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Explore your toothpaste

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Abstract

A simple packet of toothpaste is a good starting point for investigations by students. By looking at (i) the modern packaging and (ii) the fine abrasive material in the toothpaste, pupils can appreciate one way in which modern technology shapes the world around us.

Introduction

We are part of the consumer society. Industry blesses us every day with new products, wrapped in new attractive packaging, with new names and slogans and new strategies for TV advertisements. The health and beauty industry is certainly among those that is growing fastest and giving the largest profits. As we know (but seldom admit), we could easily live without many of these products. So why should we talk about them in school? There are at least two good reasons. First, one of the important goals of science in schools, and in physics in particular, is to educate students as scientifically literate consumers and decision-makers who will be able to form their own objective opinion about so-called scientific statements (think for instance about the impressive results of a ‘scientific’ proof on TV that compares new and ordinary washing powder). Here is the second reason: though many of us may despise the overwhelming production of unnecessary items, the fact is that many of these items are the result of modern technology. They, and even their packaging, may contain materials or parts with special properties that may not have been known or widely accessible even as little as ten years ago. Having these high-technology low-cost items at hand opens a lot of new possibilities for refreshing physics in school and in this way fulfils at least two goals at the same time: physics in school becomes more relevant to our everyday lives (which usually results in higher motivation for learning) and students become aware that a large part of the world around us is the result of modern technology (which may result in a greater appreciation of science and technology).

This article describes two stories that are connected to toothpaste. One story tells about how its iridescent packaging is made and the other story is about the role of a fine grit (powder) in the toothpaste called abrasive. Through these two stories some useful experimental ideas are presented and discussed.

Exploration of the toothpaste’s iridescent packaging

Some toothpaste packaging (and also packages of other cosmetic products) shines in iridescent colours that change if you watch them at different angles, almost as if small pieces of a CD are glued on the paper (figure 1).

Are these colours produced in the same way as colours on CDs (i.e. by the interference on reflecting diffraction gratings)? And if so, can we say something about the structure of these pieces? One way to find an answer is to point a laser at the iridescent part of the package and observe the reflected light. But as always when using lasers in school there is a danger that the reflected beam will be directed towards somebody’s eyes. In the following experiment we will show you how to make a simple device that allows your students to safely observe the reflected laser light.

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Figure 1. What can we find out about the iridescent pieces on the toothpaste package?

Figure 2. Safe Laser Inspection Device made from one hemisphere of a painted Christmas ball.

Take one hemisphere of a transparent Christmas plastic ball (another unnecessary consumer item...) and spray it inside with white paint. Measure the diameter of the plastic hemisphere (4 cm in my case) and cut a semicircular stencil of the same diameter from a piece of cardboard. When put on the top of the hemisphere the stencil should fit exactly onto it. Mark ticks on the stencil for every 5° from −90° to 90°, using a protractor and a permanent marker. Then drill a hole on the top of the hemisphere (at zero degrees). The hemispherical screen is now ready; you only need to add the holder for the laser pointer. Any plastic tube with an inner diameter equal to the outer diameter of the laser pointer will do. I cut mine from a used whiteboard marker. Glue the plastic holder exactly on the top of the hemisphere and your Safe Laser Inspection Device (SLID) is finished (figure 2).

Place the hemisphere on the iridescent part of the toothpaste package and switch on the laser (use a clothes peg to keep the switch-on button pressed for a longer time). Light spots that appear in pairs on both sides of the laser pointer will reveal the diffraction pattern, which proves that the iridescent colours seen in the white light are produced in the same way as colours on a CD. It is instructive to compare the diffraction patterns produced by the red and green laser light respectively (see figure 3).

In my case the red laser light (650 nm) produced only the first order diffraction maxima while the green laser light (532 nm) produced the first and the second order diffraction maxima. If you move your SLID along the package you will notice that other parts of the surface give the same diffraction patterns but with randomly distributed orientations, suggesting that the metal foil has grooves which are oriented in different directions.

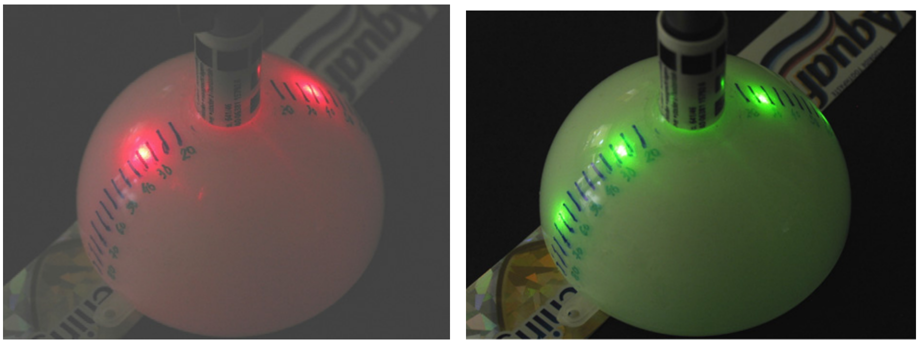


Figure 3. Diffraction patterns produced by the shiny part of a toothpaste package using red and green laser light respectively.

