Materials education for engineers: a transformation
PTAS project 2011-2013

Introduction

"Materials are at the heart of all branches of engineering. It can be argued – and with not much exaggeration – that engineering is the creative and rational use of materials for practical purposes… Engineers are better engineers if they have a good understanding of the properties of the materials which they use." [Hall 2009]. It is essential that we educate engineers with deep knowledge of materials. To do this the students must understand the basics well. The key aim of this project was to develop new methods, based on Socratic dialogue, to enhance interactive engagement and deepen students' fundamental understanding of materials. (*Socratic dialogue* seeks to get the other person to answer their own questions by making them think and drawing out the answer from them).

This report describes our success in developing new methods, parts of the project that proved to be more difficult, and what we can take from the project – specifically in terms of Socratic dialogue in Materials teaching and more generally.

An RA was employed on the project, full details of the project can be found her MSc thesis (*Introducing Socratic Dialogue in Materials Science and Engineering Education*, Eirini Theofanidou, MSc thesis, University of Edinburgh, April 2013).

The project

The key aim of the project was to develop a new Socratic dialogue approach for Materials tutorials to enhance the interactive engagement of the students. In the project new questions were devised and used with students on the course (see Appendix for questions and dialogues). These were highly effective in promoting engagement and curiosity with the undergraduate students (and also the postgraduate tutors). Many of the students were clearly increasingly engaged when they could actually handle the materials, and experience material behaviour with multiple senses. For example: kinaesthetic awareness of materials is powerful in that it is possible to quite literately "get a feel" for many materials properties: density, modulus, strength, thermal conductivity, surface roughness, deformation and fracture behaviour. Encouraging students to link the qualitative data they can "collect" through their senses with quantitative data e.g. from data books, promotes deep learning. This approach is very "transferable" for the students in developing their own learning within much of engineering (however it is worth noting that not all students have the maturity and interest at second year level in engineering to appreciate and apply this approach).

The secondary aims of the project were to: make a thorough diagnosis of the problems our engineering students encounter in Materials and evaluate the effectiveness of this Socratic dialogue approach in the course in educationally scientific ways. These turned out to be more difficult to address. Good short/multiple choice style questions are rather hard to devise, especially as we wished to probe initial understanding and how this changed after the students had engaged with the "hands-on" Socratic dialogue questions. On reflection this methodology may have been somewhat flawed – as we had to use the same short-questions before and after the students had engaged with the new Socratic questions, and the short-questions were devised first before new Socratic questions were completed. And, more fundamentally, testing the impact of the deep learning we wished to promote with the hands-on Socratic questions is not well matched to a series of short-questions.

The overall nature of this learning may be too fuzzy to assess quantitatively (certainly quantitative assessment is not easy). However, qualitative assessment: from being involved in the tutorials and engaging with the UGs and PG-tutors, from observation the spark and curiosity that was created was clear. More generally, though beyond the scope of this project, it seems there is important learning that can be brought about with this style of deep engagement – which is absolutely a part of what we should be doing within a university – but which is not easily congruent with quantitative assessment and the culture of metrics.

Concluding remarks

The approach of Socratic dialogue, particularly “hands-on”, is extremely good for promoting deep learning. It is a good method to highlight common misconceptions, which can then be addressed in lectures and feed into future iterations of the questions.

For those involved in the project, including PG-tutors, it has been an opportunity for developing and refining questioning and listening skills – both within the Socratic dialogue approach and more generally.

Socratic dialogue works well in the tutorial questions we devised, and with PG-tutors; the approach is highly effective in learning basic concepts in materials science. Equally Socratic dialogue is a good approach for encouraging deep learning in materials science and engineering MSE, however deep subject-specific expertise is required to do this. This project has inspired JB– the course lecturer – to increasingly use this approach where appropriate in teaching Materials. MSE is a huge subject area, this project has highlighted how extensive my understanding of the whole subject is – having spent many years in research, working with strong connections with industry, collaborations within physics, biology, & geosciences, as well as teaching materials to UG students). It is not feasible for PG-tutors to have this level of understanding of the whole subject area, so use of Socratic dialogue methods needs to be carefully thought out.

Perhaps the most generic point to take from this project is a subtle shift in ways of thinking and interacting (questioning and listening) to promote learning – which may be as applicable to research as it is to teaching. This is reflected in the international outputs of the project:

- *Is ice a good substance for educating engineers about materials?* European Geophysical Union, Session organized and sponsored by ESF research networking Programme on the Micro-Dynamics of Ice (Micro-DICE), 2011, Vienna, Austria.
This contribution highlighted the use of Socratic questioning approaches, related to ice and snow, and then encouraged students to make links with the structure, manufacturing and behaviour of conventional engineering materials. [A journal paper related to this is in preparation].

- *Basics of materials: properties and microstructure of ice, and Ice and industry*, Summer School on Microstructures of Ice and Snow, 2012, Obergurgl, Tyrol, Austria.
This presentation used Socratic questioning in the Summer School to engage students with engineering materials and how everyday awareness of materials can be applied to the material of prime interest in the Summer School: ice.

Jane Blackford, Nov 2014.

Appendix: Socratic questions & selected dialogues

From MSc thesis (chapter 4): *Introducing Socratic Dialogue in Materials Science and Engineering Education*, Eirini Theofanidou, April 2013.

1.1 Water drops on a lotus leaf

The following tutorial was given as the first example of a theme for Socratic dialogue.

Water drops on a lotus leaf:

Fig 1 The lotus leaf image given during the tutorial.

(a) Draw a sketch to indicate the interfacial energies that act on the drops.

