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Appendix: Long exercises with worked solutions

THIS DOCUMENT IS INTENDED FOR USE BY STUDENTS.

Introduction

Manufacturing and Design contains a large number of exercises. For reasons explained elsewhere, we advise that students should only make use of the hints to these exercises – the worked-out answers, along with some background material, are provided for teachers. We believe this is the best set-up to facilitate teaching and learning. At the same time, it is helpful for both students and teachers to have additional practice questions covering the key issues, with worked-out solutions. This is where this Appendix comes in.

This document presents ten worked-out "exam-style" questions used by the authors. Not all chapters lend themselves to such in-depth questions – we have provided one or two questions for each of Chapters 3-10. They indicate the level of understanding you should ideally obtain after working through the book. The level of refinement and detail in the answers will probably go beyond what most students can supply, but the core answers should be accessible to all. Note that simpler, factual questions (e.g. "name five engineering plastics", or "can heat treatment influence the Young's modulus of metals?") are deliberately excluded – questions of this type have been covered in the main text, and add little here. Each question could be considered a typical 20-30 minute exam problem; alternatively, the questions could be used as mini-projects, enabling deeper investigation and use of other resources.

NB: in several questions you will find the phrase 'Explain briefly'. By this we mean, explain using just a few sentences.

Chapter 3: Casting of metals

Figure A3 shows a cast iron manhole cover, in which the design freedom inherent to casting has been put to good effect: it has two sets of two holes to facilitate removal, an anti-slip pattern consisting of small square knobs and surface relief that is both decorative and informative. The actual product consists of two parts: the round cover and the frame around it – here we focus on the round cover. Its diameter is 60 cm, and its thickness is 4 cm.

Figure A3: cast iron manhole cover

(a) The latent heat of solidification of this cast iron is 270 kJ/kg, the specific heat in the solid phase is 500 J/(kg.K). Assuming we de-mold at 500°C below the $T_{solidus}$, which is larger: the latent heat of solidification or the heat that is to be dissipated after solidification?

(b) Determine the thermal modulus of this round cover. You may simplify the shape as a flat disk.

(c) Theoretically, we can cast this part in a sand mold (sand casting), a steel die (gravity die casting) or a ceramic shell (investment casting). In practice, one of these three will be clearly preferable. Which one, and why? Explain briefly.

(d) Now estimate the solidification time for the method chosen under (c). Data: Chvorinov coefficient, sand mold: C = 68 sec/cm^2, steel die: C = 2.2 sec/cm^2, ceramic shell: 130 sec/cm^2.

(e) Cast iron shows minimal shrinkage, yet still some sort of feeder will be used. How will this affect the solidification time? Explain briefly.

Answers

(a) Latent heat of solidification is given as 270 kJ/kg; heat to be dissipated after solidification is 500 x 500 = 250 kJ/kg. The former is (slightly) larger.

(b) Volume V = 11,309 cm^3, surface area A = 6,409 cm^2 (NB: 2 sides). Thermal modulus V/A = 1.76 cm.

(c) The combination of cast iron and steel dies is very rare: the temperatures are too high for ordinary steel dies. Investment casting of cast irons can be done, but this relatively simple part does not merit this expensive process: it can be assumed to have positive draft angles all around, so investment casting is not needed here. Sand casting of cast iron is very common, and clearly the best choice here.

(d) Using Chvorinov's Rule, we get $t_{solidification} = C\,(V/A)^2$ = 212 sec.

(e) A feeder can only fulfil its purpose if it stays liquid longer than the part that it feeds. So, the use of a feeder will always increase the solidification time.

Chapter 4: Sheet metal forming

4A: 2D sheet metal forming

Imagine a typical box-shaped steel computer casing. Its key manufacturing steps are: (i) punching out ventilation slits and other functional holes; (ii) blanking to obtain the folded-out flat shape; (iii) bending to 90° of all sides and flanges; and (iv) joining, e.g. by riveting the corners. Assume the casing is made of 1.0 mm thick mild steel (pre-coated with paint to facilitate finishing) with 1.5 mm radii all around. The steel has a yield stress of 315 MPa, a tensile strength of 525 MPa, a Young's modulus of 210 GPa, and a strain-to-failure of 40%.

