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Chapter 4: Sheet metal forming – HINTS

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Exercise 4.1 Look at home and find at least two examples of sheet metal parts or products. Distinguish between single- and double-curved parts and find at least one of each.

Hint 4.1: a quick scan through the chapter should already give some ideas for applications. In addition, a simple image search on the Internet (e.g. with search term "metal stamping" or even just "sheet metal forming") will provide suggestions – but be sure to lay your hands on actual parts.

Exercise 4.2 Which of these alloys has the 'best' formability, and which has the 'worst'? Explain briefly. Hint: consider which property is inextricably tied to tensile plastic deformation as a principle and which property can, at best, only be a limitation for the method and/or means of manufacturing.

Hint 4.2: in addition to the hint already given in the Exercise, consider that in theory, you can always find (or build) a bigger machine. So, yield stress can at best only be a practical limit to formability (in combination with sheet metal size and thickness, it can be a problem for a given piece of machinery), not a principal constraint. Also, be aware that the issue of formability comes up in several subsequent exercises: what starts off as relatively straightforward will become quite complex in the end.

Exercise 4.3 Choose a couple of alloys from Table 4.1, then use Hooke's Law ($\sigma = E\,\varepsilon$) to calculate the maximum elastic strain in these alloys before plastic deformation begins. How does this value compare to the maximum plastic strain-to-failure?

Hint 4.3: whatever your answers, they should be *much* less than the plastic strain-to-failure in each case.

Exercise 4.4 Consider Figure 4.2, and suppose we deform the metal to a stress halfway between its yield stress and its tensile strength, and then unload it. On a sketch of the stress-strain curve, show how you would find the permanent strain up to this point. The sample is then re-loaded to find its new, strain-hardened yield stress. Explain why the value will be higher than the nominal value at the point when unloading was started in the previous test. (Hint: think carefully about how the sample dimensions change during a tensile test, and how yield stress is defined.)

Hint 4.4: in addition to the hint already given, consider that a tensile test bar that has been stretched beyond the yield point is not only longer, but also (to conserve volume) thinner and narrower.

Exercise 4.5 At first sight, Figure 4.2 shows something peculiar: the material apparently fails at a stress level below its tensile strength. Explain this mystery. Hint: consider how the stress level is defined and measured during tensile testing.

Hint 4.5: the key word here is 'necking', i.e. the localised fall in width and thickness of the test bar once the maximum nominal stress is reached.

Exercise 4.6 Derive a generic formula for the MBR as a function of geometry and formability, assuming that the strain-to-failure in bending is the same as it is in a tensile test. (Hint: how much longer does the outermost fibre of the bending zone get, relative to the length of the neutral axis?) Choose a couple of alloys from Table 4.1 and calculate the MBR for a bending angle α = 60° (= ⅓ π) and a sheet thickness t = 3 mm.

Hint 4.6: in addition to the hint already given, you can expect the bending angle α to drop out of the equation (it will crop up again in Exercise 4.9).

Exercise 4.7 In his steel bookshelf 'Storyline' (see Figure 4.4), Dutch designer Frederik Roijé has made elegant use of the bending process. What would this product look like if he had chosen aluminium instead? Bonus question: would it then be lighter, and if so, how much?

Hint 4.7: this question is more complex than it may at first sight appear to be. First, consider that since Roijé wanted to make a striking design, he must have minimized the thickness, making the Storyline just thick enough to not flex visibly under a typical load of books. Second, consider that he likely has minimized all bending radii in the steel version also to make an even 'sharper' design. This should give you some clues as to how the aluminium version would look (in terms of thickness and bending radii).

Exercise 4.8 Look closely at the single-curved product(s) you found in Exercise 4.1. What is the sheet thickness, and what is (approximately) the bending radius? What does this tell you about the material that was used?

Hint 4.8: many possible answers. As for material, note that low carbon or low alloy steel is virtually always coated, e.g. with zinc, tin or a polymer; also note that (austenitic) stainless steel is non-magnetic.

Exercise 4.9 Make a clear sketch of the transition zones. Do you think it is more influential in reducing the MBR for small bending angles than for large ones, or vice versa? Explain.

Hint 4.9: as for the angles, consider the volume of material in the transition zones relative to the volume in the actual bending zone.

Exercise 4.10 Return to Exercise 4.2. How would you now refine your original answer?

Hint 4.10: the keyword is, again, 'necking', or more specifically, if the metal in question shows diffuse or local necking (diffuse necking would increase formability as compared to local necking).

Exercise 4.11 Select any alloy from Table 4.1 and estimate the maximum elastic energy that this metal can store, as well as the maximum plastic energy that can be absorbed, per unit volume. To facilitate the calculation, assume a stress level in the plastic region that is equal to the mean of the yield stress and the tensile strength.

Hint 4.11: if you observe the use of units well, this calculation should pose no difficulties. As the table presents ranges for the data, we advise you always use the mean values for your calculation. To give a single example for the outcome: for low alloy steel, the elastic deformation energy per unit volume is just 0.2% of the plastic deformation energy per unit volume.