Table 1.

Light wavelength	$\bar{\varphi}_N$	d (nm)
650 nm (red)	35°	1100
532 nm (green)	27°	1200
532 nm (green)	65°	1200

That is also why they appear to be different colours when observed in white light.

Knowing the wavelength of the laser light (λ) and the angles of the diffraction maxima φ_N (N indicates the order of the diffraction maximum), it is easy to determine the distance between the adjacent grooves d in the metal foil pieces using the well known expression

$$d = \frac{N\lambda}{\sin \varphi_N}.$$

The scale in degrees that you marked on the hemisphere helps you to estimate the angles to within about 2°. Take the average value between the two equivalent maxima. To eliminate any folds in the inspected part of the surface you may find it necessary to cut the interesting part of the toothpaste package out and fix it on a flat board.

The measured values and calculated groove width for my toothpaste package are given in table 1. The estimated average groove width (to two significant figures) is 1200 nm. This value is between the typical value for CDs (1500 nm) and DVDs (750 nm) so it is not surprising that all these surfaces produce similar colourful effects when viewed in white light. Needless to say, the laser inspection device described is also very useful for analysing the reflections and diffraction patterns produced by other surfaces such as those from CDs and DVDs.

Explorations of the size of the abrasive grains in toothpaste

The principal components of toothpaste are fine grit, called abrasive, and detergent. Abrasive gives toothpaste its cleaning power. It physically removes stains and plaque, as well as polishes teeth, and thus prevents decay. Detergent creates the foaming action of toothpaste and also helps the fight against plaque. Foam keeps the toothpaste in our mouth, preventing it from dribbling out as we brush our teeth. In addition to abrasive and detergent, modern toothpaste contain several other compounds. A typical recipe for toothpaste is shown in table 2 (for more information see for example [1]). The bad taste of the detergents is masked by the addition of strong flavouring agents and sweeteners. Thickeners determine how ‘thick’ your toothpaste is. Modern toothpastes often contain fluorine compounds, such as sodium fluoride, which have been shown to be effective in reducing the incidence of tooth decay.

Table 2. Typical recipe for toothpaste.

Ingredient	Function
Hydrated silica	Abrasive
Sodium dodecyl sulphate	Detergent
Glycerine, sorbitol	Sweetener
Xanthan gum	Thickener
Peppermint extract	Flavouring
Water	—

Abrasives commonly used in toothpastes are hydrated silica, titanium dioxide, precipitated calcium carbonate and others. The typical size of abrasive particles measures from 4 to 12 μm [2, 3]. The size and the chemical compounds of which these particles are composed are critical factors that determine how effective the abrasive will be. The toothpaste must be abrasive enough to remove stains and plaque but it should not damage tooth enamel. If the toothpaste is too abrasive (or teeth are brushed too often for too long a time) this may lead to thinned and damaged tooth enamel, revealing the yellowish dentine layer below. So, in addition to ‘whitening action’, toothpaste can also have ‘yellowing action’ if applied incorrectly.

Making and observing scratches

Let us see how we can link this little bit of knowledge about the toothpaste with some school physics.

As mentioned above, the typical size of the abrasive particles in the toothpaste ranges from 4 to 12 μm. This corresponds to about 8 to 24 visible light wavelengths (taking 500 nm as an average value). Knowing that waves do not ‘see’ any obstacles that are smaller than their wavelength, we may anticipate that scratches produced by the toothpaste should be visible in white light.

To check this, obtain toothpaste with ‘whitening action’, a clean flat transparent piece of plastic (the new cover of a plastic CD case works very well) and a cork. Put a little toothpaste on the cork, press the cork hard onto the transparent plastic and rub it on the plastic several times in one line, keeping the cork pressed down all the time. Wash the plastic cover very gently to remove any toothpaste from it. Now carefully inspect the plastic. You will notice fine scratches on the rubbed parts. (They are best seen in reflected light. Why?)

We can make further explorations. Repeat the procedure with other toothpaste brands and make other similar stripes of scratches next to the first one. Leave the toothpaste on the cork for several hours to dry out and then rub the plastic. You will notice that this time the scratches will be more visible. You can also make a control experiment and rub another part of the plastic with a clean wetted cork to demonstrate that the scratches indeed come from the toothpaste.

