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Chapter 8: Injection moulding of thermoplastics – HINTS

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Exercise 8.1 Look around your house for injection moulded parts and products, and begin to consider how important the following might be in their design: form freedom, colour, surface texture, stiffness, strength, or cost.

Hint 8.1: with the ubiquity of injection moulded products, you should have no difficulty to find samples (for instance, the product you disassembled in Chapter 2 very likely contained several such parts!).

Exercise 8.2 How many monomers typically comprise a polymer chain?

Hint 8.2: trick question!

Exercise 8.3 Sketch the main differences in chain structures for a thermoplastic material, a thermosetting material, and a rubber. Explain these differences in a few keywords.

Hint 8.3: one keyword should be 'chain entanglement', another 'cross-links'.

Exercise 8.4 There are six 'commodity plastics', each having its own recycling logo. Which ones are they, and what are their monomers? Name a typical application for each one. Are they semi-crystalline or amorphous, or can they be both, depending on the specific grade?

Hint 8.4: a quick Internet search (e.g. with search term "plastic recycling logo") will reveal which ones these are, and the CES EduPack will provide the other data. But do not just copy-and-paste information (e.g. applications): instead, think about your answers.

Exercise 8.5 Next, name five 'engineering plastics' (defined here as all non-commodity plastics with prices below 10 euro/kg). Give typical applications, and indicate if they are semi-crystalline or amorphous.

Hint 8.5: use the same approach as the previous exercise. Note that several of these plastics are better known by their trade names than their rational names (e.g. 'nylon' for 'polyamide', or 'lexan' for 'polycarbonate').

Exercise 8.6 What are the values of T_g for the six commodity plastics? And what are their maximum service temperatures?

Hint 8.6: either use CES EduPack (level three recommended: try unfilled grades designated something like 'general purpose/moulding and extrusion'), or try www.matweb.com. Note that there is a difference between the maximum service temperature that plastics can briefly withstand, and the one they can stand for longer periods (which is considerably lower). Accordingly, there are several different tests to determine these temperatures: be sure to use the same definition for all plastics that you list.

Exercise 8.7   Which kinds of plastics have been used in your sample products from Exercise 8.1? Tip: ensure that your answers match what you said in Exercises 8.4-8.5!

Hint 8.7: all kinds of possibilities; note that the type is usually designated on the part, either as the abbreviation or as the recycling logo.

Exercise 8.8   Thermosets and rubbers do not melt on heating. What happens instead, and why is this? What are the implications for the recyclability of these polymers compared to thermoplastics?

Hint 8.8: if in doubt, look ahead at Chapter 14, Section 14.2.

Exercise 8.9   Determine the pressure difference that is required to fill a cell phone housing in one tenth of a second. Model the shape as a flat plate that is injected over its full width, assume Newtonian behaviour and use a viscosity μ = 36 Pa.s.

Hint 8.9: you will need the length and thickness to make this calculation. For an l/d ratio of 100, the answer would be 43.2 MPa, or 432 bar.

Exercise 8.10   What happens to the pressure difference if – at equal injection time – the thickness is halved?

Hint 8.10: just observe the formula!

Exercise 8.11   Low molecular weight grades require less pressure to process than high molecular weight grades. But what disadvantages do they have?

Hint 8.11: the key word here is toughness.

Exercise 8.12   Repeat Exercise 8.9, but now using a 10% lower viscosity thanks to increased processing temperature. What is the gain in terms of the required pressure difference? Would this increase also have drawbacks?

Hint 8.12: the drawback will become apparent after reading Section 8.5.

Exercise 8.13   Calculate the minimum clamping force necessary for injection moulding of the cell phone housing from Exercise 8.9. Tip: first sketch the position of the parting plane! Now do the same for one of your sample products (Exercise 8.1, repeating the estimate of Exercise 8.9 for this product).

Hint 8.13: for your answer, assume single-cavity moulds – unless your sample product is quite small, and obviously produced in huge numbers (as cell phone housings are), in which case two, four (or even more) cavity moulds are used (see Figure 8.8).

Exercise 8.14   Suppose that to injection mould a round 10 litre PP bucket we require a pressure of 900 bar. How large should the minimum clamping force be?

Hint 8.14: if your answer is below 400 tons then you have made a mistake somewhere!

Exercise 8.15   Determine for your sample products (Exercise 8.1) where the gates have been placed. How can you tell, and how can you know?

Hint 8.15: many possibilities; see also Exercise 8.17.

Exercise 8.16   Are there any disadvantages to multi-point injection?

Hint 8.16: Section 8.4 holds the answer.

Exercise 8.17   For a product that is essentially rotationally symmetrical, such as the bucket from Exercise 8.14, what are the two possible locations for single-point injection? Which is best, and why?