Exercise 4.12   Assume that during bending of a certain steel computer casing we get 2° springback. What will the springback be if we double the bending radius? And what if we exchange the steel for aluminium (keeping the thickness the same)?

Hint 4.12: the ratio of elastic to total deformation energy determines the result. Make sure that you only change one variable (thickness, bending radius or material i.e. yield stress) in your comparisons, keeping the other two constant.

Exercise 4.13   Do you think that there was a lot of springback during the manufacture of your single curved product(s) from Exercise 4.1, or not? How can you tell?

Hint 4.13: the key lies in the material (some show more springback than others) as well as in the bending radius.

Exercise 4.14   For car body panels, dimensional tolerances are very tight, and springback must be tightly controlled. Use this to explain why the car industry allows only small variations in the yield stress of any sheet metal it buys. And could the same tooling be used if the manufacturer changed from steel to aluminium of the same strength and thickness, in exactly the same shape?

Hint 4.14: for the first part of your answer, consider exactly (i.e. in the formulas) how the yield stress affects the springback.

Exercise 4.15   A certain high strength steel (HSS) can absorb 200 MJ/m^3 of deformation energy. How many kg of such HSS must be fully deformed to bring a 1500 kg car moving at 100 km/h to a standstill? (Hint: assume the density of the steel is 7,900 kg/m^3).

Hint 4.15: the car's kinetic energy is of course equal to $\frac{1}{2} m v^2$. Your answer will be a surprisingly small amount, given that the body-in-white of a typical mid-size car, including closures and bumpers, weighs around 300 kg.

Exercise 4.16   Place the three manufacturing methods discussed previously in order of form freedom (meaning part size, sheet thickness, material choice and shape complexity). Next, place them in order of flexibility: how easy is it to make small changes to parts? What do you conclude?

Hint 4.16: consider that in bending, we need not restrict ourselves to a single bending operation. Instead, we can also bend a piece of sheet metal repeatedly, creating an increasingly-complex shape.

Exercise 4.17   Think of a sensible application that combines two of these three methods (e.g. roll forming and roll bending).

Hint 4.17: just be creative here – but also realistic: for instance, recall that roll forming is a high-volume method, so be sure to take the production volume into proper account.

Exercise 4.18   Is it possible – without raising the temperature! – to bend glass, or roll form a strip of plastic, such as polyethylene (PE)? And what about rolling plywood? Explain your answer.

Hint 4.18: this exercise refers to *plastic* bending, not elastic bending. As for wood, a quick Internet search for "Michael Thonet" is recommended for inspiration.

Exercise 4.19   Propose two additional design guidelines for single-curved metal parts. Ensure that they are specific and/or that they refer explicitly to the theory covered in Sections 4.2-4.4. Look back at your sample product(s) from Exercise 4.1: are your guidelines reflected in these parts?

Hint 4.19: work around concepts such as the minimum bending radius *MBR* and springback, and you will make useful design guidelines.

Exercise 4.20   If we have a nominal strain of 50%, then what is the accompanying true strain? And how much is a true strain of –0.16, expressed as a nominal strain?

Hint 4.20: simply use the formulas provided.

Exercise 4.21   Suppose we stretch a piece of sheet metal first 30%, then another 20% and finally another 10%, all in the same direction. What is the total nominal strain after these three steps?

Hint 4.21: (as above).

Exercise 4.22   Again we deform in three steps, now with true strains of 0.30, 0.20 and 0.10. What is the total true strain after three steps? And what is the difference – or more to the point, the advantage – compared to the calculation you made in Exercise 4.21?

Hint 4.22: what is simpler: addition or multiplication?

Exercise 4.23   Show that during plastic deformation, when the volume remains constant ($\Delta V = 0$), the sum of the true strains must be zero: $\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0$. Hint: consider a rectangular block of initial dimensions (L_0,B_0,H_0) and final dimensions (L_1,B_1,H_1), noting that $L_0\, B_0\, H_0 = L_1\, B_1\, H_1$. Start by writing down the true strains in terms of the dimensions.

Hint 4.23: good luck – it's not as difficult as it perhaps looks!

Exercise 4.24   Explain how the behaviour of dislocations in metals means that plastic deformation takes place at constant volume.

Hint 4.24: this will become apparent if you make a sketch of how a dislocation moves through the material, at the level of atoms.

Exercise 4.25   Refer to the FLC in Figure 4.10 and estimate the through-thickness strain (ε_3) along the curve. Where is this strain component a maximum?

Hint 4.25: *$\Delta V = 0$!*

Exercise 4.26   Make a sketch of a small, rectangular plate element. Next, sketch what this element will look like after undergoing the combined strains of tension-tension (zone 4), tension-near-zero strain (zone 3), tension-compression (zone 2) and uniaxial stress (zone 1).

Hint 4.26: this should pose no special problems; simply make accurate sketches.

Exercise 4.27   Revisit Exercise 4.2 once more. What is your answer now?

Hint 4.27: basically, the strain-to-failure gives a very incomplete picture for the formability with respect to double-curved shaped. The concept needed is the topic of the current section.