(b) Give an example of a different system that is hydrophobic (as in the picture), and an example of a systems that is hydrophilic. Consider their use in applications.

(c) Use the web to find out about "self-cleaning" surfaces (potentially amazing!).

What structure do they typically have? What are their current disadvantages?

1.1.1 Concept

Students were asked to develop a deeper understanding on interfacial energies (or tensions), wetting, dewetting, the hydrophobic and hydrophilic behaviour associated with that and also relates these phenomena to examples from real life. Interfacial tension/energy determines the wetting behaviour of a drop of liquid on a flat solid surface. In such a system changing one of the interfacial energies that exist will result in a change of the wetting behaviour of a drop. The example for the lotus leaf was given and the lotus effect was discussed with the students.

1.1.2 Application

A tutor drew a drop on a flat surface and students were asked to determine the different interfacial tensions that exist in this system and the direction of the vector for each of them.

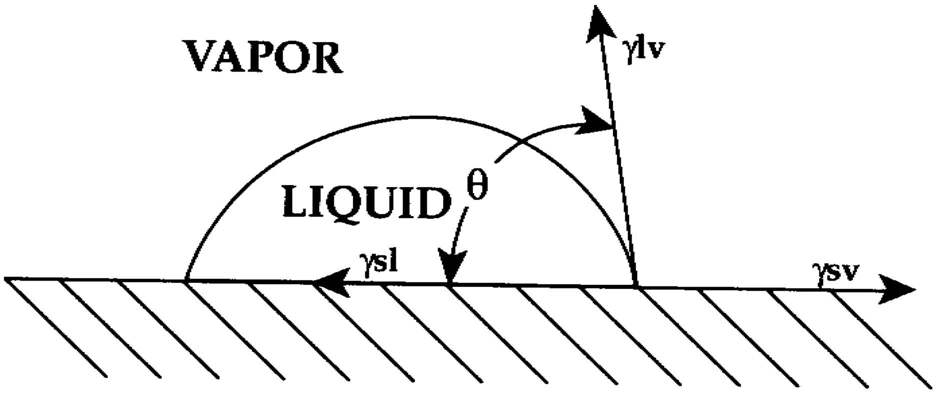

Fig 2 Liquid drop on a flat solid surface. Interfacial tension (or energy) is defined by the letter γ; γ_{lv} is the interfacial tension between the drop and the air, γ_{sv} is the interfacial energy between the surface and the air and γ_{sl} is the one between the surface and the liquid. The angle θ is defined as the contact angle and its magnitude determines the wetting behaviour of the drop, *i.e.* how close the drop will be to a complete sphere ($\theta = 180^o$) or a flat wetting layer ($\theta = 0^o$) on the surface. Of course, these are extreme cases and many a time the angle is between 30^o - 150^o.

T: Could someone identify the different interfacial energies (or tensions) that exist in the physical system depicted in drawing?

S1: We have the interfacial energy between the solid and the water and between the water and the air.

S2: And also between the solid and the air.

T: Right, which direction do they go?

After drawing the tension vectors students were asked to apply force balance and construct the equation that holds (Young's equation).

$$\gamma_{sl} + \gamma_{lv} \cos \theta = \gamma_{sv}$$

So the angle θ determines the wetting behaviour of the droplet. The bigger the angle the drop becomes closer to full sphere and this means that the contact between the solid and the drop is very small so we have hydrophobic behaviour as the liquid tends to leave the solid surface. So solids with contact angles (with water) of more than 90° degrees exhibit hydrophobicity, while in the case of small contact angles (i.e. $\theta < 90°$) the water drop is more flat as it attaches to the solid more and the latter is referred to as hydrophilic.

T: Could you think of a system which is hydrophobic/hydrophilic?

S: ……..

T: Try to find an example from everyday life. In which cases do we want something to be hydrophobic?

S: When it rains?

T: Exactly….an example?

S: The coats

T: Yes the waterproof jacket….in this case we want the garment to be able to repel water, otherwise we will soak. Waterproof clothes are made by fabric which is resistant to water either inherently (natural fabric) or after treatment (synthetic fabrics). In the latter case a waterproofing material like rubber, polyvinyl chloride (PVC), polyurethane (PU), wax *etc.* are used to coat or laminate to a piece of cloth thus no water can pass through.

Later on the discussion, we focused on the lotus leaf. Students were asked whether they searched the web to find any self-cleaning surfaces like the lotus leaf and discover what is actually happening.

T: And what about the lotus leaf? Is anyone aware of how it self-cleanses?

S: ……

T: Has anyone searched the internet?

S: …….

T: Why do you think this is happening?

S: ……

T: The lotus leaf exhibits one property that has to do with …what?

S: The leaf

T: What do you mean?

S: The make of the leaf

T: You mean the structure of the leaf

S: Yes

T: What structure do you expect the leaf to have in order to be able to self-cleanse itself?

T: Will it help if I describe the surface of the leaf?

