MANUFACTURING AND DESIGN, 1st edition, 2014
Erik Tempelman, Hugh Shercliff, Bruno Ninaber van Eyben

Chapter 9: Thermoforming – HINTS

THIS DOCUMENT IS INTENDED FOR USE BY STUDENTS.

Exercise 9.1 Search around your house for examples of thermoformed and blow-moulded parts or products. (Hint: don't forget to look at packaging applications).

Hint 9.1: for inspiration, feel free to do an Internet image search (tip: the search term "vacuum forming" is also quite productive), but as always, make sure to lay your hands on actual products.

Exercise 9.2 Strictly seen from the manufacturing point of view, thermoforming is best done with high molecular weight grades. Explain why. Do you expect that such grades are also well-suited to injection moulding? Explain your reasoning.

Hint 9.2: think how the graph of stiffness versus temperature would look for a high-molecular weight grade, and recall that thermoforming is an open process (so, a process with inherently poor temperature control as compared to closed processes, such as injection moulding).

Exercise 9.3 Sketch the graph of stiffness versus temperature for both an amorphous and a semi-crystalline plastic. Indicate clearly the temperature ranges where you can thermoform these materials, and where you can injection mould them. What range is suitable for the actual use of the materials in products?

Hint 9.3: if in doubt, re-read Section 8.2.

Exercise 9.4 We want to make a square PS box as shown in Figure 9.1. The semi-finished product we use as input material is a 1 mm thick sheet of PS. What will be the wall thickness of the box if it measures L x W x H = 200 x 200 x 100 mm? And what if we use a foil that is 0.2 mm thick?

Hint 9.4: $\Delta V = 0$!

Exercise 9.5 Suppose we want to thermoform a transparent hemispherical cupola from PC with a 3 mm wall thickness. What should be the thickness of the input sheet? Hint: the surface area of a sphere with radius R is equal to $4\pi R^2$.

Hint 9.5: same as previous exercise; also, note that this involves a hemisphere.

Exercise 9.6 Why is the wall thickness at the corners less than in the middle? Hint: once cooled below T_g the material will no longer deform, and further deformation has to come from the parts that are still hot.

Hint 9.6: imagine carefully (tip: sketching helps) how the forming process unfolds, and which parts of the product are first to make contact with the mold.

Exercise 9.7 Take a close look at your sample products from Exercise 9.1. How does the thickness vary over the cross-section? Tip: if appropriate, feel free to cut up your products, and use callipers to make accurate measurements.

Hint 9.7: all kinds of possibilities. Note that in case of products made using pre-stretch thermoforming, the thickness variation may be too small to measure.

Exercise 9.8 We can sometimes reduce this 'corner thinning effect' by reducing the temperature difference between (heated) plastic and the mould. Does this also have a disadvantage? Explain.

Hint 9.8: Section 9.5 goes deeper into this topic.

Exercise 9.9 What is the maximum cycle time if we want to make a million products per year with a single-cavity mould? Assume production in two shifts. Do you think this will be a product with large or small wall thicknesses? What advantage would a multi-cavity mould offer?

Hint 9.9: you will have 3,000 effective production hours/year (never 100% of the time, as equipment needs to be maintained, and may have some downtime when different orders for products do not quite line up in the planning). Another hint: see Table 9.1. For a final hint, consider that standard thermoforming machines, as well as the ingoing sheet and foil materials that are commonly available (and therefore cheapest), have certain fixed dimensions.

Exercise 9.10 Take a good look at your sample products (Exercise 9.1). Any sign of air outlets? And do you think these products were vacuum formed, or pressure formed? How can you tell?

Hint 9.10: all kinds of possibilities.

Exercise 9.11 Think of one potential benefit of using higher pressure differences and one potential drawback. Explain.

Hint 9.11: perhaps surprisingly, increasing the formability is *not* a benefit: for 'difficult' products (e.g. very deep, very detailed etc.) it is better to increase the forming temperature instead of the forming pressure. You will find the answer in Section 9.5.

Exercise 9.12 A manufacturer of roof-mounted luggage compartments for cars wants to use thermoforming to shape the upper and lower shells of these products. The outside should be textured. Should the two shells be positively or negatively formed?