To show the fine scratches to the whole class (and to demonstrate the fact that their widths are larger than the wavelength of the light) aim the laser pointer towards a screen holding the plastic cover from the experiment in front of the laser. If you move the laser from the place with no scratches to the place with scratches, the pattern on the screen will change from a single point to a point with lines added on both sides of it. Show and discuss how the pattern changes if the plastic cover is rotated.

Removing scratches

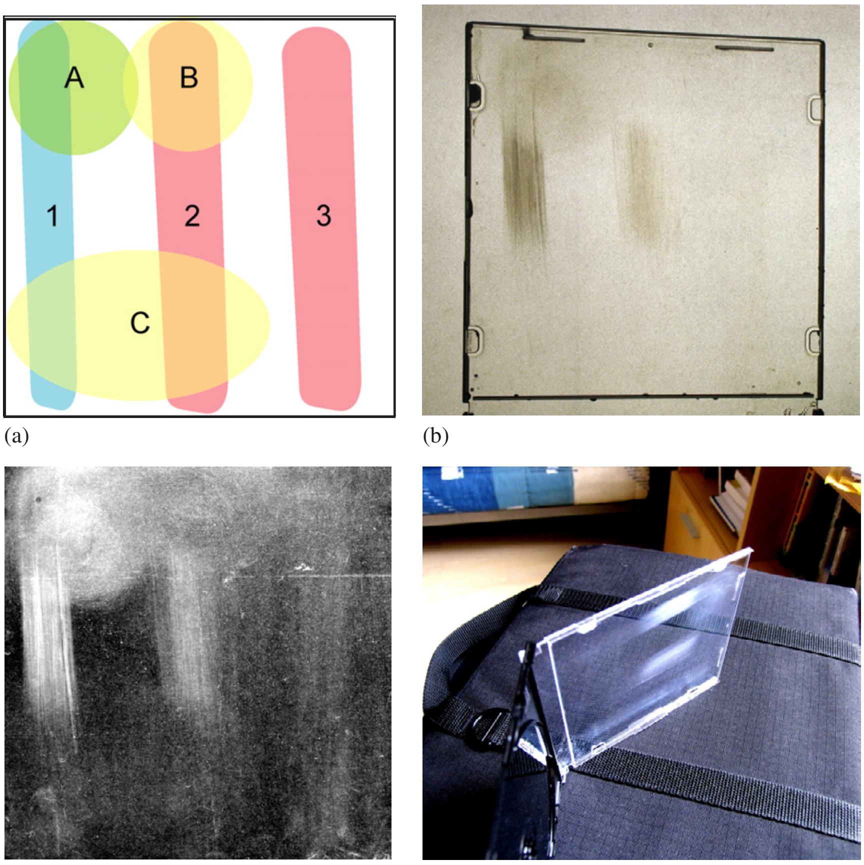
In the experiment above we showed that the particles in toothpaste abrasive can produce scratches that are larger than the wavelength of visible light—this agrees with what the producers say about the size of the particles. Now, let us do another experiment. Obtain a soft kitchen mop (such as Vileda; do not use tissue paper!). Wet the mop and put some toothpaste on it. Now with this mop polish one half of the most visible stripe of scratches that you made in your previous experiment. Move your hand in circles and keep the mop gently pressed on the plastic. Keep polishing for about a minute. Then wash the plastic cover very gently to remove any toothpaste from it, dry the plastic with a soft cloth and observe the results. You will notice that at the place where you polished the plastic the scratches have almost disappeared. It looks as if the same toothpaste that first produced the scratches is now able to remove the scratches and make the plastic clear again. (Again you can perform a control experiment and polish another part of the scratches with a clean wetted mop for the same time and you will see that the scratches will remain unchanged.)

How is this possible? We are not surprised that the particles of the size of a few micrometres produce visible scratches, but how can it happen that these same particles can remove the scratches they have produced? The secret does not lie in a single factor but in the combination of factors such as size of the abrasive particles, material of the mop, gentle pressure and patience. These secrets were already known to lens makers in the 17th century. The phenomena related to polishing glass surfaces also attracted the attention of Sir Isaac Newton, as evidenced in his *Opticks, Book II, Part II, Prop VIII* [4]:

> *Lastly, were the Rays of Light reflected by impinging on the solid parts of Bodies, their reflections from polished Bodies could not be so regular as they are. For in polishing Glass with Sand, Putty or Tripoly, it is not to be imagined that those Substances can by grating and fretting the Glass bring all its least Particles to an accurate Polish; so that all their Surfaces shall be truly plain or truly spherical, and look all the same way, so as together to compose one even Surface. The smaller the Particles of those Substances are, the smaller will be the Scratches by which they continually fret and wear away the Glass until it be polished, but be they never so small they can wear away the Glass no otherwise than by grating and scratching it, and breaking the protuberances; and therefore polish it no otherwise than by bringing its roughness to a very fine Grain, so that the Scratches and Fretting of the Surface become too small to be visible.*

Interestingly Newton correctly described the effect of the size of scratches on the light, though for him light had a corpuscular nature and so he did not think about the interaction of light and scratches in terms of waves, as we do here.