(a) Determine the minimum bending radius (MBR) for this steel and verify that the radius used for the casing is larger than this lower limit.

(b) Given that during bending to a radius of 1.5 mm springback is 2.0°, what will this springback become when we reduce the radius to the 1.3 mm? Assume that only the radius is changed; type of material, sheet thickness, and bending method are kept constant.

(c) The manufacturer wants to make a premium version of this housing using bare aluminium, selecting an alloy with a 200 MPa yield stress, tensile strength of 270 MPa, Young's Modulus of 72 GPa and strain-to-failure of 15%. The total strength of the housing should not be reduced. Which changes to the design would certainly be necessary, if we only look at the bending step? Explain briefly.

Answers

(a) $MBR = t\,/(2 \times \varepsilon_{max}) = 1.0\,/(2 \times 0.40) = 1.25$ mm. This is less than the 1.5 mm that is required here, so the radius does exceed the *MBR*.

(b) For this, we need to first determine the elastic deformation energy per unit volume *EDE*, which is in this case equal to *EDE* = 236.25 kJ/m^3 (note: elastic strain at yield equals 0.15%). Next, we must determine the maximum strain during bending for t = 1.0 mm and R = 1.5 mm: this equals 33%. The third step is to determine the plastic deformation energy per unit volume, *PDE*. Since the stress-strain curve beyond yielding is not given, we simplify the situation by assuming a constant stress during plastic deformation equal to the mean value of yield stress and tensile strength, i.e. 420 MPa. Then, *PDE* = 420x0.33 = 140.0 MJ/m^3. This in turn means our total deformation energy per unit volume *TDE* = *EDE* + *PDE* = 140.2 MJ/m^3, and *EDE*/*TDE* = 1.69x10^{-3}.

If the radius is reduced to *R* = 1.3 mm, the strain increases to 38%. *EDE* remains the same, but *PDE* increases to 159.6 MPa/m^3, *TDE* to 159.8 MPa/m^3, and *EDE*/*TDE* now decreases to 1.48x10^{-3}. Given that the ratio between elastic and total deformation energy (per unit volume) is proportional to the springback, we finally arrive at the answer of (1.48/1.69) x 2.0° = 1.75°.

(c) If strength has to be maintained, the first design change is to increase the sheet thickness to make up for the reduced yield strength. For a simple comparison we can assume that the product of thickness and yield strength has to be kept constant, so for the aluminium housing, *t* = 1 x (315/200) = 1.575 mm. (This particular thickness will *not* be normally available, but 1.5 mm will probably do.) The second change is that all radii must be significantly increased, as the aluminium has a much lower strain-to-failure. For 1.5-mm thick aluminium, the *MBR* = 1.5/(2 x 0.15) = 5 mm.

Side note: for such products, dent resistance will likely be the design driver, which scales with the thickness cubed, not linearly with thickness. So, even a small increase in thickness can make up for a sizable reduction of yield stress. Still, some increase in sheet thickness will be needed for the premium aluminium version.

4B: 3D sheet metal forming

Figure A4B shows the design of an air intake for sea-going yachts. It is designed to be formed by stretching an ingoing blank measuring 200 by 300 mm so that the required bulged shape is obtained, with the formed blank then being cut in two across the width to obtain a pair of intakes. These can then be mounted onto the yacht hull, facing forward. Target production volume is 1,000 units per year. As a further requirement, the client wants these intakes to be bare metal, without any coating.

