Chapter 3: Casting of metals – ANSWERS

Exercise 3.1   Look around your house and find one or more examples of cast parts or products. How important do you think form freedom, strength and cost were in choosing casting for these products?

Answer 3.1: (all kinds of possibilities!)

Exercise 3.2   Look up the compositions of several zinc and magnesium casting alloys (at least two of each). Also, find a typical composition of brass. What are the key alloying elements? How do the melting temperatures of all of these alloys compare to those of the pure metals?

Answer 3.2:

- Zinc: the most commonly used zinc alloys all have aluminium as the main alloying element and go by the trade name of ‘Zamac’. For instance, ‘Zamac5’ has 5% aluminium and a melting range of 379-388°C, against 420°C for commercially pure zinc.
- Magnesium: two common alloys are AZ91 with 9% aluminium and 1% zinc (melting range: 420-600°C) and AM60 with 6% aluminium and 0.3% manganese (melting range: 445-632°C). Pure magnesium melts at 650°C (essentially the same value as aluminium).
- Brass: all brasses have copper as the primary element and 10-40% zinc as the main alloying element, sometimes with minor additions of other elements, such as lead or tin. Alloy EN CW509L (a.k.a. C85500 or CuZn40) contains 40% zinc and melts at 882-902°C, against 1,080°C for pure copper.

Side note for aluminium: two common aluminium casting alloys are EN-AC-42000 (also known as A356 or AlSi7Mg) and EN-AC-46000 (a.k.a. A226 or AlSi9Cu3(Fe)). The former contains silicon (7%) and magnesium (~0.4%) as its main alloying elements and has a 582-648°C melting range, the latter has silicon (9%), copper (3%) and some iron (up to 1.3%) and has a similar melting range. (Thanks to its high tolerance for other elements (e.g. iron) AC-46000 is commonly made from post-consumer recycled metal, while AC-42000 is usually made from virgin metal, also because it is often heat treated.) By comparison: commercially pure aluminium melts at around 650°C.

Exercise 3.3   Do you think that ‘18/8’ stainless steel (AISI 304) can be cast as well as cast iron? In fact, do you think it can be shape cast at all, for practical purposes?

Answer 3.3: with a melting range around 1,450°C, AISI 304 is highly unsuited to shape casting, also because of it poor fluidity and high shrinkage.

Side note: stainless cast irons, of which the so-called ‘Ni-Resist’ types are the most commonly used ones, are a much better choice. These have iron as the primary element, with nickel (typically around 20%), chromium (2%) and carbon (3%) the main alloying elements, usually plus some silicon and manganese. The high carbon content lowers processing temperature, viscosity and shrinkage, comparable to cast iron. Note on applications: as corrosion resistance generally also implies heat resistance (!!), we can expect these types to be used for e.g. engine exhaust manifolds and other ‘hot’ components.
Exercise 3.4  Are high viscosities beneficial (i.e. do they postpone the transition to turbulence to longer flow lengths and/or higher filling speeds) or detrimental for mould filling?

Answer 3.4: as viscosity is in the numerator of the formula for the Reynolds number, high viscosities reduce this number, effectively postponing the onset of turbulence to longer flow lengths and/or higher filling speeds. This is positive, but high viscosity also means that higher filling pressures are needed to overcome friction and to accurately reproduce mould detail. So, in this respect it is detrimental.

Exercise 3.5  Beneath its white plastic shell, the Apple G4 iMac had a hemispherical support frame (Figure 3.3), weighing 2 kg and cast in Zamac, a common zinc alloy. With part thicknesses as low as 3 mm, the filling time had to be less than 0.2 s to prevent cold running. Do you think this involved laminar or turbulent filling? Explain!

Answer 3.5: assuming – for lack of other data – the same flow speed limit of 0.5 m/s, we arrive at a ‘safe’ flow length of 0.1 m. This is certainly less than the distance that the flow had to travel to reach everywhere in the G4 iMac’s support frame if a single gate was used (which most likely was the case), so filling must have been turbulent. However, since the application demands neither high ductility nor high fatigue strength, the entrapment of oxides is not a problem.

Exercise 3.6  Look closely at the products you selected for Exercise 3.1. Can you see where the gate (or gates) was placed to fill the moulds? Can you also spot any air vents? And which metals and alloys have been used in these castings, and how can you tell?

Answer 3.6: (too varied to tell – see ‘hints’ section).