At this point the picture in figure 4.3 was presented to the students

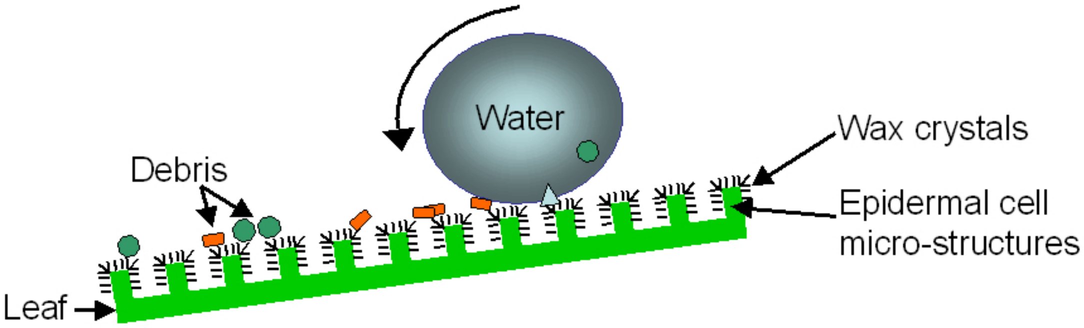

Fig 3 Diagram of Lotus effect. Water forms droplets on the tips of the epidermal protrusions and by rolling off the leaf it collects dirt and small insects. (The picture was taken from http://www.thenakedscientists.com/HTML/features/article/biomimeticsborrowingfrombiology/

T: The picture is just a schematic drawing of images taken with a scanning electron microscope. As you can see the lotus leaf has a very characteristic structure with a complex micro and nano-roughness; its self-cleaning ability is due to a double structure of the surface. The first layer consists of micro-lumps and bumps of protruding epidermal cells, which are around 10 to 20 μm in height and 10 to 15 μm in width and they are covered by wax crystals of 1 nm size. These superimposed waxes are hydrophobic and they form the second layer.

Now if we recall the water droplets we said that they have relatively high surface tension and they tend to minimize their surface by forming spheres. Also we have just discussed the contact angle of a water droplet on a hydrophobic surface. So what contact angle do you expect the lotus leaf to have?

S: A quite big one.

T: Exactly and in this case due to its double structure the contact angle of the lotus is about 170°. So the water doesn't stay flat on the leaf but it stays at the top of the lumps (the roughness enhances the hydrophobic behaviour) as we can see from the picture and it does not slip on the surface, it actually rolls, what about the other dirt and small insects?

S: It depends on their contact angles and adherence to the leaf.

T: Yes, but these small particles actually make contact only at the tip of the wax crystals so what do you expect? Will they adhere well to the surface of the leaf?

S: No.

T: In that case the adhesion between the dirt particle and the water is higher than between the lotus surface and the particle (regardless of its chemistry) so the water by rolling down the leaf traps the dirt and it cleans the leaf.

1.2 The paper clip

1.2.1 Tutorial

Experiment Question *(can be done before tutorial or in the tutorial if you bring paper clips with you)*

Consider a metallic paper clip.

(a) Bend it. What happens? Explain why by considering the processes that occur at an atomic level.

(b) Bend it back. What happens? Again explain why.

(c) Bend it repeatedly. What happens? [We've not covered this in the course yet, but you may be able to work out why this happens. Think about why this behaviour is important in engineering)]

1.2.2 Concept

This tutorial question focuses on the plastic deformation of steel and how this relates to dislocations. Also it covers the fatigue process of the steel sample.

1.2.3 Application in the tutorial

Most of the students had not brought a paper clip with them so the tutors either brought a few or they discussed what we would expect from common experience.

T: Imagine that you have a paper clip made from a typical steel (not a plastic one), and you bend it slightly. What happens?

S: It will bend.

T: If you bend it slightly?

S: No, it comes back to its initial position.

T: Right. So what kind of phenomenon do we have?

S: A deformation that lasts only during the application of a force.

T: How do we call this deformation that ceases to exist upon the removal of the small force?

S: Elastic

T: Correct.

T: Imagine now that you bend it more. What happens?

S: The clip bends and it stays in another position

T: So in this case what kind of deformation do we have?

S: Plastic.

T: Right, so if you think in atomic level terms, what happens that leads to this kind of permanent deformation?

S: The microstructure changes permanently

T: Yes, but what exactly happens to this microstructure, what is the structure of a metal?

S: Crystalline.

T: Yes, so what happens during elastic deformation?

S: The atoms in the crystal move away from each other but upon the removal of the force they return in their initial positions

T: And at plastic deformation?

S: Again they move away from each other, but they move so much that they cannot return back.

T: It is not a bad answer but I will add that when the atoms move away from each other, we have the appearance of linear defects in the crystal lattice called dislocations

S: Oh, yes, we have talked about them in the lectures. It is clearer now to me that they are brought about by the deformation.

T: Yes, now if we bend it back what do you observe?

S: It is actually more difficult to put it back to its initial position. It requires more effort!

T: You have to apply higher force, right?

S: Yes.

T: How do you explain this?

S: …

T: Seems that the plastic deformation has made the material harder.

S: Yes.

T: What about the dislocations? When we did not have many of them were easy to make and plastically deform the sample, but now that we have probably many of them, they seem to inhibit the movement of the atoms.

S: Yes, it seems that having too many of them inhibits the deformation of the sample.

T: As we say dislocation motion and plastic deformation are hindered by dislocation accumulation. This is the basis of work hardening. The next step is to think of what is going to happen when we start bending it repeatedly back and forth.

S: At some point it will break.

T: Correct even if the force is not that high, why do you think this is happening?

S: The repeated deformation even if it is small will induce a large density of dislocations, possibly building up slowly but steadily extensive defects.

T: In the end, no more elastic or plastic deformation can be sustained and the material fails.

T: Could you guess why this process is important for engineers?

S: I guess that in many engineering applications we have repeated application of stress which can induce failure in this way.

T: Yes, and this can happen because of this repeating motion even if the stresses involved are not that high, they can be much lower than the yield stress. We say that this failure is due to fatigue.

1.3 The silly putty

1.3.1 Tutorial question

Watch the videos of silly putty (hit with a hammer, dropped and allowed to “rest” on a surface) on Doitpoms: [use google & underlined words to find the videos].