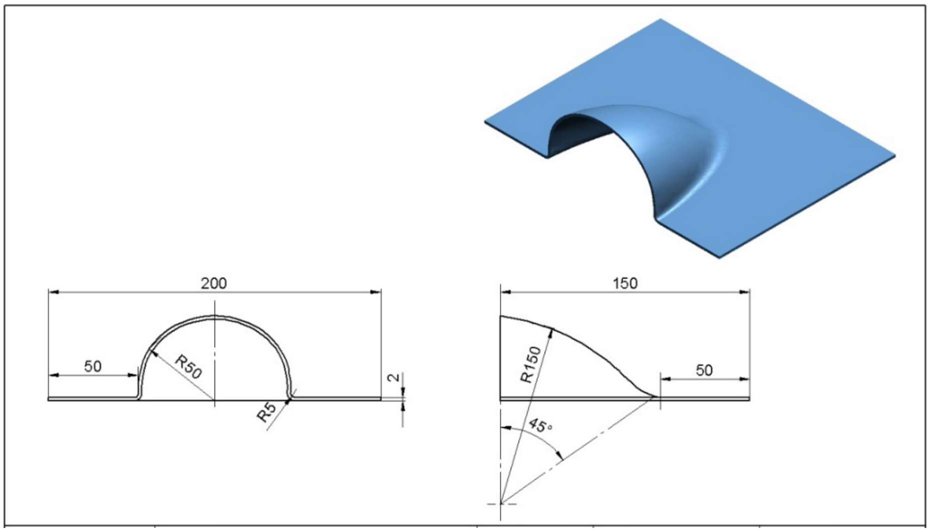


Figure A4B: yacht air intake (sheet metal part)

(a) Figure 4.11 in the textbook shows data for five different metals. Which one(s) of these can you recommend for this application, and why? Explain briefly.

(b) Of the sheet metal forming methods mentioned in the book, which one(s) can you recommend, and why? Again, explain briefly.

(c) Calculate the strains along the length and width of the part during forming. Assume a best case scenario, in which all of the blank's material is homogeneously stretched. In this, you may ignore the extra strain due to bending in the radius (R = 5 mm).

(d) Recalculate the strains, now assuming a worst case scenario, in which the part's flange does not deform.

(e) Referring again to Figure 4.11, can the metal(s) you recommended in part (b) sustain the strains calculated in parts (c) and (d)? Based on this, what is your conclusion regarding the principal formability?

Answers

(a) From the metals shown in Figure 4.11, only the aluminium AA 5051 and stainless steel AISI 316 can be used 'bare' i.e. without coatings in sea-going applications. The carbon steels, even the ones with zinc coating ('galvanized'), will not be suitable at all without coatings.

(b) At 1,000 units/year, the best method will be rubber forming. Panel beating will be too slow, while matched die forming and sequential die forming are too expensive in terms of investment – these processes are also not well-suited to a small, relatively simple product such as this one, also because close tolerances will not be required.

(c) In-going width is 200 mm, out-going width is 257 mm (two flanges of 50 mm each plus the hemispherical shape of 157 mm). So, strain across the width ε_w = ln(257/200) = 0.25. Similarly, in-going length is 300 mm, out-going length is 336 mm (two flanges of 50 mm each plus the arched shape of 236 mm). So, strain across the length ε_l = ln(336/300) = 0.11.

(d) Now, in-going width is 100 mm, outgoing width is 157 mm, giving a strain of ε_w = ln (157/100) = 0.45. Similarly, in-going length is 200 mm, outgoing length is 236 mm, for a strain of ε_l = ln (236/200) = 0.16.

(e) By definition, in a forming limit diagram, $\varepsilon_1 \geq \varepsilon_2$. In this situation, $\varepsilon_1 = \varepsilon_w$ and $\varepsilon_2 = \varepsilon_l$. So, we want to know if the points ε_1 = 0.25, ε_2 = 0.11 (best case) and ε_1 = 0.45, ε_2 = 0.16 (worst case) lie under the forming limit curves of AA 5051 and AISI 316, as shown in Figure 4.11. As it turns out, both points are above the curve for AA 5051 but below the one for AISI 316 (though for the worst case scenario just barely). We conclude that in principle we should be able to make this shape in AISI 316 but not in AA 5051.

Side note: it is a common mistake to switch both strain components, in which case one would perhaps conclude that the shape can be made from both metals in Figure 4.11. However, the definition $\varepsilon_1 \geq \varepsilon_2$ matters deeply: the point ε_1 = 0.11, ε_2 = 0.25 is not valid, nor is ε_1 = 0.16, ε_2 = 0.45.

