might approach structural design with such materials, and to understand how they might fail. To ensure engagement, our goal was to go beyond simply watching a video, or reading about the test, by enabling hands-on participation. To this end, we have designed a practical session, in which students can purchase their own sandwich composite test materials from a local shop and experience the practical together, online, in their own homes. Since the practical did not involve the use of any specialist equipment, participants could perform the experiments themselves, gaining a qualitative understanding of the key results. Following the home-test, we provided the participants with the quantitative data, obtained using equipment in our Materials Science and Engineering teaching laboratory, to contextualise the theory and to facilitate discussion surrounding the implications of the results in component design.

3. A sandwich chocolate composite

The choice of material was a simple caramel wafer chocolate bar. Whilst most people see this as a tasty treat, figure 1, Material Scientists and Engineers look at it as a sandwich structure composite.

In fact, the caramel wafer bar is a multiple layer sandwich structure of length 92 mm,

Figure 1. The caramel wafer bar used in this experiment with five layers of wafer (skins) and four layers of caramel cores.

thickness 19 mm and width 27 mm. The selected brand, Tunnock's Caramel Wafer, consists of five layers of wafer (the skins), separated by four layers of caramel (the cores). However, other bars with similar composite structures are available and could be used instead. The bar is coated in chocolate, which can be considered as a delicious aesthetically pleasing surface finish that does not affect the results.

4. Bend it yourself

To measure the bend (flexure) strength of the material, we used a three-point bend test. Typically, a specialised piece of equipment or a re-configured tensile testing rig is used, which provides a vertical force applied to the top surface at each end of the test piece, with a fixed support placed centrally on the underside as seen in figure 2(a).

This mechanical test is used to determine the flexibility of a material and how it will fail; important in the design of structures incorporating ductile materials, such as the wing of an aircraft or a steel support in a building. Observations in the deformation, fracture process and surfaces also give a good indication of the material behaviour, how it has failed and the weakest feature. For example, as the bend force is increased, high stresses can build up at the interface between the skin and core material. Due to the individual layers having different mechanical properties, the bond between the layers is tested to the extreme, leading to them to break away from each other in a process known as delamination.

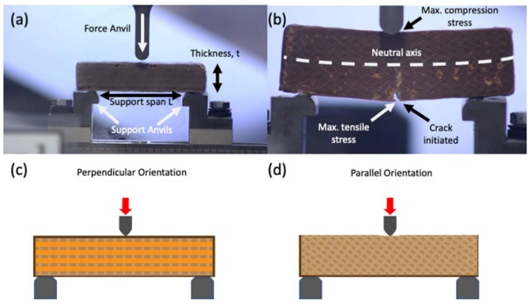

Figure 2. The bend test (a) the setup of the bend test showing the support span L, (b) the bending of the material, showing the locations of the maximum stresses, neutral axis through the centre of zero stress and a crack initiated at the maximum tensile stress. Figures (c) and (d) are the two orientations tested for the wafer layers being perpendicular or parallel to the applied force respectively.

To perform this test in a laboratory, we use a Zwick Roell testing frame. This uses two anvils (points of contact), which provide support to the sample as shown in figure 2(b). This distance was set to be 65 mm, which is known as the support span (L). This distance, whilst being wide, still provides a good support on either side of the sample. To start the bend test, the top anvil is then brought down from above, making contact on the upper surface of the material. This force causes the material to bend.

As the sample flexes, the upper surface is forced downwards causing it to compress, leading to a maximum compression stress just under the central point. The bottom surface is forced to curve outwards, and, therefore, is strained by a greater amount. This increase in strain generates a tensile stress on the lower surface, which has a maxima directly opposite the top anvil. Since most materials generally fail under a tensile stress before they fail under compressive stress, the maximum tensile stress the test piece can support defines its flexural strength and the point of failure is typically opposite the top anvil.

We increase the bend force until the material fractures. The bend (flexure) strength of the material is defined as the highest stress that can be applied before the material begins to yield and fail. It is also worth noting that a 'neutral' axis also runs through the centre of the bar where the material experiences no stress as it goes from tensile to compressive through the thickness as shown in figure 2(b).

To calculate the stress (which takes into account the fact that the composite does not have a square cross-section), we convert the applied force into the stress that the material experiences. The maximum tensile stress on the lower surface of a three-point bend is given by equation (1):

$$\sigma = \frac{3FL}{2wt^2} \tag{1}$$

where F is the applied force and L is the support span length (65 mm). The values of t (thickness, mm) and w (width, mm) depend on orientation, but a higher stress from a given force is produced if the material is thinner or narrower.