How does the behaviour of the silly putty change with different strain rates?

Think about why.

1.3.2 Concept

The main concept of this and the following tutorial question focuses on how the mechanical behaviour of thermoplastics and rubbers is affected by temperature (*T*), time (*t*) and load and also how these parameters interact with each other. It is very important for engineers to develop an awareness of the different possibilities. Before these two tutorial questions students were asked to identify the different types of polymers, *i.e.* thermoplastics, thermosets and elastomers, to describe the stress-strain curves for each of them and describe the differences in their behaviour. Another tutorial question was related to the glass transition temperature (*T*g) of thermoplastics and why it’s so important for elastomers.

1.3.3 Application

Students were given real silly putty samples to explore during tutorials; for each tutorial class we had at least one sample which was laid to rest during the previous night. While playing with the samples student were asked what they would expect to happen when different strain rates applied to the silly putty. For safety reasons the strain rate applied with hammer was only asked to be discussed and not performed in the class.

During discussion, movies from the web-site were shown to students to see what actually happens while the strain rates applied to silly putty.

As one can see from the following snapshots when the silly putty is hit with a hammer it fractures, while it bounces when it is dropped. In the case where is left to rest on the surface it creeps/flows. The latter happens at an extremely slow time-rate and we get an indication by observing the silly putty relative to the graph paper that exists behind.

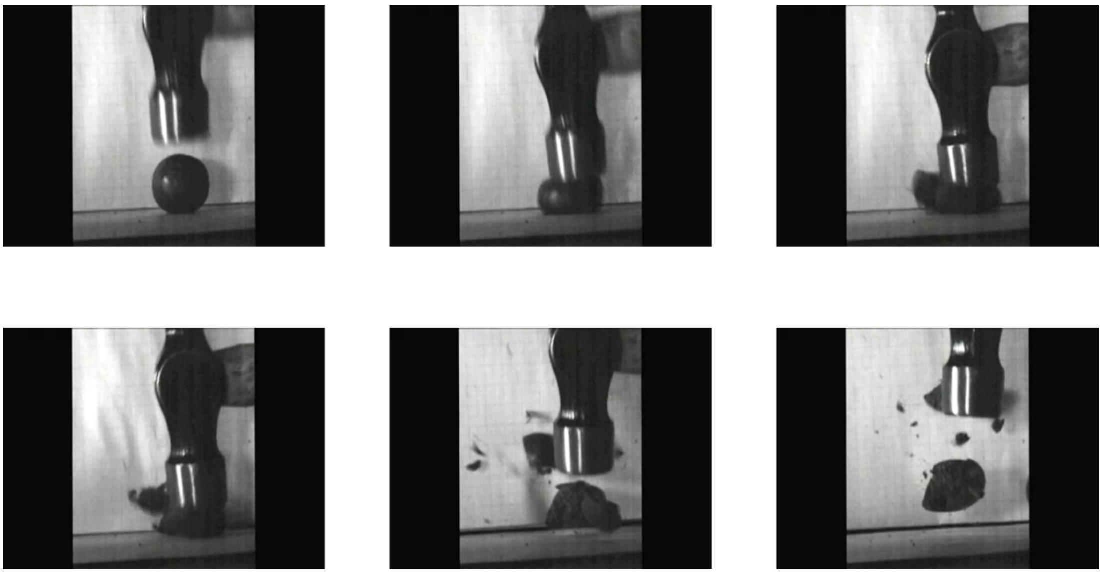

Fig 4 Snapshots of the silly putty hit with a hammer. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/index.php)

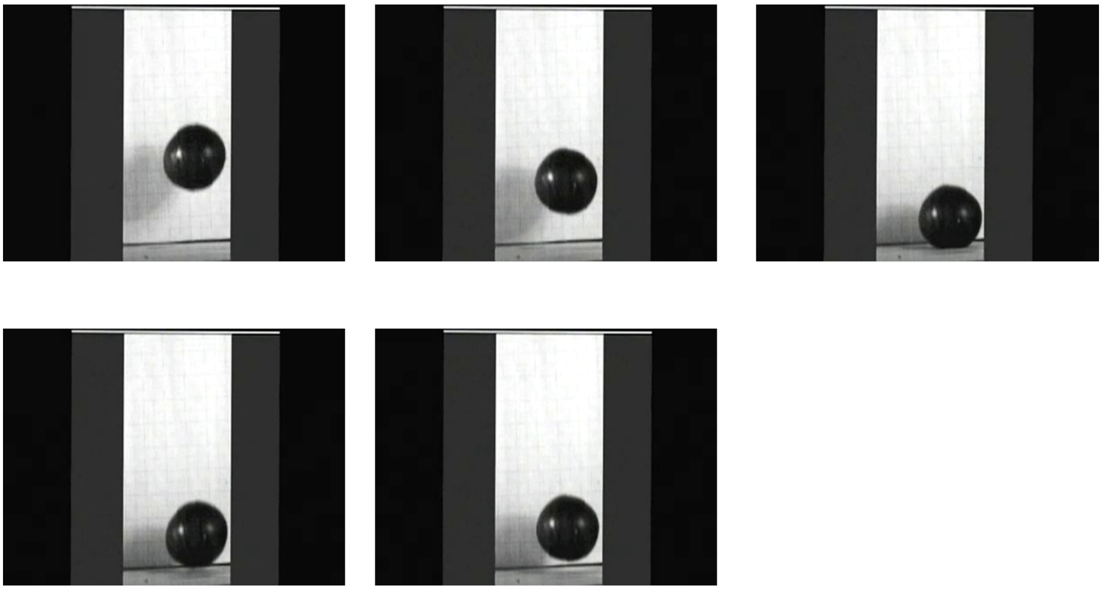

Fig 5 Snapshots of the silly putty bouncing and rebouncing on the floor. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/index.php)