Second side note: for the AA 5051 (or rather, this particular type: depending on the amount of strain hardening, other versions of this alloy can be more or less formable), we can in fact obtain substantial strains during stretching in the primary direction, i.e. ε_1 = 0.50 or so, but only if the second strain component is comparable in magnitude. Since forming this component requires a relatively large ε_1 and a much smaller ε_2, it is unfortunately not possible – unless we can somehow ensure that ε_2 is increased. Experienced rubber formers have ways to do this, so depending on the manufacturer's skill, this air intake may be formable from AA 5051.

Chapter 5: Extrusion of metals

Figure A5 shows a sketch of the cross-section of the housing of some kind of electronic product. It is intended as a 6000-series aluminium extrusion with a length of 300 mm. The base shape is a rectangle, rounded at the top right corner. The designer has anticipated that two PCB's will be placed in the C-shaped slots, has made a provision for thermal management (the 30-mm long fins on the left), and has provided two additional assembly functions on top (a box-shaped intrusion and a narrow slot).

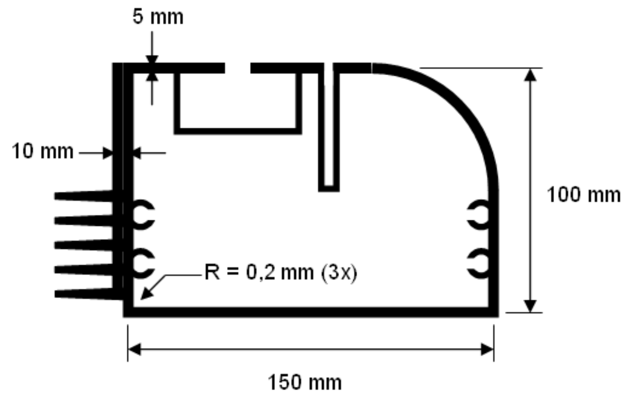


Figure A5: sketch for electronics housing (extruded aluminium profile)

(a) What is the billet size that will most likely be used to extrude this profile? In your answer, estimate the extrusion ratio *R,* given that the profile's cross section is 3400 mm^2. Explain briefly.

(b) Do you expect this profile will be easy to extrude using a one-chamber closed die? If not, give up to four potential problems, and explain briefly. How would you change the profile?

(c) To complete the housing, two end plates will be screwed onto the profile. What additional design change(s) does this suggest to you?

Answers

(a) Total width is 180 mm, total height is 100 mm, so the smallest circumscribed circle will be 206 mm (ignoring the rounded-off corner). Minimum billet diameter is 125% of this dimension, or 257 mm. We could probably just make this profile from a 10" billet (254 mm diameter). Then, the extrusion ratio R = 14.9. However, since this is quite low for aluminium (R = 20 or more is preferred), we are better off using the next larger size: a 12" billet would give R = 21.5. So, a 12" billet is the best option.

(b) No, it will not be easy to extrude at all: (i) the box-shaped intrusion in the top is too large for its small opening, and (ii) the slot in the top is far too narrow for its depth. Also, (iii) the different wall thickness on the left (10 mm instead of 5 mm) will be hard to balance. As a fourth problem, we can identify (iv) the much-too-small internal radii. We can make this profile much easier to extrude if the opening on the top is made larger, if the slot is made either less deep or less narrow, if wall thickness is kept constant at 5 mm and if all internal radii are at least 0.5 mm.

(c) Add screw holes in the corners (these do not have to be fully closed and would therefore not need any additional 'chambers').

Side note: it is of course hard to comment on a first drawing as there is limited information about the application (for instance: is a 5 mm wall thickness really needed, or can the dimensions of the box-shaped opening be changed?), yet this is exactly what extrusion companies are often asked to do! For a more radical design change, it can be considered to make this housing not out of a single, closed profile, but out of two open profiles that are tightly joined with snap-fits.

Chapter 6: Forging of metals

(a) Give three guidelines for the design of steel forgings made using closed-die drop forging. Explain each guideline briefly by referring to the theory and practicalities covered in Chapter 6.

(b) Why does it usually make good sense to combine forging with heat treatment, for steel forgings? Again, explain briefly.