Exercise 3.7  How can we deal with the contraction between \( T_{\text{solidus}} \) and \( RT \), in the design or casting of products? How can we deal with shrinkage?

Answer 3.7: if the contraction between \( T_{\text{solidus}} \) and \( RT \) is (say) 1%, we can compensate for it by making the mould (and hence, the product at \( T_{\text{solidus}} \)) 1% bigger. Shrinkage we can deal with by adding extra material during solidification: this is known as ‘feeding’.

Exercise 3.8  Why do different alloys have different shrinkage? Hint: consider the possible differences in crystal structures, and also consider what happens to certain alloying elements before and after solidification.

Answer 3.8: reason one is that the various crystal structures that metals possess have different packing densities. Face-centred cubic (fcc) and hexagonal close-packed (hcp) achieve a packing density of 74%, whereas body-centred cubic (bcc) achieves only 68%. So, we can expect fcc metals, such as aluminium, and hcp metals, such as zinc, to shrink more than bcc metals, such as (ferritic) iron. Reason two has to do with the different solubility of elements in liquid and solid phases. Cast iron presents an interesting and important example: in the liquid phase, a lot of carbon can be dissolved in the iron (the relatively small carbon atoms fit in the empty space between the unordered and much larger iron atoms). In the solid phase, with the iron atoms neatly packed, there is much less (not zero!) available space for the carbon to go, and consequently, it separates into ‘islands’ in the iron matrix. These carbon regions (usually shaped as flakes, in the case of lamellar cast iron, or spheres, in the case of nodular cast iron) have a low density, and as a result, the shrinkage is counteracted. Together with crystal structure, solubility explains most of the differences in shrinkage between casting alloys. Silicon represents another special and important case in this context, as it is one of the few pure substances to expand during solidification – hence, the higher the silicon content of an aluminium alloy, the lower the alloy’s shrinkage will be.
Exercise 3.9  For each alloy in Table 3.1, determine the amount of heat that must be dissipated to cool 1 kg of this metal from the bottom of its solidification range ($T_{\text{solidus}}$) down to RT. Compare your answers to the latent heat of solidification of the various metals. Which is bigger, and by what factor?

Answer 3.9:

<table>
<thead>
<tr>
<th>metal</th>
<th>heat from $T_{\text{solidus}}$ to RT, J/kg</th>
<th>latent heat, J/kg</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminium</td>
<td>963 (572-20) = 505,575</td>
<td>389,000</td>
<td>0.77</td>
</tr>
<tr>
<td>grey cast iron</td>
<td>500 (1130-20) = 555,000</td>
<td>270,000</td>
<td>0.49</td>
</tr>
<tr>
<td>zinc</td>
<td>420 (381-20) = 151,620</td>
<td>112,000</td>
<td>0.74</td>
</tr>
<tr>
<td>bronze</td>
<td>384 (854-20) = 320,256</td>
<td>230,000</td>
<td>0.72</td>
</tr>
<tr>
<td>magnesium</td>
<td>1090 (468-20) = 488,320</td>
<td>373,000</td>
<td>0.76</td>
</tr>
</tbody>
</table>

The latent heat for cast iron is about half of the heat to cool the metal from its $T_{\text{solidus}}$ to RT. For the other four metals, it is around 75% of that heat. In other words, the latent heat represents a sizable portion of the total amount of heat that must be dissipated during casting!

Exercise 3.10  In practice we can de-mould when the casting is cool enough that it will have sufficient hot strength. Assuming this occurs at a temperature of 0.5 $T_{\text{solidus}}$ (in Kelvin), revise the analysis made in the previous exercise.

Answer 3.10:

<table>
<thead>
<tr>
<th>Metal</th>
<th>heat from $T_{\text{solidus}}$ to $T_{\text{solidus}}$/2, J/kg</th>
<th>latent heat, J/kg</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminium</td>
<td>963 x 422.5 = 406,868</td>
<td>389,000</td>
<td>0.96</td>
</tr>
<tr>
<td>grey cast iron</td>
<td>500 x 701.5 = 350,750</td>
<td>270,000</td>
<td>0.77</td>
</tr>
<tr>
<td>zinc</td>
<td>420 x 327 = 137,340</td>
<td>112,000</td>
<td>0.82</td>
</tr>
<tr>
<td>bronze</td>
<td>384 x 563.5 = 216,384</td>
<td>230,000</td>
<td>1.06</td>
</tr>
<tr>
<td>magnesium</td>
<td>1090 x 370.5 = 403,845</td>
<td>373,000</td>
<td>0.92</td>
</tr>
</tbody>
</table>

The latent heat now increases in importance: for bronze it is now even larger than the heat dissipated in going from $T_{\text{solidus}}$ to the de-moulding temperature.