Exercise 4.28   In an FLD, sketch the trajectories that the four areas A-D travel through, each one beginning at the origin. Which area will reach the FLC (wherever that curve may be) the soonest, and what does that mean for the manufacture of this beaker?

Hint 4.28: in your diagram, A and D should be at right angles. B and C should first move in the same direction as D, but should deviate from that direction at one point (C later than B).

Exercise 4.29   Determine how much a small segment of area D must be compressed if it is to end up at the edge of the beaker, starting at the edge of the blank. Hint: its arc length before and after deformation is proportional to its 'old' and 'new' diameter, and you may assume that the thickness remains constant. If the tangential radial compression is ε_2 then how large is the radial strain ε_1?

Hint 4.29: simply use the expression for true strain around the circumference (arc length) and use $\Delta V = 0$.

Exercise 4.30   Assuming now that the bottom does not deform at all, determine all three strain components ε_1, ε_2 and ε_3 in the wall of the beaker. Hint: $\Delta V = 0$.

Hint 4.30: an important hint is that the wall of the beaker must get thinner during drawing, i.e. for this part of the product, ε_3 is negative. This is different for the flange, which was assumed to have no change in thickness ($\varepsilon_3 = 0$).

Exercise 4.31   Choose realistic values for the dimensions of the beaker and blank, then select one alloy from Figure 4.11. Can this particular beaker be produced from this metal? Explain.

Hint 4.31: simply assume some reasonable dimensions for the blank and the beaker, e.g. D_{blank} = 100 mm, D_{beaker} = 50 mm and H_{beaker} = 80 mm. Calculate the strain components that arise (in the flange as well as in the wall of the beaker) and see if the pertinent combinations of components ε_1 and ε_2 fall under (so, not to the side of) the FLD to see if the beaker can be made.

Exercise 4.32   Calculate the extra strains due to this out-of-plane bending, if the bending radius is given as five times the blank thickness. Give your answer as a true strain. Exactly where (over the thickness of the material) do these extra strains occur? Are they significant?

Hint 4.32: recall that in bending, the neutral axis sees no change in length. So, initial length $L_{old} = R$, and new length $L_{new} = (R \pm ½ t)$. Using the expression for true strain you can quickly determine the answer, given that $R = 5t$.

Exercise 4.33   Take a closer look at your double-curved product sample(s) from Exercise 4.1. Which areas will have experienced deep drawing, which ones stretching? Which areas have seen much deformation, and which only little? Any new thoughts on the material that has been used?

Hint 4.33: (all kinds of possibilities).

Exercise 4.34   What kind of springback do you expect in producing a shallower product, such as the Alessi bowl depicted in Figure 4.13a, and why?

Hint 4.34: the more shallow it gets, the more pronounced the springback will be. The why is for you to consider!

Exercise 4.35   In terms of the deformations that are required to make it, the rectangular tray shown in Figure 4.13c is not a difficult product. However, what about springback? More specifically, do you expect the sides to remain straight, or curve inwards or outwards due to springback?

Hint 4.35: whatever you think that answer is, the sides will not stay straight – unless their edges have been stiffened by folding the material double, or rolling it over in a tight curve (the former is how such products are in fact usually finished).

Exercise 4.36   What do you recommend for making the Alessi bowl: first forming, then stamping out the figurines, or vice versa? Explain.

Hint 4.36: surprisingly enough, both options are possible in principle, but in practice they have quite different results. Here you should encounter the manufacturing triangle again, which predicts that the same shape can always be made with better quality provided you invest in terms of cost.

Exercise 4.37   Revisit Exercise 4.2 one last time. What is your answer now?

Hint 4.37: formability turns out to be even more complex than you might have thought! For double-curved products you not only need the FLD (and not just the strain-to-failure), but in addition it is necessary for the material to have a large difference between yield stress and tensile strength, i.e. it must have a large capacity for strain hardening (especially for deep drawing, where considerable strain hardening of the beaker wall is needed to draw in the material from the flange).

Exercise 4.38   List the six methods discussed in ascending order of design freedom, using a three-point scale for part size (small-medium-large), range of metals (soft-medium-hard) and shape complexity (lower-medium-high).

Hint 4.38: careful reading of the text and keeping score of the various parameters should reveal that matched die forming offers the most design freedom. Hydroforming comes out as offering the least form freedom, but considering that it is more suited to tubes and pipes it can best be seen as a different process altogether, not competing directly with any of the other methods.

Exercise 4.39   Now list the six by investment level and finally make a sketch-plot of design freedom versus investment. What is your conclusion?

Hint 4.39: again, careful reading is the key.

Exercise 4.40   Make two clear, specific guidelines for the design of double-curved parts, aiming to achieve a good trade-off between form freedom, cost (e.g. investments, but also cycle time) and quality (e.g. tolerances, surface finish). Explain by referring to Sections 4.6-4.9.

Hint 4.40: many possibilities! Here, a quick Internet search can help (with search terms as “design rules for deep drawing” or “design guidelines for rubber forming”), but be sure to interpret your search results carefully.

Exercise 4.41   Take another look at your sample products (Exercise 4.1). How can you see your design guidelines reflected in them?

Answer 4.41: (many possibilities).