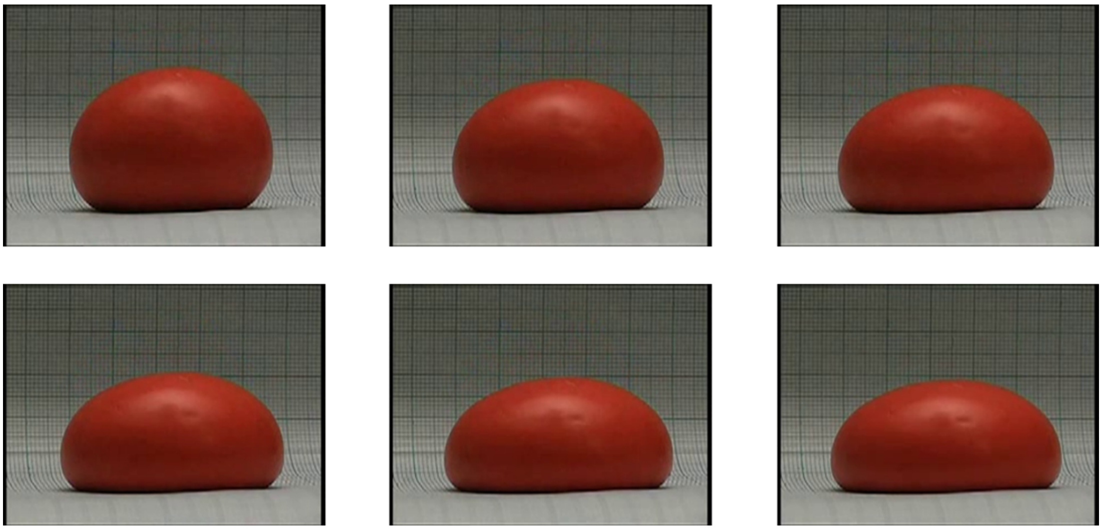

Fig 6 Snapshots of the silly putty left to rest on a flat surface. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/index.php)

A typical discussion between tutor and students was the following:

T: You are given the silly putty in the form of a ball and we hit it with a hammer; what do you expect to happen?

S: It is going to get deformed.

T: right but how?

S: it is going to change its shape

T: what shape do you expect the ball to have now?

S: something more flat and elliptical

T: imagine that you have extreme power and you hit it VERY hard. What do you expect its shape to be?

S: completely flat, like a pastry…..

T: well let's see what happens when we do that….through a video demonstration.

After the video

T: well, as you can see we have not just a simple deformation but a?

S: crack….

T: it's not a crack

S: it breaks

T: so we have a fracture….why do you thing this happens? Why a polymer or an elastomer something that is considered soft breaks? How can we explain that?

S:…

T: in order for a material to be able to break it has to exhibit what type of property?

Which materials can be broken?

S: those we can break….

T: how do we call these materials? What kind of behaviour?

S: brittle?

T: yep…and if you can recall form the lecture when a polymer can be brittle?

Remember what we did here…we applied an extremely high force at a very short time interval. This force stresses the ball …so we have applied what kind of strain rate

S: a big one….

T: exactly by hitting the ball with a hammer we have applied a high strain rate. What does this mean for the material at the molecular scale?

S: What do you mean?

T: What does this mean for the molecules of the material, the polymer chains?

S: They will bend.

T: Does really the fracture that we have witnessed indicate bending?

S: It doesn't, it indicates break, sudden rupture.

T: So, what do you think it happens at the molecular scale when we apply a force at high rate?

S: Molecules don't have time to deform to get out of the way and break. This is strange but in the end it makes sense.

T: Indeed, if the strain rate is high enough the polymer behaves in a brittle manner and that's why it fractures. However, it is interesting to go a bit deeper. At the molecular scale again, what do you think determines if the behaviour will be brittle or ductile?

S: It is the response of the molecules, if they will deform/bend or break. I guess is the magnitude of the force. If it is too high they will break, if low they will bend.

T: Do you believe that the result would have been the same if we did not hit the sample with a hammer, to apply the force at high rate, but we just pressed the hammer on the sample slowly, at low rate, from 0 N force to the same maximum force accomplished with the hitting?

S: … (After some thought) probably not, it wouldn't fracture in a brittle manner, it is not the force, it is the rate of application of the force.

T: Correct. But what determines if the rate is high enough?

S: It is the molecular properties, if the molecule itself is brittle or ductile?

T: Then, why the rate plays a role? If it is the molecule itself that is brittle or ductile the result wouldn't depend on the rate. For the same material, i.e. for the same molecules, the behaviour would be only brittle or ductile at any rate.

S: I see, it has indeed to do with how the molecule behaves but I cannot think of what property of the molecule. It has to do with time as there is a rate effect. But I cannot connect time with molecular properties.

T: Do the molecules stay still or move?

S: The jiggle around in random fashion because of thermal motion.

T: Will a polymer chain move more quickly or more slowly compared to a small molecule of a simple liquid at the same temperature?

S: I know this, the chain will move more slowly, it is big, there is internal friction, the motion will be sluggish; that's why polymers are tough in the first place.

T: What will happen if we try to move the molecules at low rate?

S: They will move out of the way, bend, deform.

T: What will happen if we try to move the molecules at high rate?