Exercise 3.11  Glass is very different from metals, but can nevertheless be cast quite well. What do you think would be the shrinkage for glass? And which property of molten glass allows a skilled glass-blower to mould and shape the material on the end of a hollow rod in the open air, whereas this is impossible for metals?

Answer 3.11: since solid glass is fully amorphous, its shrinkage is zero (i.e. as opposed to metals, it has no transition from an unordered, low-density liquid phase to an ordered, high-density solid phase). Molten glass has considerable viscosity (much like molasses), which allows glass-blowing in the open air – and unlike molten metals, it is also immune to oxidation (it already is an oxide!), which helps considerably as well. For further details and information, and for the real meaning of ‘crystal glass’, see the section on press-blow moulding of glass in Chapter 13.

Exercise 3.12  On skateboards, the wheels are mounted onto the board by means of a ‘truck’, which consists of a ‘hanger’ and a ‘base plate’. Both are usually aluminium castings (Figure 3.5). Using Chvorinov’s Rule, estimate the solidification times of these parts by modelling them as simple geometrical shapes. Which takes longest?
Answer 3.12: assuming the hanger is a cylinder with – say – 3 cm diameter and 15 cm length, it has a volume \( V = 106 \text{ cm}^3 \) and a surface area \( A = 84.8 \text{ cm}^2 \). Then its thermal modulus \( V/A = 1.25 \text{ cm} \) and, assuming sand casting with \( C = 105 \text{ s/cm}^2 \), its solidification time \( t_{\text{solid}}(\text{hanger}) = 162 \text{ s} \). Similarly, for a base plate measuring – say – 7 by 5 cm, 0.8 cm thick, we get \( V/A = 0.31 \text{ cm} \) and solidification time \( t_{\text{solid}}(\text{base plate}) = 10 \text{ s} \). This is much shorter than the hanger!

**Exercise 3.13** In two-shift production, we typically have around 3,000 hours per year of effective production time. What then is the maximum time to produce one part (i.e. the ‘cycle time’) if we want to produce 60,000 skateboard trucks per year? Will the solidification time you estimated in Exercise 3.12 allow this volume?

Answer 3.13: assume we have single-cavity moulds for both parts. Then, the cycle time must be less than \( 3,000/60,000 = 0.05 \text{ hours/unit} \), or 3 min/unit. The solidification time estimated in Exercise 3.12 for the hanger would not allow this volume: solidification alone takes almost three minutes, and all other process steps (filling, cooling to de-moulding temperature, ejecting) are not even included.

Side note: even with sand casting we can easily reach the necessary speed if we either use multi-cavity moulds or use multiple single-cavity moulds in parallel (as is common for high volume sand casting). With low-pressure die casting (lower Chvorinov constant, so faster production) or especially high-pressure die casting (also lower constant, but in addition, allowing thinner parts) we can even achieve one million units/year for such small parts, looking only at production speed.

**Exercise 3.14** Estimate the solidification time for a brass church bell measuring 20 cm across and 30 cm high, with a 15-mm wall thickness (model as a hollow cylinder, open at one end). Do this for a worst case scenario (i.e. zero internal surface area) as well as for a best case scenario.

Answer 3.14: modelled as a hollow cylinder with the given dimensions, the bell’s volume \( V = 2,956 \text{ cm}^3 \) (and at a density of 8.9 g/cm\(^3\), its weight would be 26 kg). In the worst case scenario, its surface area \( A_{wc} = 2,286 \text{ cm}^2 \); in the best case, it is \( A_{bc} = 4,035 \text{ cm}^2 \). So, \( V/A_{wc} = 1.29 \) and \( V/A_{bc} = 0.73 \), and solidification time is between 27 and 83 s, assuming sand casting.

**Exercise 3.15** For a thin, flat plate with thickness \( d \), the thermal modulus can be approximated by \( d/2 \). Explain why.

Answer 3.15: a plate with length \( l \), width \( b \) and thickness \( d \) has a volume \( V = l b d \). Its surface area is equal to \( A = 2 l b + 2 d (l + b) \). For a large, thin plate, we have \( l, b >> d \). Then, the area \( A \) can be approximated well by \( A = 2 l b \). Finally, we get \( V/A = l b d/(2 l b) = d/2 \).