There are two ways in which a bend test can be performed on a sandwich composite. We define a 'perpendicular' orientation where the wafer layers, or sandwiches, are perpendicular to the applied force as in figure 2(c). When the wafer layers are 90° to this, we term this a 'parallel' orientation as in figure 2(d).

Typically, such equipment is not available for use at home, so a readily available alternative was required. Luckily, most of us already know how to perform a three-point bend test by hand.

To get a similar result to those obtained using laboratory equipment, put your thumbs together and place them in the middle of the bottom of the bar. Then place your fingers, which will perform the bending, on the upper surface, at the ends, as shown in figure 3(a). This creates a simple three-bend test. If your thumbs are too far apart, the maximum stress will be distributed over the section between the two central narrower loading points. This is actually known as a four-point bend test and is particularly suitable for brittle materials where the presence of microscopic flaws (such as holes or cracks) have a larger effect on measuring the strength.

Since the force that your fingers impose on the chocolate bar cannot be easily quantified, nor accurately reproduced, bend testing by hand is not quantitative. However, qualitative differences can be felt and a range of observations made. As the force is applied, the maximum stress will occur directly opposite your thumbs and the point at which a crack of a failure might occur. This allows the students to be able to 'feel' the force required

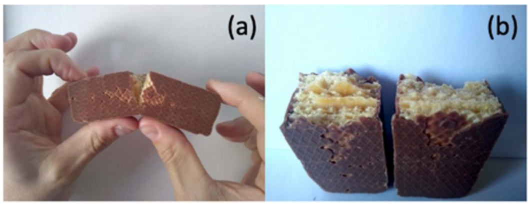

Figure 3. A photo of a 'three-point bend' in a *parallel* orientation, with crack generated oppose the thumb at the highest point of stress. (b) The fracture surfaces of the chocolate bars after breaking by hand at room (ambient temperature) in a *perpendicular* orientation. While the caramel was quite rough, the wafer layers were much smoother. This results in a combination of brittle and ductile fracture.

to break the material and to compare with other orientations of the same material, or with different samples (e.g. different chocolate types) for a comparative study, along with seeing the crack form and hearing it. When combined with the laboratory data provided below, allows for an engaged discussion of their experiences.

5. Results

We asked students to try at least one of the following. To bend their 'sample' in a *perpendicular* or *parallel* direction at one of three temperatures, *ambient* (around 20 °C), *cold* (left in the freezer, so approximately −5 °C) and *warm* (around 30 °C, direct sunlight if available or a radiator), reporting back anything they observed or felt.

5.1. Observations—ambient temperature

Holding the wafer bar in a *perpendicular* orientation, students observed the bar start to bend as they began to apply the force, however, they did not really feel or hear anything. As the force increased there was the sensation of the wafer bar starting to 'give way'. Sounds of cracking could be heard, with a fracture appearing opposite their thumbs. In some cases, students felt the material break, layer-by-layer, as the wafer (skins) started to fail. Once a break was formed, students found the force reduced but that they had to bend further in order to fully break the bar since the bottom layers were still intact.

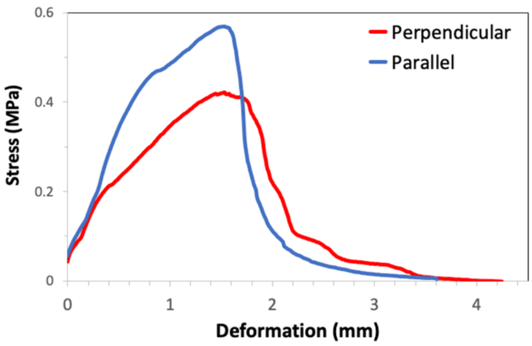

Figure 4. The laboratory bend test of the room temperature sample. The two lines highlight the differences in the orientation of the sample when being tested.

When the stress was applied in the *parallel* orientation, it was found to be significantly more difficult to bend. Nothing seemed to be happening for a while and quite a bit of effort was needed to get things going. As the force increased there was a sensation of little or no flexibility in the sample but then lots of cracking was heard until the bar broke quite suddenly. In both cases the fracture surface, shown in figure 3, was a little rough with noticeable 'tearing' of the caramel layer.