(c) Steel can be cast, using investment casting, and can also be integrally machined, yet especially for larger production volumes, forging will usually be the better option. Explain why, using the relevant aspects of the manufacturing triangle.

Answers

(a) Three straightforward guidelines would be:
(i) ensure that the overall shape has no undercuts with respect to a parting plane that lies perpendicular to the direction of die travel;
(ii) to promote good metal flow and avoid excessive die wear, ensure that all radii are generous, that ribs, if any, are at least as wide as they are high, and use a draft angle of at least 5°;
(iii) ensure that closely-toleranced dimensions are placed along the length or width of the part (i.e. lie in the parting plane) instead of along the part thickness, because die deformations will cause dimensional inaccuracies along the direction of die travel.

Other possibilities include (not exhaustive):
(iv) if possible, avoid warm or hot forging, as these process variants introduce thermal stresses and hence, dimensional inaccuracies, and also negate the strength increase due to work hardening during forging;
(v) given that forging will be followed by (secondary) machining, strike the right trade-off between formability and machinability, balancing material costs against process costs and investments.

(b) Forgings are usually applied when static strength and/or fatigue strength is critical (if stiffness were critical, then sand casting of nodular cast iron would probably be better suited). Heat treatment, especially the common quench and temper process, can substantially increase strength at relatively low cost, saving material and leading to an overall cost reduction. Part weight savings are an additional benefit.

(c) Investment casting offers more form freedom (e.g. it allows undercuts) than closed-die drop forging and has lower investments, but it is slower and, because of the inevitability of casting defects, offers less control over the final material properties; it is also more limited in terms of the part size. Integral machining offers even more form freedom and can be done using universal equipment (zero investment, also shorter time-to-market), but it is even slower than investment casting; furthermore, steels that are easy to machine tend to be lower in toughness and not well-suited to applications requiring toughness and ductility.

Side note: at this point, students may wonder if sintering could not be a third alternative for closed-die drop forging. At first glance, typical production volumes, investment levels, and times-to-market are indeed comparable. However, sintered steel parts are considerably smaller, and final material properties are *very* different.

Chapter 7: Machining

On the first page of Chapter 7 in the textbook, you see the *BramBrake*, a high performance racing bike brake. This brake consists of several parts, the two main ones of which are the two actual brake calipers. Both are made by integral machining from a solid slab of aluminium (7000-series alloy) as separate parts and subsequently assembled.

(a) Assume that we have at our disposal a triaxial CNC milling machine, equipped with a standard, small diameter end mill. Do you think we can make either one of the calipers in a single fixing, or do we need to re-clamp the workpiece during processing? Explain briefly.

(b) The finished calipers will require precipitation-hardening to obtain their final mechanical properties. What do you recommend: machining in the softer 'O' temper and then heat treating, or first heat treating and machining in the final 'T6' temper? Explain briefly.

(c) *BramBrakes* are currently a specialty item, selling in limited numbers. But what if sales pick up to 10,000 per year or so: would first extruding the basic shape, then machining to the final shape be a better option? Explain briefly. Assume quality (material properties, tolerances) has to remain at the same level.

(d) In the finished product, both brake calipers are anodized. Give three advantages of this finishing process that are relevant for this application.

Answers

(a) Both calipers will need re-clamping. From direct visual inspection it is clear that they require machining from the top to create the many small weight-saving chambers, and from the side to create the extra holes where the brake pads are mounted. (Closer inspection reveals they are in fact machined in a more complex way, as the caliper thickness is not constant. This also requires re-clamping, as the milling machine cannot reach both sides in a single clamping. Furthermore, all edges are rounded, which also requires multi-side access, and ideally, a 5-DOF milling machine.)

(b) First precipitation hardening, then machining: in the 'O' temper the material is quite soft and too ductile, leading to very long chips that are difficult to remove. A second practical benefit is that aluminium in the harder T6 temper is less susceptible to scratching and other damage that may arise from clamping.

(c) No. 7000 series Al alloys have limited formability in extrusion, so only the basic shape can be made this way, and certainly not the final shape (complete with all chambers). So, the benefit of extrusion is small. Also, integral machining offers considerable room for optimization (e.g. 'nesting' of calipers into one another to minimize material losses, using custom designed fixtures), and can be effective even at high volumes.