**Exercise 3.16** Estimate the solidification times for your various sample products (see Exercise 3.1).

Answer 3.16: of course, this depends on the product. Note once more that for thin-walled parts and products, Chvorinov’s Rule will underestimate the solidification time.

**Exercise 3.17** Which of the alloys in Table 3.1 is probably the most susceptible to porosity formation? Why?
Answer 3.17: based on the information in the text, this will be the one with the highest shrinkage, so first bronze, then magnesium, then aluminium.

Side note: especially in sand casting, but also in several other casting methods, it is easy to use feeders to counteract solidification shrinkage. This leaves only the susceptibility to gas porosity, which generally presents more of a problem in the light metals than in bronze.

Exercise 3.18  Again, consider the G4 iMac frame. This casting has an average wall thickness of 3 mm, but has local sections measuring up to 15 mm thick (see Figure 3.3). How do the cooling times of these thicker sections compare to those of the thinner wall?

Answer 3.18: assuming a linear relationship between local thickness and solidification time, these cooling times will be several times longer (not quite five times, as the thicker sections will also cool by dissipating heat to the thinner sections attached to them, keeping these hot). Assuming a quadratic relationship (as in Chvorinov’s Rule), the differences would get huge, but this is not then realistic (same reason).

Exercise 3.19  Consider a cast iron manhole cover with ribs for increased stiffness. Suppose that during casting we get a certain temperature difference $\Delta T$ between the thicker and thinner sections of this product. How large does $\Delta T$ need to be to cause permanent deformation (typically at a strain of order 0.1%)? Is this difference likely to occur during casting?

Answer 3.19: we need to find out whether the thermal strains $\varepsilon_{\text{thermal}} = CLTE \Delta T$ are larger than the maximum elastic strain given by Hooke’s Law, i.e. $\varepsilon_{\text{max elastic}} = \frac{\sigma_{0.2}}{E}$. Using the data from Table 1, we get at $\Delta T = 111^\circ$. Compared to the casting temperatures of 1200-1180$^\circ$, this seems not unreasonable. However, once we factor in that cast iron nearly always involves sand moulds it gets unlikely that this $\Delta T$ will occur in practice. Heat flow from thicker to thinner sections will be larger than heat flow from thicker sections to the mould.

Exercise 3.20  Look closely at the parts you selected (see Exercise 3.1). Do you think that porosity and/or internal stresses or distortion are present? Explain. Hint: measure your products carefully and estimate the thermal moduli of the various sections. Another hint: cut right through the thickest section and see if you can see any porosity – polishing the section and using a microscope will help, but in cast aluminium, you can often see porosity with the naked eye.

Answer 3.20: many options possible, but notably in aluminium and magnesium die castings we can expect porosity in all thicker sections, if such sections are present.

Exercise 3.21  Estimate the number of grains across the thinnest section of the casting you identified in Exercise 3.1. Hint: what about the cooling rate?

Answer 3.21: in castings that are cooled rapidly (e.g. high pressure casting), grains are of the order of magnitude of 0.05-0.5 mm. So, in (say) a 5-mm thick section we can expect 1-10 grains. Conversely, in slowly cooled castings (e.g. sand casting), grain sizes well over 1 mm are common, unless sufficient amounts of grain refiners are added (as is commonly done, because large grains are detrimental to the mechanical properties).

Side note: in aluminium castings alloyed with silicon, it is not so much the grain size that matters but the so-called dendrite arm spacing, i.e. the distance between the arms that form in a single solidifying grain, which tend to be shaped like tree structures (‘dendrites’), rather than spheres, until they impinge on one another and the spaces between the arms solidifies. Consult e.g. John Campbell’s book for details.
Exercise 3.22  Which element(s) can be used to ensure that the carbon in cast iron emerges as nodules ('nodular cast iron') instead of as flakes ('lamellar cast iron')? Look it up! And what is the key difference in material properties and hence, applications?

Answer 3.22: the elements used to obtain this microstructure in cast iron are magnesium (typically 0.05%), cerium and certain rare earth elements. The key difference in material properties is the ductility: strains-to-failure of 20% are no problem, while lamellar cast iron essentially has no ductility. Nodular cast iron is common for highly loaded parts (although for safety-critical parts, forged steel will often be the better choice). Lamellar cast iron also has high damping (from rubbing of the carbon flakes) – useful for example in the mounting beds for machine tools, reducing vibration.