Hint 8.17: again, Section 8.4 is where you should look.

Exercise 8.18   Now imagine that to increase strength, the bucket wall thickness has been increased near the two handles. How would you then inject the product, and why?

Hint 8.18: you need an uneasy compromise (from which you can draw the conclusion that injection moulded products should ideally have a constant wall thickness – here is a clear design rule!).

Exercise 8.19   What measures can you take to influence the location where knit lines are formed, given a certain fixed product shape with several holes?

Hint 8.19: the key word is ‘injection points’ (i.e. gates).

Exercise 8.20   Calculate the cooling time for the cell phone from Exercise 8.9. What would this time be if we double the thickness? Answer the same questions for the bucket from Exercise 8.14.

Hint 8.20: simply use the formula. Of course, the ejection temperature must be not too close to the mould temperature, or the cooling time will become very long indeed.

Exercise 8.21   Revisit your answer to Exercise 8.12. Did you make the right prediction for what the drawback would be, and can you now also give a quantitative answer?

Hint 8.21: in other words, how much longer does the cooling time get?

Exercise 8.22   Determine for your sample products (Exercise 8.1) where the ejection pins were located. Can you tell why have they been placed right there?

Answer 8.22: just observe carefully - with very few exceptions, ejection pins are round, and leave round marks.

Exercise 8.23   Suggest three different ways to prevent the ejection from leaving visible marks on the part. For each, give one disadvantage also. Hint: see Equation (8.3) and Table 8.1.

Hint 8.23: in addition to the hint already given, also consider the number of ejection pins; furthermore, Section 8.7 also contains one of the answers.

Exercise 8.24   Do you see any sink marks on your sample products (Exercise 8.1)? And what plastics are used in them: amorphous or semi-crystalline types?

Hint 8.24: many possibilities – just look closely on the surface anywhere there is some concentration of material (e.g. above stiffening ribs or screw bosses).

Exercise 8.25 How much extra pressure would we need to fully counteract shrinkage in PS? And how much in PP, assuming it has the same compressibility as PS?

Hint 8.25: all the data you need are in Section 8.6.

Exercise 8.26 Which layout is best if manpower is cheap and investment must be minimal? And which is best if labour must be minimal and investment can be higher?

Hint 8.26: this should be no problem – just study the text.

Exercise 8.27 Which layout would minimize the formation of production scrap (i.e. material that gets processed, but that does not end up in the actual part or product)?

Hint 8.27: again, this should pose no difficulties – there is only one correct answer.

Exercise 8.28 For your sample products (see Exercise 8.1), determine where the parting planes have been placed, and why. Also, determine if all draft angles are positive. If not (i.e. there are 'undercuts' – places with negative draft angles), how have they been made?

Hint 8.28: many different possibilities! Note that at the location of the parting plane there usually is some kind of linear surface defect visible.

Exercise 8.29 The set-up shown in Figure 8.8 will not produce identical products. This is because the two central blocks have a shorter runner than the other four, and hence receive more pressure. How can we fix this problem?

Hint 8.29: the key word here is 'runner length'.

Exercise 8.30 A standard snap fit joint has a negative draft angle. Think of three different solutions to this problem. Which drawbacks do they have, and what is your preference?

Hint 8.30: here it is best to examine a part that in fact has a snap fit, so you can simply see how things can be done. As for your preference, this should depend on the product in question and on its function, cost and quality.

Exercise 8.31 Opening and closing of moulds takes time (typically, the moving half moves at 1-2 cm/s). What does this imply for the cycle time of flat products as compared to deeper ones?

Hint 8.31: one of the two will have a (possibly substantially) shorter cycle time.

Exercise 8.32 Choose a common engineering plastic, such as ABS or PA, and look up what changes in mechanical properties (strength, stiffness, strain-to-failure, fracture toughness etc.) can be made by addition of glass fibres. (The CES software is particularly useful here).

Hint 8.32: simply tabulate and compare the data (or better in CES, plot 'property charts', annotating filled and unfilled variants in different colours).

Exercise 8.33 Glass fibres have a lower specific heat capacity and a higher thermal conductivity than plastics. What does that imply for the cooling time for such grades: specifically, which term changes in Equation (8.3)?

Hint 8.33: just study the equation and decide which terms are material-dependent.

Exercise 8.34 Look up the key mechanical and thermal properties of PLA. Also, consider its price. How do these values compare to those of PS or PE?

Hint 8.34: again, simply tabulate the data and compare (or plot suitable CES property charts).

Exercise 8.35 In injection moulding of PLA, the injection time is typically three times longer than that of most comparable plastics. Gate design is also different. Explain why, with reference to the theory covered in Sections 8.3 and 8.4.