S: They won't have time to move out of the way. They could break. So, I see now, as we hit the polymer sample with the hammer at very high rate the chains don't have time to move, they are effectively frozen, the break.

T: So, the rate or as we say the characteristic time of testing has to be compared with what?

S: With the characteristic time that the molecules take to move.

T: Do you know the name of the technical term that gives us the time that a molecule moves a distance of its own size?

S: The relaxation time. I knew that but I had no idea that of its practical significance…

1.4 The bouncy balls

1.4.1 Tutorial Question

Watch movies of the behavior of an elastomer during different temperatures. Think about the similarities between the behaviour of elastomers (or silly putty) at different strain rates [*the above question*] and different temperatures [*this question*].

1.4.2 Concept

Continuing from the previous question this one focuses on the glass transition of an elastomer and how the stress strain behavior changes with temperature.

1.4.3 Application

Four movies were shown to students at different temperatures on the wall screen. Below are snapshots from the movies. In all movies the bouncy ball was left to drop from an initial height of ten units. The first movie was recorded at room temperature of 25°C. Below are five indicative snapshots; the first one is the initial release of the ball, the second shows the first reach on the ground, the third the highest height after the rebound, the fourth the second hit on the ground and the fifth is the last frame of the movie and it shows the highest height after the second rebound.

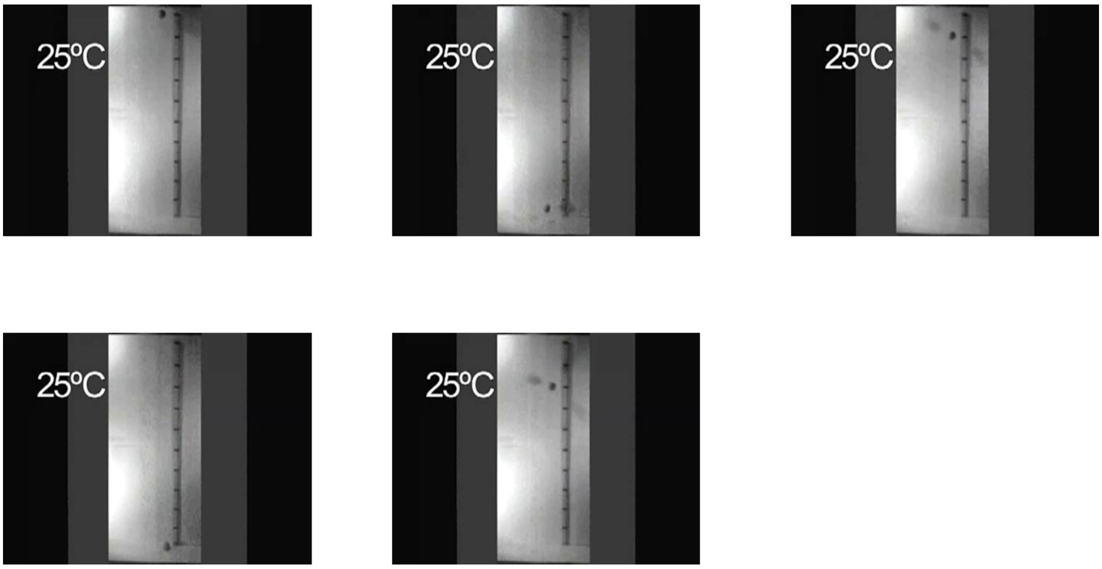

Fig 7 Snapshots of the movie where a bouncy ball is left to drop from an initial height of 10 units at room temperature 25°C. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/demos.php).

Students watched the first movie and then we had the following typical dialogue:

T: Now let’s move to another temperature, lower temperature, what do you anticipate it’s going to happen?

S: The ball will bounce again up and down until it stops.

T: is it going to be the same with the previous one?

S: no

T: what is going to change?

S: the time?

T: what do you mean by the time?

S: How long it takes to rebounce

T: can you explain that

S: well the time it will take to hit the ground and rebounce and hit again and rebounce again and the stop will be different.

T: So you mean that the time-length of the entire movement until it comes to a rest is going to change

S: yes…

T: Ok but why? I mean if the time changes it means that something else has changed…

S: ……..