(d) Anodizing greatly increases corrosion resistance (relevant for 7000 series alloys used outdoors), increases surface hardness and resistance to scratching, and allows colouring in a wide range of colours.

Chapter 8: Injection molding of plastics

Injection molding problem 1

Figure A8A shows a familiar injection-molded item: the remote control. Its housing consists of two black ABS shells that are joined together with snap fits; a third (much smaller) ABS part is the hatch for the batteries (on the rear, not shown).

Figure A8A: remote control (injection molded ABS housing)

(a) Assuming Newtonian flow, estimate the minimum injection pressure needed to fill the mold for the top shell. You may simplify the shape as a flat plate, 160 mm long, 50 mm wide and 2 mm thick, and assume it is injected over the full width from one end to the other. Injection time t_{in} = 0.1 sec, melt viscosity μ = 40 Pa.s.

(b) Give three reasons why in practice, this injection pressure will be substantially higher. Explain briefly.

(c) Estimate the cooling time for the top shell. Use the following data: processing temperature T_p = 230°C, ejection temperature T_e = 80°C, mold temperature T_d = 60°C; and thermal diffusivity a = 75x10^{-9} m^2/s. Using the *very* rough rule-of-thumb that cycle time in injection moulding is approximately 10 s. per mm part thickness, comment on the realism of your estimation.

(d) What would happen to the injection pressure and the cooling time if the thickness is reduced to 1.8 mm?

Answers

(a) Using Equation 8.1 in the text for the pressure difference in a flat channel, i.e. Poiseuille flow, we obtain: ΔP = 30.7 MPa = 307 bar.

(b) Reason one is that in part (a) we only estimated the pressure difference needed to overcome friction, but we also require pressure on end furthest from the injection point, to gain good reproduction of mold details. Reason two is that extra pressure helps counteract shrinkage and obtain a more closely-toleranced part. Reason three is the fact that the shape is considerably more complex than a flat plate, and the shape details will increase friction.

(c) Using Equation 8.3 for the cooling time, we obtain: t_{cool} = 10.3 s. If cooling takes 50% of the cycle time, we get a cycle time for this part of 20.6 s. This is very near to what the rule-of-thumb predicts (= 20 s.), so the cooling time estimate can be considered realistic.

(d) Reducing thickness to 1.8 mm would increase the injection pressure (the pressure difference needed to overcome friction increases to 373.9 bar), but would decrease the cooling time (to 8.3 s, assuming the temperatures settings are the same).

Injection molding problem 2

Figure A8B shows a handy product for use during picnics: a cup-holder. It is hollow, with its basic shape being that of a cup with a spike at the bottom; the flower-shaped flange adds a final flourish. The spike allows it to be pushed into the grass to provide a simple yet reliable support for a lightweight drinking cup. For the first production runs, the designer proposes to make the product out of PS, using a simple two-plate mould with a single product cavity. The cup-holder is 80 mm high, has a 120 mm diameter and a 1.5 mm wall thickness.

Figure A8B: picnic cup-holder (injection molded PS; design: Floor-Jan van Schaik)

(a) For gate placement (injection), there are basically two options for a rotationally-symmetrical product such as this one, if we inject using a single gate. What are these options? Explain which option you would choose for this product.

(b) Make a sketch of the mold in cross-section. Indicate clearly where it is injected.

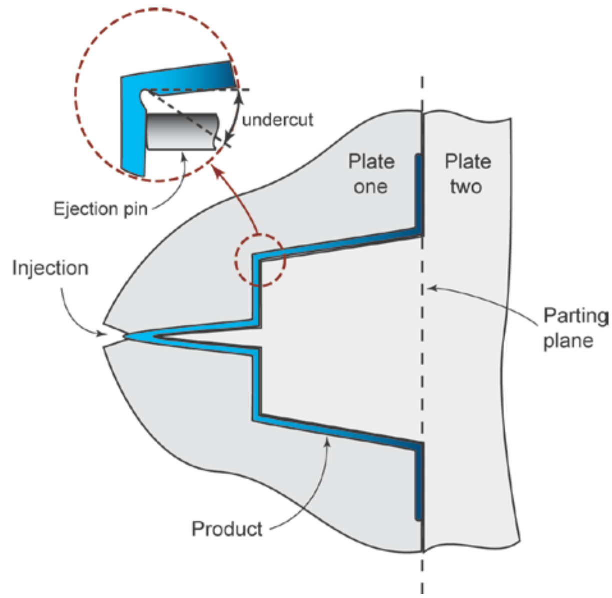
(c) What will be the minimum clamping force for the cup-holder? Assume an injection pressure of 800 bars.