5.2. In laboratory testing—ambient temperature

Figure 4 shows the results for the laboratory testing at ambient temperature. For the *perpendicular* orientation, it was found the bar withstood a stress of approximately 0.41 MPa at an elongation of 1.70 mm. The wafer (skin) is relatively flexible and able to bend, and in doing so, the soft pliable caramel core material was able to support and distribute the forces and stresses around the wafer, throughout the body of the bar. The process of bending the material to failure was relatively slow and required hard work, due to the increased ductility and toughness of the material. This final process caused the material to tear and resulted in the roughness that the students saw on the fracture surface.

When the force was applied *parallel* to the wafer orientation, the bar withstood a much greater stress, of 0.56 MPa, with a slightly reduced deformation of 1.53 mm. With an increased strength and lower strain, the sensation of breaking in the *parallel* orientation would feel like it was more difficult to bend. This indicates that the material has a greater stiffness, as seen by the increased gradient in that region.

The sounds and sensations that the students experienced, along with the experimental bend test data, indicates a more brittle-like failure. The laboratory results help us to understand why and can be explained as follows. The material in the *parallel* orientation can withstand greater stress (high bend strength), but as soon as a crack is formed, it runs through the composite quickly as seen by the steep decent at 1.70 mm deflection (figure 4). This is dangerous for design and is known as a catastrophic failure. In comparison, the *perpendicular* direction has a lower bend strength, slightly greater deformation and breaks in a less catastrophic way.

5.3. By hand observations—warm temperature

The students turned up the temperature and did the same experiment with the sandwich composite at approximately 30 °C. This is slightly messy due to the melted chocolate coating, but a clear change could be felt. Holding the wafer bar in a *perpendicular* orientation, students felt the material slip and slide, breaking with a much reduced force. The deformation was dramatically increased with a noticeable amount of flexibility and a sensation of layer debonding and sliding. In the *parallel* direction, there was also a dramatic reduction in force needed to bend the composite, but students felt they had to bend it further to get the material to break.

The fracture surface the students saw was very rough (figure 5), looking very much like the material had torn instead of fracturing both the caramel and the wafer layers.

5.4. In laboratory testing—warm temperature

When we raise the temperature of a material, we introduce more energy into the system through internal vibrations. As the atoms vibrate more, the bonds are easier to break, but the atoms are also more mobile and so the material becomes more ductile. So rather than a crack forming and

Figure 5. The fracture surface of the warm sample broken in a *perpendicular* orientation. Much of the surface actually tore and no flat surfaces could be seen. This results show a clear ductile fracture.

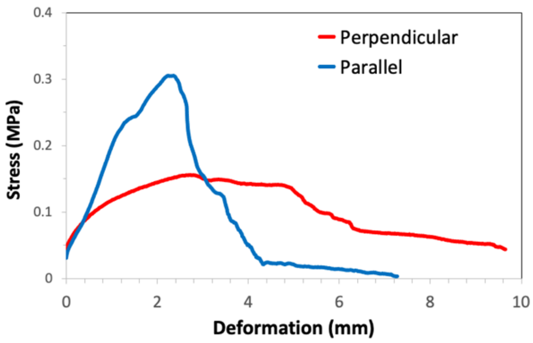

Figure 6. The laboratory bend test of the elevated temperature. A reduced bend strength is seen but much greater deformation.

moving through the material quickly, it is possible for the atoms to move, to re-bond and reduce the speed of the crack propagation. This would be seen as an increase in ductility, reduction in the bend strength and an increase in the flexibility (i.e. reduction in stiffness).

In our tests, we found this to be true as shown in figure 6. When the bar was tested *perpendicular* to the wafers it started to break at a force of just 0.16 MPa and deformed by 2.93 mm before a crack was formed. The crack, instead of moving quickly through the material causing catastrophic failure, moved slowly through the material reducing the force, leading to a final displacement that continued to well over 6 mm. This led to the material tearing instead of cracking, resulting in a very rough fracture surface.

For the bar tested *parallel* to the wafers, the maximum force was decreased to 0.3 MPa—half that of that at room temperature—but the deflection before failure increased to 2.35 mm with a much slower, ductile failure. This sample did eventually break into two after 6 mm deflection.

5.5. By hand observations—cold temperature

Breaking a frozen sample was no easy feat and, in fact, some students found this very hard to do no matter which orientation they used. Those that were able to break the wafer said that they could feel no bending at all in the *parallel* direction,

Figure 7. The fracture surface of the cold sample broken in a *perpendicular* orientation. The fracture surface is smooth and shiny, with the caramel and wafer fracturing. This results in a clear brittle fracture.

hearing a single, very short sharp 'snap' as the material fractured. In fact, a few found that the bar flew out their hands due to the stress they were having to apply and how quickly it failed. They also noticed that the fracture surface of the bar looked very flat rather than the rough surface they saw in the room temperature tests, and that there was less 'stretch' in the caramel layers, as shown in figure 7 .