Exercise 3.23  Look up a cast alloy composition in detail. What are the impurities? What elements are deliberately added, and why?

Answer 3.23: an example would be EN-AC-46000, a common aluminium casting alloy for semi-structural applications (e.g. the foot of a steam iron). Its composition is (mass %):

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Cu</th>
<th>Fe</th>
<th>Mn</th>
<th>Mg</th>
<th>Ni</th>
<th>Zn</th>
<th>Sn</th>
<th>Ti</th>
<th>Pb</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass %</td>
<td>8-11</td>
<td>2-4</td>
<td>&lt;1.3</td>
<td>&lt;0.55</td>
<td>0.05-0.55</td>
<td>&lt;0.55</td>
<td>&lt;1.2</td>
<td>&lt;0.25</td>
<td>&lt;0.25</td>
<td>&lt;0.25</td>
<td>&lt;0.15</td>
</tr>
</tbody>
</table>

Silicon and copper are the two main alloying elements and are, of course, deliberately added (Si for castability, Cu for static strength). Iron is also added deliberately (though primary Al always contains some iron already as an impurity) – it increases static strength and facilitates processing (upon making contact with the steel die, liquid aluminium absorbs some iron, and adding iron to the alloy reduces this unwanted effect). However, as it forms an intermetallic compound with aluminium that reduces the alloy’s fatigue strength and corrosion performance, concentrations of iron in this alloy are often lower that the limit given above. Magnesium is also a deliberate addition (as is obvious from the fact that both a lower and upper limit are given!), as is titanium: in aluminium, the compound TiB₂ is often used as a grain refining inoculant. The other elements are basically impurities. Note that trace elements (e.g. sodium) are not yet given in this overview.

Exercise 3.24  Do you think inoculants will affect the cycle time?

Answer 3.24: no, they don’t. Apart from physical process steps (mould opening and closing, mould cleaning between cycles) and pouring/mould filling, cycle time is determined by the speed at which heat can be removed, not by the size of the grains formed during solidification. Note also that the total amount of inoculants is very small – see previous exercise.

Exercise 3.25  Which method(s) would you choose if you want maximum design freedom? Think of the size of the casting and its material, but also of the ability to create undercuts, deliver fine detailing and sharp radii, or allow for changes in section thickness.

Answer 3.25: investment casting offers the best design freedom purely regarding form (e.g. it can make undercuts, re-entrant hollow shapes such as flasks, and depending on the metal in question, also allows considerable thickness variation). For size, sand casting is the best; this method also allows some thickness variation. Finally, purely for surface detailing, high pressure die casting is the best choice.
Exercise 3.26  Which method(s) would you choose for castings that are highly loaded and therefore require high strength and good ductility? And which one(s) would you choose in order to realize narrow tolerances?

Answer 3.26: compared to the other methods presented here, gravity die casting and low pressure die casting offer superior strength and ductility (all else being equal, e.g. metal, shape and size). They are also the best choices when it comes to tolerances, although in this respect high pressure die casting is also a good option. NB: the ‘vacural’ process developed by AUDI and ALCOA, i.e. high pressure die casting under vacuum, does provide excellent ductility (even suitable for automotive crash structures!), but is very expensive in terms of investments and therefore strictly high volume. Another limitation of this specific method is that slides cannot be used in a die that is to be put under vacuum.

Exercise 3.27  Which method wins when it comes to investments, that is, which is best for small production volumes? And which offers the lowest part price, provided that production volumes are sufficiently large to amortize the mould or die costs?

Answer 3.27: sand casting has the lowest investments; high pressure die casting eventually has the lowest costs (thin parts, so low material costs; also often no need for secondary machining beyond separating the casting system).

Exercise 3.28   Look back at one of the product examples you located (see Exercise 3.1). Consider which metal and which method were involved, and then draw up three design guidelines for this combination. How are these rules reflected in your product?

Answer 3.28: an easy and obvious first design rule is to ensure positive draft angles over the entire products; a second one is to use ‘organic’ shapes (so, preferably no flat areas) and constant section thickness. Slightly less obvious but very important: match production volume with method, and avoid making products that are too large for the method in question. (NB: the precise answers and ‘rules’ would of course require a material choice.)