(d) PS is amorphous and does not shrink that much, especially at the relatively high injection pressure given under (c). How can we ensure that the product remains attached to the ejection side during mold opening? Indicate this clearly in your sketch in part (b).

Answers

(a) Option one is to place the (single) gate at the edge. This would be well-suited for molds with multiple product cavities, as we can then place the injection system on the parting plane between the (two) mold plates and between the various cavities; a disadvantage is then that the product is not filled symmetrically and is therefore likely to warp. Option two is in the centre, with the benefit of symmetrical filling flow. In a multi-cavity mold this would require a more expensive three-plate mold, but as we have only a single-cavity mold here this option is preferred for this product.

(b) Sketch of mold for picnic cup holder.



(c) Assuming an effective product diameter of 110 mm, the projected area is 9503 mm^2 and the minimum clamping force is 760 kN, or 76 tons (!).

(d) The solution is to place small undercuts at strategic points of the product that pull the product towards the ejection side during mold opening. These are best placed at or near the ejection pins (see inset in figure above).

Chapter 9: Thermoforming

Figure A9A shows a conceptual design for a children's sled to be made using thermoforming of ABS. Figure A9B presents this same product, in front and side view. The basic shape is a somewhat rectangular bucket with a sloping front that carries the logo and with two gliders attached to the lower edge, plus four ribs for added stiffness.

Figure A9A: thermoformed children's sled (thermoformed ABS)

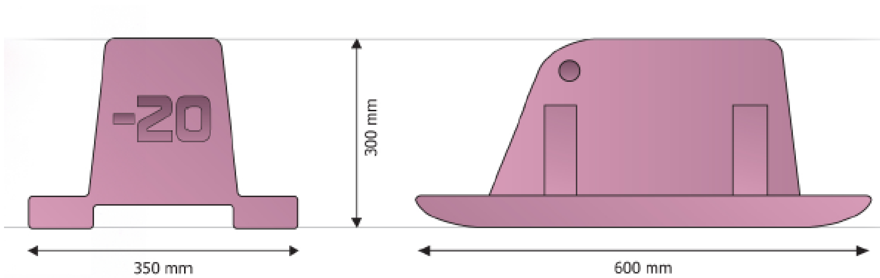


Figure A9B: children's sled, front and side views.

Table A9: data for manufacturing cost calculation (all costs in Euros)

Mold costs	11,000	Cycle time, edge trimming	1 min
weight	1.5 kg/sled	Machine costs, edge trimming	60 /hour
Material cost (ABS)	3.50 /kg	Labor costs	8 /hour
Cycle time, forming	2 min	Machines/operator	1
Machine cost, forming	150 /hour	Transport (20 ton container)	1,000

(a) To be sufficiently strong, this sled should have a wall thickness of 3 mm. Estimate how thick the ingoing sheet material has to be.

(b) The –20 logo has to be prominently visible and well-defined. What do you recommend: positive or negative forming? Explain briefly.

(c) Which thermoforming method can you recommend, given that the variation in wall thickness for this product has to be minimal? Again, explain briefly.

(d) Using the data in Table A9, estimate the manufacturing costs per sled, including transport, for a production volume of 5,000 units. Which percentage of these costs is due to the material?

Answers

(a) The product can be estimated to have a total surface area of some 5,500 cm^2. The ingoing sheet will measure 300 by 650 mm = 2,100 cm^2 (this is excluding the flange that will not be formed). At an average product wall thickness of 2.5 mm, the ingoing material should therefore be 2.5 x (5,500/2,100) = 6.5 mm thick.