5.6. In laboratory testing—cold temperatures

We performed tests at two different low temperatures in the laboratory. The first was at a temperature straight from the freezer (approximately -5 °C). This showed a slight reduction in the

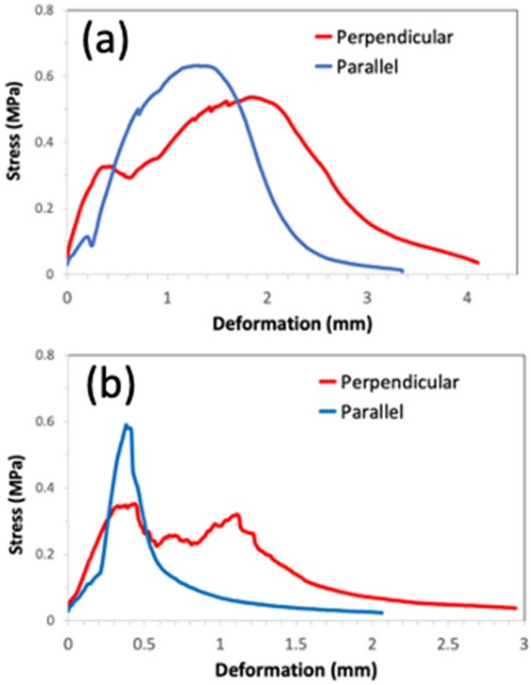

Figure 8. The breaking of cold samples (a) a bar places in the freezer for 10 min showing a change in behaviour (b) frozen using liquid nitrogen resulting in significant brittle failure.

deformation of the test pieces and a slight increase in the bend strength (figure 8(a)). For the *perpendicular* orientation, a 25% increase was found in the bend strength of the material, rising to over 0.52 MPa. Similarly, the strain exhibited was greater than at room temperature, with a measurement of 1.98 mm.

The effect of cooling a material to low temperatures is that the bonded atoms vibrate less. With a reduction in the vibrations, the force and associated stress required to break the material is high, however, once started, the atoms are no longer as mobile to re-bond. Therefore, when a crack is formed, it can begin to move rapidly through the material, effectively ‘unzipping’ the material into two pieces. The temperature at which this fracture behaviour switches is known as the ductile-to-brittle transition temperature (DBTT). This has been shown previous for chocolate [4] but was first observed in steels by Constant Tipper [7]. Known as catastrophic failure and is very dangerous in engineering applications leading to disasters such as the Liberty ship failures [8, 9] and even contributed to the Titanic [9].

The ‘shape’ of the bend test was different to those performed at ambient and enhanced temperature, and gives a clue to what is occurring. Small ‘saw tooth’ shapes (red line in figure 8(a)) can be seen in the test. This represents where each of the individual layers of the sandwich composite skin (wafer) are failing through cracking, and where our sandwich composite has started to undergo a ductile-to-brittle transition. While the wafer is now quite brittle, the caramel remains somewhat ductile, holding the structure together. When the wafer crack reaches the caramel, it arrests, and the stress in the structure can then be redistributed. This continues with each wafer layer: applied stress increases, a crack forms, followed by a sharp reduction in stress as the wafer layer fails and the material bends further. Eventually, all of the layers fail and the material then undergoes a typical ductile failure as the caramel is the only element holding the bar together.

In the *parallel* orientation, similar behaviour is observed, but as cracks can now run from top to bottom in the wafer layer, the caramel is not as effective in stopping cracks in this orientation. As such, the deformation length at which the materials start to break is reduced to 1.48 mm but with an increase in bend strength of 0.62 MPa. This catastrophic failure led to a ‘snap’ sound as the fast moving crack travelled through the material and resulted in a very flat fracture surface.

To test what happens when the caramel undergoes a DBTT, as well as the wafer, we had to go colder. We tested the same wafer bar but now at liquid nitrogen temperature: −192 °C (we do not advise this test at home!).

The frozen bar tested in the *perpendicular* orientation withstood 0.37 MPa before the initial crack started, but had only deformed 0.47 mm (figure 8(b), red line). However, the crack that was formed reduced the stress in the material to a level where it temporarily stopped moving through the sample. As the bending continues, the stress builds, and at about a stress of 0.36 MPa, the crack begins to move again and the material finally fails. This is shown by the presence of two peaks on the red line in figure 8(b).