Hint 8.35: Equation 8.1 holds the answer to the first part of the exercise. As for gate design, consider that the full product cavity must have been filled before the gate freezes shut (in other words, to prevent what injection moulders call a 'short shot').

Exercise 8.36 Is PLA a sustainable material? Explain your judgment!

Hint 8.36: consider your answer at three levels: (a) compare the embodied energy or CO_2 footprint of PLA directly with that of a competing material; (b) consider a life cycle assessment (LCA) of two products, one made of PLA, one made of the competing material – and consider that there may be differences in product weight, use, lifespan etc.; (c) consider resource scarcity.

Exercise 8.37 Give three guidelines for the design of 'standard' injection moulded products. Each time, make explicit reference to the theory covered in the preceding sections. How are your guidelines reflected in your sample products (Exercise 8.1)?

Hint 8.37: many possibilities, which can also be found on the Internet (for this manufacturing principle perhaps more so than for any of the others in this book). Be sure to study the rules you make closely, and try to make them specific. Also, do not give manufacturing rules (for instance: "minimize the processing temperature" is *not* a design rule).

Exercise 8.38 Differences in thermal expansion between insert and plastic may cause problems. Calculate this difference for a typical injection moulding temperature for a flat, straight 0.5 mm thick steel strip placed flush onto a 1.5 mm nylon plate. What exactly will be the problem?

Hint 8.38: consider that the steel is much stiffer than the nylon, and the strains induced. How does this compare to the nylon's yield strain?

Exercise 8.39 Using a cross-sectional view, explain why a gas bubble will most likely not remain in the centre of a non-symmetric part. Hint: melt viscosity goes up where the melt cools down. What kind of design rule does this suggest?

Hint 8.39: make a sketch! Which part of the cross-section is first to cool down? So, where would the bubble move towards?

Exercise 8.40 On which side of the part do you get the decoration: injection or ejection side? And what does that mean for the suitability of IMD in practice?

Hint 8.40: not a trick question – there only is one good answer.

Exercise 8.41 Which of these five methods can be combined with one another? Also, think of a realistic application for each combination.

Hint 8.41: looking for ideas? Read Section 8.11.

(Questions 8.42-8.48 are taken together, below)

Exercise 8.42 Make a first, rough estimate for the manufactured cost of a 2K-swiffer. (Hint: due to taxes, margins, sales costs and so on, sales price for products of this type is typically 3-5 times the manufactured cost).

Exercise 8.43 Look up the costs of PP and EPDM. What is the material cost per 2K Swiffer? Is it reasonable to assume the same material cost for the 1K alternative? How does it compare with the estimate made in Exercise 8.42?

Exercise 8.44 For both 2K Swiffer and the 1K alternative, what is the capital cost of the moulds, per part, when shared over production runs N of (a) 100,000; (b) 1 million; (c) 10 million?

Exercise 8.45 What are the labour costs per hour, and per Swiffer, for both varieties? Determine these costs for all three regions mentioned.

Exercise 8.46 Determine the machine costs per hour, and per Swiffer (both varieties, all three regions).

Exercise 8.47 Estimate the number of packaged Swiffers that can be transported in a full 12 metre long container (with a cross-sectional area of 2 x 3 metres). Hence estimate the transport cost per Swiffer, for manufacture in the Czech Republic and in China (for batches of 100,000, 1 million and 10 million). What other disadvantage is there to off-shore manufacturing?

Exercise 8.48 Now, add up cost components (1) – (4) to determine the total costs of both Swiffers, for all three regions. What is cheaper: 2K or 1K? Which region is 'best'? Also, compare your answers to the estimation you made in Exercise 8.42.

Hint for Exercises 8.42-8.48: simply run the numbers – although we advise you to do this in a spreadsheet. The machine costs will turn out to be surprisingly high, especially for significant production volumes (when the depreciation of the investments gets comparatively small).

Note that instead of using sequential injection of the 2K Swiffer in the mould, we could also use a two-cavity 2K mould with simultaneous injection of the PP and EPDM. The mould would then become more expensive, but its depreciation is quite low (at least for 1 million shots) and this would cut machine costs in two – with added reduction of labour costs. As Exercise 8.49 should show you, the given machine size is actually sufficient to make this bigger product.

Exercise 8.49: Time for a reality check! Use Sections 8.3 and 8.5 to determine whether the cycle times and machine tonnages assumed in the analysis are realistic, at least for the 2K Swiffer.

Hint 8.49: for the machine tonnage (i.e. clamping force), assume an injection pressure of 1,000 bars. For the cycle time, assume this is primarily the cooling time (Equation 8.3, with suitable assumptions for T_p, T_e and T_d). For such a flat product, the cycle time will be only slightly longer, as injection, mould opening, ejection and mould closing take only seconds.