(b) Negative forming (seen from the perspective of the bucket-like main shape, not the gliders). This will ensure that the outside makes good contact with the mold and accurately reproduces the mold details.

(c) The shape is fairly deep and especially the top corners may get quite thin during standard thermoforming. For this reason, it can be recommended to use pre-stretch thermoforming: the costs associated with the extra process time will be easily recouped through improved product performance.

(d) (i) depreciation of mold costs (per part) is 11,000/5,000 = 2.20;
(ii) material cost is 3.50 x 1.50 = 5.25;
(iii) machine costs are 150 x (2.00/60) + 60 x (1.00/60) = 6.00
(iv) labor costs are 8.00 x (3/60) = 0.40
(v) transport cost is 1,000/5,000 = 0.50 (assuming the full batch fits in one container)

Total costs, summing (i) – (v), are 14.35. Material costs are thus 37% of the total.

Chapter 10: Resin Transfer Molding

Figure A10 shows an Ovation guitar. Its main components are the neck with tuning mechanisms and fretboard, a wooden soundboard and the patented 'Lyrachord' back shell, which revolutionized guitar building in the 1960s. The shell itself is made of composites (polyester and randomly-oriented glass fibers with an estimated 40% fiber volume fraction) and is ideal for resin transfer molding: it has a flowing, organic shape without sharp radii or undercuts, and constant wall thickness. Body length is 500 mm, body thickness is 120 mm.

Figure A10: Ovation guitar (rear view)

(a) Assuming we would make this shell using light RTM (so, two semi-rigid mold halves), how would you inject this part? Where would it need finishing, and what would the injection length be?

(b) Estimate the injection time, given that we use volume-controlled injection with ΔP = 0.8 bar, a resin of viscosity μ = 0.28 Pa.s, and a permeability $k = 0.2\text{x}10^{-9}$ m^2.

(c) Which other process steps will be needed to make one shell?

(d) How many shells can we expect to make in one year (regular one-shift production, low degree of automation)? Be sure to list the assumptions you need to make.

(e) What would be realistic ways to speed up manufacture? Explain briefly.

Answers

(a) Given the fiber volume fraction of 40% and simple shape, we can use a single runner around the entire contour of the shell and a single, centralized suction cup, placed on the inside. The injection length would be approximately 320 mm. Finishing would only be required at the contour (trimming off the runner), as the suction point and any surface defect it may give are hidden from view.

(b) Using d'Arcy's equation, we get $T_{inj} = ½ L_{inj}^2 \mu/(\Delta P\ k) = 0.5 \times 0.32^2 \times 0.28/(0.8\times10^5 \times 0.2\times10^{-9}) = 896$ s, or just under 15 minutes.

(c) The full process consists of: (i) mold preparation (placing fiber mats, mold closing); (ii) injection; (iii) resin curing; and (iv) de-molding (mold opening, ejecting shell, mold cleaning). Preparing the fiber mats (i.e. cutting) and contour trimming are additional steps but can those be done in parallel. With polyesters we can assume step (ii) takes approximately 10-15 minutes; steps (i) and (iii) probably take up to 5 minutes each.

(d) From (c) we know that the total cycle time per shell is 35-40 minutes, assuming a one-cavity shell. With some 1,500 hours effective production time per year we could make 2250-2500 shells/year.

(e) Since resin injection (15 min.), resin curing (10-15 min.) and preparing plus de-molding (5+5 min.) take comparable amounts of time, it would make sense to use three sets of molds: one can be injected while the other cures, with one worker simultaneously preparing the third mold and de-molding a shell. The additional costs of having two extra molds will likely be small, as we deploy light RTM here, while the productivity increase is threefold. Note that simply increasing the injection pressure would not be very effective as it would only reduce part of the cycle time and still increase mold costs.

Side note: actual Ovation guitar back shells are not made using RTM but compression molding, in a version that is most likely highly mechanized to maximize productivity. Still, it could be an RTM application, from production volumes between 1,000-10,000 per year. Furthermore, Ovation guitars also use carbon fibers, not just glass fibers.