The frozen bar tested in the *parallel* orientation withstood a load of 0.57 MPa before

Table 1. The summary of the results obtained from in laboratory testing.

	Perpendicular		Parallel	
	Bend strength (MPa)	Displacement at max load (mm)	Bend strength (MPa)	Displacement at max load (mm)
−192 °C	0.37	0.47	0.57	0.39
−10 °C	0.52	1.98	0.62	1.48
Ambient	0.41	1.70	0.56	1.53
30 °C	0.16	2.93	0.30	2.35

catastrophically failing with a deformation of just 0.39 mm.

6. Summary

The purpose of this study was to develop a practical experiment to demonstrate simple material testing procedures to understand the properties of sandwich composite materials. We have devised an experimental procedure that can be carried out at home, without the need for special equipment and using materials that are available (to buy) from many shops.

We have also generated quantitative data in the laboratory (table 1) so that the qualitative data generated at home can be compared and put into context with genuine scientific results, thereby giving students an insight into some of the complexities of the failure of materials allowing discussion points on designing with sandwich composites and the importance on how materials respond to temperature.

We also wanted to give students the opportunity to find out about the discipline of Materials Science and Engineering, engage with the subject and start asking questions like: 'Why is this object made of that material?', or 'What would happen if this was made of something different?'.

While we present here the data of the bend test, we performed quite a lot of further analysis of the sample using further techniques such as microscopy, thermal analysis and fracture toughness which can be seen here [10].

We hope that some of the students who try the experiments are interested enough to undertake further studies within the discipline of Materials Science and Engineering and become the materials inventors and innovators of the future. Or perhaps, help to develop another tasty treat for us to test.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

Thanks to James Knight and Millie Bourke for help in breaking things, and Zoe Papadakos, James Perkin and Roger Del Barco Valdivia for their contribution to the video explaining the experiments.

We would also like to thank Thomas Tunnock Limited for supplying the test pieces, and in general for inventing and producing such yummy comestibles. These are often the cause of healthy debate amongst colleagues in the Department of Materials Science and Engineering at the University of Sheffield: which is better, the Caramel Wafer or the Teacake? We have concluded that there is no correct answer to this.

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Received 25 March 2021, in final form 26 April 2021
Accepted for publication 7 May 2021
https://doi.org/10.1088/1361-6552/abfece

References

[1] EconHP Holding GmbH 2021 The History of Sandwich Construction and Honeycombs The History of Sandwich Construction and Honeycombs (available at: www.econhp.com/history/) (Accessed 22 March 2021)

[2] Bangert K *et al* 2020 Remote practicals in the time of coronavirus, a multidisciplinary approach *Int. J. Mech. Eng. Educ.* (https://doi.org/10.1177/0306419020958100)

[3] Parsons L B and Goodall R 2011 Testing the fracture behaviour of chocolate *Phys. Educ.* **46** 50–56

[4] Johnson C, Bates J, McLaughlin K, Mason S and Dean J S 2016 A sweeter way of teaching health and safety *Phys. Educ.* **51** 053006

[5] Dean J, Thomson K, Hollands L, Bates J, Carter M, Freeman C, Kapranos P and Goodall R 2013 High-performance composite chocolate *Phys. Educ.* **48** 465

[6] Yin D, Shumeyko C M, Cline J E, Dunstan M K, Goins P E and Field D M 2019 Snap, Crackle, and Pop: Breaking chocolate to understand composite design *J. Mater. Educ.* **41** 27–40

[7] Zappas K 2015 Constance Tipper Cracks the Case of the Liberty Ships *JOM* **67** 2774–6

[8] Zhang W 2016 Technical Problem Identification for the Failures of the Liberty Ships *Challenges* **7** 20

[9] Felkins K, Leightly H P and Jankovic A 1998 The royal mail ship Titanic: Did a metallurgical failure cause a night to remember? *JOM* **50** 12–18

[10] Dean J S and Birch S M I 2019 TestATunnocks TestATunnocks (Available at: www.sheffield.ac.uk/materials/testatunnocks) (Accessed 22 March 2021)

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Amanda comes from a Mechanical Engineering and Project Management background followed by 15 years in Teaching. Her current role at the University of Sheffield involves coordinating outreach activities for schools as well as working with Student Experience and Admissions teams.