Hint 9.12: just imagine (or better: sketch) how this would look.

Exercise 9.13 Typical 'clamshell packaging' only works if the edge is well-defined. Should we use positive or negative forming? And what about your sample products (Exercise 9.1)?

Hint 9.13: for the clamshell, there is only one good answer!

Exercise 9.14 State three additional factors that determine the cooling time, and explain if these factors increase or decrease the time.

Hint 9.14: Section 9.5 digs deeper into this topic.

Exercise 9.15 What is easier: de-moulding of positively-formed products or de-moulding of negatively-formed ones? Explain.

Hint 9.15: recall that products shrink during cooling (especially semi-crystalline ones).

Exercise 9.16 Take a close look at the edges of your sample products (Exercise 9.1). What do you find? More specifically, does this kind of edge finishing look and feel attractive?

Hint 9.16: look closely – and feel.

Exercise 9.17 Assuming that plastics are as sensitive to infrared as to normal visible light, what is faster to heat up: white sheets, black sheets or transparent sheets?
Hint 9.17: given this assumption, the answer should be obvious! For completeness, however, we should add that the real world is not this simple, and the transparency of substances to visible light can be quite different from that to infrared light.

Exercise 9.18 Look at your sample products (Exercise 9.1) and try to sort them on heating time. Which one has probably taken the longest time to heat, which one the shortest? Why?

Hint 9.18: all kinds of possibilities.

Exercise 9.19 Make a schematic graph of part temperature against time during cooling, showing the forming temperature T_f, de-moulding temperature T_e and mould temperature T_d (with $T_f > T_e > T_d$). If the cooling time is the time to get from T_f to T_e, when is this time then minimal? For an amorphous plastic, how close to T_f can we de-mould?

Hint 9.19: you should have guessed here that just as in any heat conduction problem, the part temperature drops off hyperbolically against time from the forming temperature T_f to the mould temperature T_d during cooling, theoretically taking infinitely long to get to T_d (recall Equation 8.3: dividing by zero!). Draw it now if you did not see this previously. So, the higher we choose our de-moulding temperature T_e, the shorter the cooling time will be. Note that for amorphous plastics, T_e has to be *below* the glass temperature T_g (otherwise, the material does not have sufficient stiffness). Also note that semi-crystalline plastics can be de-moulded (and indeed, normally are) at temperatures *above* their T_g, as their crystalline regions give them sufficient stiffness already at these higher temperatures.

Exercise 9.20 Which could be faster for cooling: positive or negative forming? Hint: think of shrinkage.

Hint 9.20: the hint in the question should lead you to the answer.

Exercise 9.21 Revisit Exercises 9.8, 9.11 and 9.14. Now, sort all factors that influence the heating and cooling time into principle-specific factors and method/equipment-specific factors. Explain.

Hint 9.21: this is one of the key exercises of this chapter, so take your time to make a solid overview. The text contains no fewer than ten (!) factors, some of which affect heating, some cooling, some both; some of them are principle-specific factors, while others pertain to the equipment. Keywords are: temperatures of forming, ejection and mould T_f, T_e and T_d; forming pressure; positive or negative forming; material thickness, type and colour; and certain facilities of the equipment used.

Exercise 9.22 Sort the aforementioned five methods by (a) form freedom (think of product size and depth, level of detail, thickness control) and (b) production speed. What is your conclusion?

Hint 9.22: a more straightforward question. Your answer should point to a trade-off you will recognize from the manufacturing triangle: the functional aspect of form freedom comes at a price.

Exercise 9.23   Write down three guidelines for the design of successful thermoforming products, with reference to the theory described in this chapter. How can you see these rules reflected in your sample products (see Exercise 9.1)?

Hint 9.23: this should not be too difficult, if (for instance) you consider which materials and thicknesses are easiest (or fastest) to process, or if you recall which side of the product will be textured and which not. But in addition, consider practicalities such as the sizes of readily available in-going materials and the fact that thermoforming always involves production scrap that is not so easily recycled as it is in injection molding.