T: ok let's see what happens

Here the second movie at temperature of -50°C was displayed on the screen

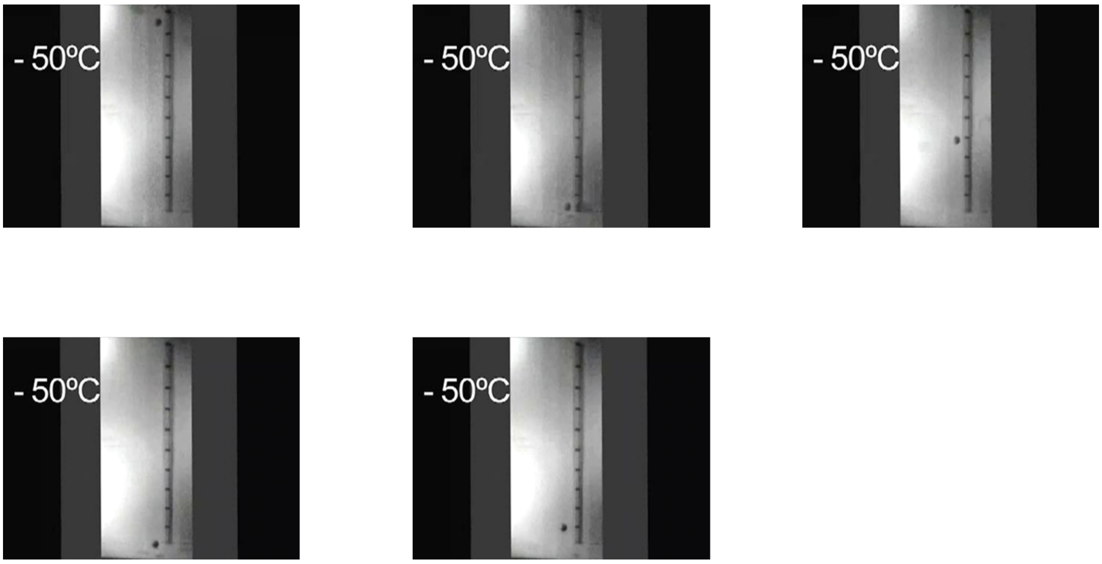

Fig 8 Snapshots of the movie where a bouncy ball is left to drop from an initial height of 10 units at room temperature -50°C. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/demos.php).

T: so what did you see?

S: The ball is bouncing at a lower height both times.

T: Correct so this explains why it takes less time to come to a rest. Imagine now what is going to happen when we go at an even lower temperature, for example -70°C. What do you expect is going to happen?

S: it is going to take even less time

T: so?

S: it will bounce back at a lower height than at -50°C. And then it will stop quicker.

T: ok let’s see if this is going to happen…

The third movie was shown.

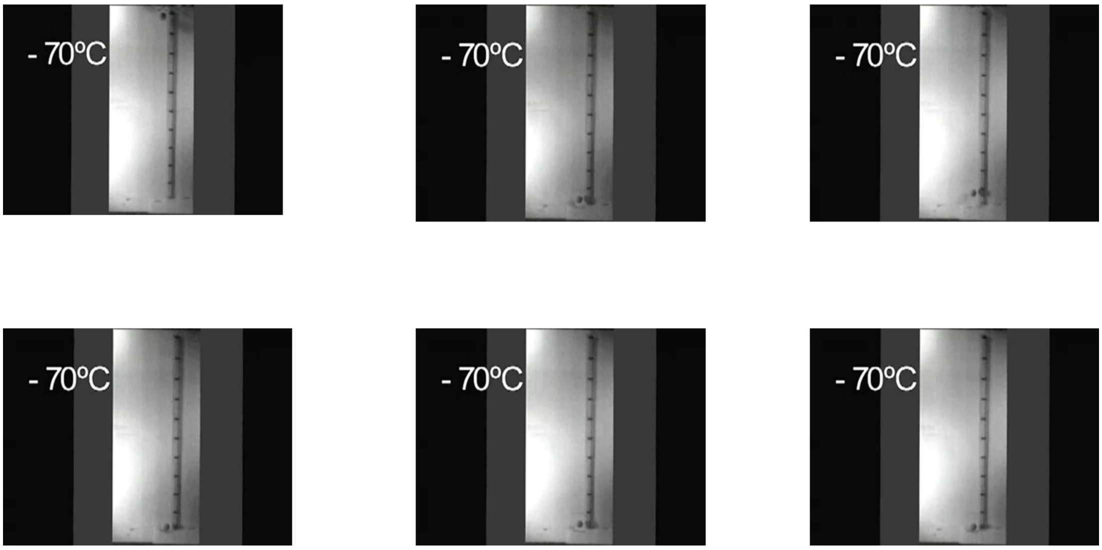

Fig 9 Snapshots of the movie where a bouncy ball is left to drop from an initial height of 10 units at room temperature -70°C. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/demos.php).

T: and now imagine that we are going further down in temperature at -190°C. In this case what will happen?

S1: It will take even less time…

S2: it will drop and stop completely without rebouncing

S3: it will stick on the ground.

T: ok…let’s see

The movie at -190°C

S: is this the correct one?

T: yep…would you like to have another look?

S: yes please….

T: so what do you think is happening? How is it possible the ball to behave similarly to -50°C?

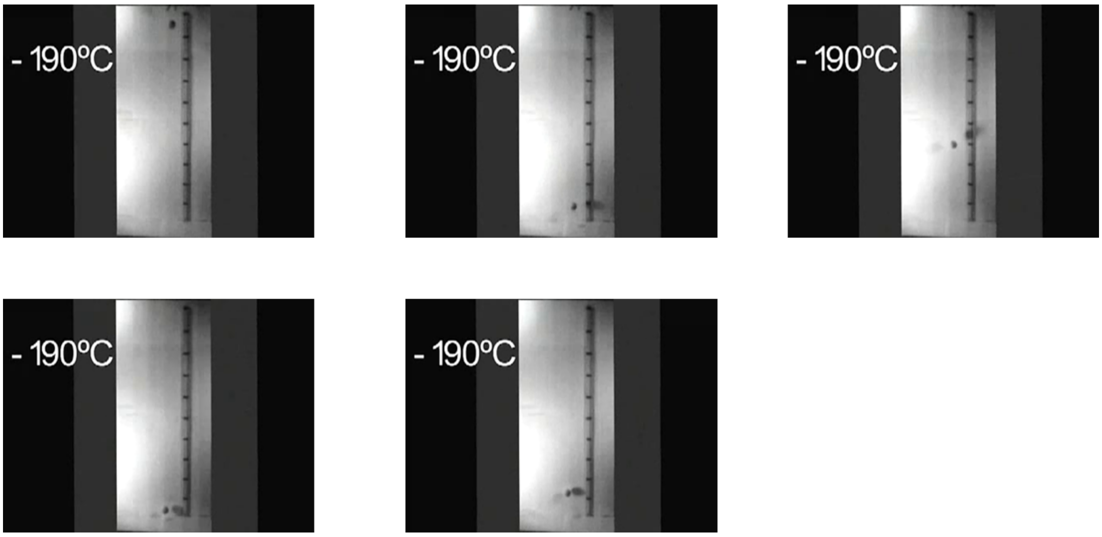

Fig 10 Snapshots of the movie where a bouncy ball is left to drop from an initial height of 10 units at room temperature -190°C. (Images are snapshots from movies found at http://www.doitpoms.ac.uk/tlplib/glass-transition/demos.php).