So how can particles the size of few micrometres remove visible scratches? During the polishing action the large abrasive particles may break into smaller particles that eventually reach a size smaller than the wavelength of visible light. In addition the large particles may sink into the soft mop and only small parts of them protrude out of the mop, just like the tips of icebergs (when polishing soft material such as plastic in our case, this is more likely to happen). These



(a) (b) (c) (d)

Figure 4. A new plastic CD cover has been treated as schematically shown in (a). Vertical stripes have been rubbed with a cork in the following ways: (1) with creamy oven cleaner, (2) with half-dried toothpaste (hard rubbing) and (3) with fresh toothpaste. After that the polishing with mop has been applied in three ways: (A) with creamy oven cleaner, (B) with toothpaste (hard pressure) and (C) with toothpaste (gentle pressure). The results have been observed in three different ways: (b) with an overhead projector (the size of the projected image is about 1.5 m × 1.5 m), (c) scanned with a conventional scanner with black paper placed behind the plastic CD cover and (d) as a photograph of reflected light (rotated by 90° with respect to the images in (b) and (c)). Automatic equalization has been applied to the scanned image (using CorelDraw) to obtain higher contrasts.

tips can be much smaller than the wavelength of the light, depending on the mop and the pressure that we apply to the surface. In any case, by applying a gentle pressure to the polished surface and patiently polishing it in circles, these small particles and tips slowly remove parts of the surface, finally leaving behind the 'landscape' in which any 'mountains' and 'valleys' are not larger in size than the size of the particles or the tips. In other words, the scratches that have been larger in size than the wavelength of light are now flattened and replaced with much finer scratches that are smaller than the wavelength of light and are thus 'invisible' for white light. Now you may also understand why the same job cannot be done by pressing the mop harder, wrongly expecting that this will spare you some time from tedious polishing. In doing so, all you will achieve is that larger parts of the tips will protrude out of the mop and thus make wider scratches that will eventually make your piece of plastic look dim.

Finally let us see how to show the results described above in an effective way suitable for classroom demonstration.

A new, clean plastic CD cover has been treated according to the plan shown in figure 4(a). First three parallel stripes of scratches have been made:

(1) with creamy oven cleaner (such as Astonish) and the hard pressing of the cork (as expected, the oven cleaner is much more abrasive than toothpaste),
(2) with half-dried toothpaste and hard pressing of the cork, and
(3) with toothpaste and moderate pressing of the cork.

For each polishing a fresh cork has been used. Then three different polishing procedures have been applied:

(A) gentle rubbing with creamy oven cleaner,
(B) hard rubbing with toothpaste and mop, and
(C) gentle rubbing with toothpaste and a wet mop.

As shown in figures 4(b) to 4(d) the results can be presented in different ways that reveal different details. If you place a treated plastic cover on an overhead projector (figure 4(b)), the whole classroom can see for instance that oven cleaner produces more visible scratches than toothpaste (which indicates that the abrasive particles in the cleaner are larger in size than those in toothpaste), but they cannot see scratches in stripe 3. The same projected image also shows that after polishing gently with toothpaste the scratches in stripes 1 and 2 are no longer visible, while polishing with oven cleaner only smears out hard scratches but does not produce a clear surface. On the other hand the scanned image (figure 4(c)) also reveals the scratches in stripe 3 and the difference between hard and gentle polishing with toothpaste. The same details can also be observed in reflected light with a black surface in the background (figure 4(d)), but taking a good photograph in this case may not be an easy task. The advantages of overhead projection are the simplicity of the method, the direct view of the evidence and the large size of the picture. But as shown, there are details that require other methods to make them visible enough to convince the students of their existence. The combination of all is the best choice, of course if time permits you.

So next time you wonder what to bring into the classroom to convince your students that physics is everywhere, take your toothpaste.

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References

[1] Hill J W and Kolb D K 2004 *Chemistry for Changing Times* 10th edn (New Jersey: Pearson Education)
[2] dopamine.chem.umn.edu/chempedia/index.php/Toothpaste
[3] www.tomsofmaine.com/toms/ifs/hydrated_silica.asp
[4] Searchable versions of different editions of Newton's *Opticks* are available online at burndy.mit.edu/Collections/Babson/Online/Opticks/

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