S: I really don’t know. It is strange.

T: It seems that the elastic ball is acting symmetrically around a temperature.

S: Yes, I see that. It seems that something changes at that temperature. We discussed in the lecture the so called glass transition temperature, but I was expecting a different behavior bellow and above that temperature, not symmetry around this temperature.

T: Could someone remind us what happens at the glass transition temperature?

S: It is the temperature at which the material changes behavior.

T: What behavior?

S/T (in some groups the students did know about that quite well but still had trouble comprehending the symmetric behavior while in some other groups this piece of information had to be provided as the students did not remember the lecture):The viscoelastic…it means that at this temperature we have a transition for the material from the rubbery state to glassy and vice versa.

T: What actually happens at the molecular scale at the transition?

S: The chains become to some extent frozen, they cannot move that much

T: This is the glassy state, the chains as you say are frozen (but of course monomers vibrate around their equilibrium positions, the ‘cages’), it is not the transition though.

S: Yes, I see, you are right; actually at the transition I guess there will be some jiggling around but quite sluggish, so not so freely.

T: What prohibits the movements?

S: The temperature is going down, it is more difficult for the chains to move.

T: If they are difficult to move, what does this imply for the friction at the molecular scale, the so called internal friction?

S: It will be high.

T: High friction is associated with what?

S: heat losses, energy will be lost.

T: So high dissipation of energy.

S: I see now, at the glass transition, as the ball hits the ground, a large amount of its kinetic energy is dissipated, lost as thermal energy.

T: Correct. Do we now understand why there is this behavior at -70 ^{o}C?

S: Yes, it indicates that we are at or close to glass transition temperature.

T: Now, why we have elastic behavior at higher temperatures?

S: Elastomeric behavior.

T: What does this mean?

S: Elastomers are elastic?

T: Yes, but why? Polymers flow at higher temperatures, they are not so elastic.

S: You see, elastomers have crosslinks. This inhibits the flow.

T: It explains the absence of creep but not necessarily the elasticity.

S: Yes, I see we have been taught about the entropic elasticity of the chains between the crosslinks.

T: What does it mean?

S/T (in some groups the students did know about entropic elasticity while in some other groups this piece of information had to be provided as the students had not comprehended at all the lecture material; a tutorial on entropic elasticity alone could be useful): The chains jiggle around because of thermal motion and have a characteristic size at a certain temperature (above T_g). If they are compressed or stretched there will be a restoring force. Macroscopically this manifests as the high elastic behaviour of rubbers.

T: Why the energy loss is low at temperatures well above T_g?

S: The chains definitely move around, there will be some dissipation.

T: You are right but is it big?

S: No, not as big as when we are close to T_g.

T: Yes, there is some internal friction but no so high. What about at very low temperature?

S: This is easier. The material is a glass, if it does not break it will bounce like a glass ball.

T: Correct, it is more conventional behaviour. But why we do not have high dissipation at the molecular scale at these conditions?

S: energy loss is low because the molecules do not move.

T: Yes, chains are quite ‘frozen’, there is no significant sliding between the chains to generate high internal friction.

S: I realize now that the behaviour is symmetric but for quite different reasons.

T: Yes, the underlying physics is different above and below the glass transition temperature.

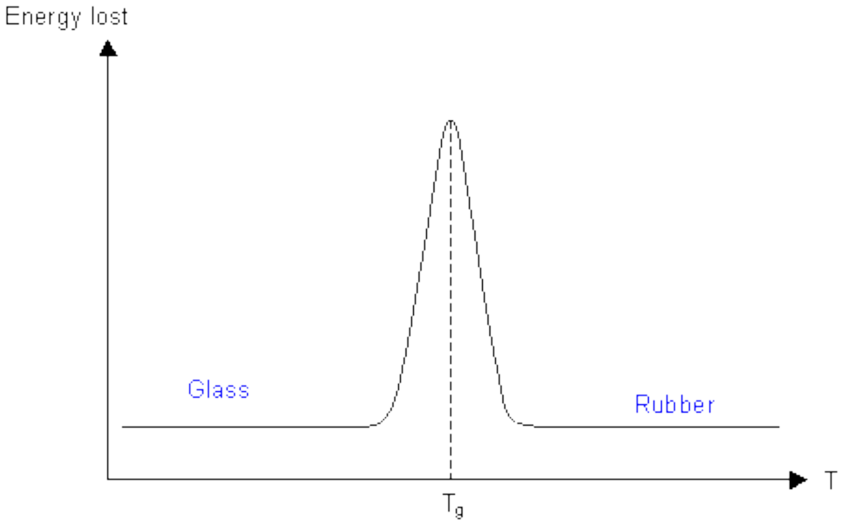

Fig 11 Glass transition temperature diagram with energy lost.

T: Finally, if we combine the last two tutorial questions what do we conclude about the mechanical behavior of polymers?

S: It changes with temperature.

S: And strain rates

T: Yes…so when are they highly elastic and potentially brittle in which regions?

S: Low temperature and high strain rates

S: And at low strain rates and high temperature are ductile/viscous.