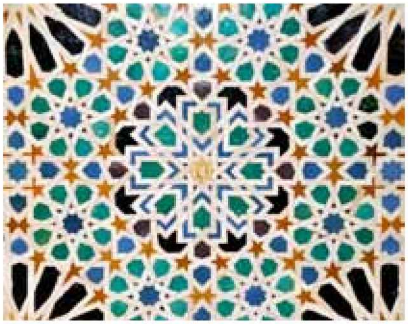
13 Reducing yield losses

Using less metal to make the same things

Separately from component design, our maps of metal flow showed that at least a quarter of all liquid steel and 40% of liquid aluminium never makes it into products, as it is cut off as scrap during manufacturing. What can we do to reduce these losses, and how much can we save?



A mosaic in the Nasrid Palace, Alhambra

Aged 68, M. C. Escher said, "filling two-dimensional planes has become a real mania to which I have become addicted and from which I sometimes find it hard to tear myself away." Escher was particularly interested in finding tessellating patterns, in which a small number of images can be replicated with some degree of regularity, in order to fill a plane completely, with no gaps. In turn he had been inspired by the incredible decorations of the 14th Century Moorish Alhambra palace in Granada, Spain. The Alhambra, now surrounded by a beautiful forest of English elm trees brought by the Duke of Wellington in 1812, three years before he defeated Napoleon I (and so, as we know, paving the way for Napoleon III to accede and promote aluminium), has walls, ceilings and floors decorated in mosaic tiles: Islamic art does not represent living beings so this exemplar of 'Paradise on Earth' takes the idea of repeating geometry to an extraordinary limit. Five hundred years before Yevgraf Stepanovich Fyodorov, Professor of Geology at the Moscow Agricultural Institute proved it in 1891, the 14th century artists of the Alhambra had identified that there were 17 possible forms of translational symmetry and exploited them all in their tilings.

Tessellation provides the starting point for this chapter, because as we've seen, the steel and aluminium industry produce intermediate stock products including plates and rolled up coils of sheet metal, which must be cut into shapes before being formed into components. If those shapes do not tessellate, some of the metal is scrapped, so we have to make more liquid metal than we really want. And in fact, tessellation isn't the only reason we do this: we also cut off significant fractions of our cast metal as part of normal manufacturing practice, generally because we only want to use perfect quality metal or because the shapes made with great efficiency by the steel and aluminium industry are not the shapes finally required by customers.

A car door panel

A steel I-beam

An aircraft wing

A drinks can

Our metal flow Sankey diagrams in chapter 4 showed us that the combination of poor tessellation, quality constraints and cutting out, causes us to scrap 26% of all liquid steel and 41% of all liquid aluminium. So this chapter is motivated to see if this is absolutely necessary. We'll start by checking our global numbers for yield loss with some product-based case studies, and then identify how yield losses influence the 'embodied energy and emissions' in components. We can then explore the causes of yield loss in current production systems, look for options to reduce them, evaluate the emissions benefit of reducing yield losses and finally examine the business case for better yield.

Case studies of yield loss

There are no national data sets about yield losses, so to find out more about how much metal we currently scrap, we conducted a series of case studies, in which we track backwards from a finished component, visiting all the companies along the journey of production, until we arrived back at liquid metal. We wanted our case studies to span both steel and aluminium, and to cover both sheet (thin) and bulk (thick) products, so the components we followed were a steel I-beam, a car door panel made either in steel or aluminium, the body of an aluminium drinks can (i.e. with no lid or opener) and the aluminium wing skin of an aeroplane. At each stage, we asked about yield losses, and also about energy and CO_2 emissions associated with each process, to build up a complete picture of the production process. Inevitably these data are commercially sensitive so, while our numbers reflect real commercial practice today, we can't identify our sources.

We had to be rather careful in defining yield loss. It's not just sensitive externally, where customers might be able to exploit yield information in negotiating prices, but in larger companies the figure is sometimes used for comparison between different production sites, so local managers wanted to give an optimistic view of their own yield figures. This is particularly true in early processes where production scrap can be re-melted: at one site, where liquid metal is made from recycled scrap, we found that around 20% of each batch of liquid metal was discarded, cooled to solid and then immediately recycled. In our eyes this is a major yield loss, because 20% of the energy used by that process was to melt metal cycling forever around a loop. However, the local manager told us that his reports on yield counted only the ratio of metal entering his factory to the weight of products leaving it, so what we saw as a 20% yield loss did not feature in his reports. Our numbers in this chapter are therefore process yield losses: for each process, the yield loss is the difference between the sum of all metal entering the process and the weight of metal moving onto the next process downstream.

We've summarised our five studies of yield loss in the column charts below. In each case we've normalised the results, to start with one tonne of liquid metal, and the different sections of each column show the metal lost at different process stages. The I-beam is extremely efficient: around 90% of the liquid metal makes it into the finished component. For the sheet products, the car door panels and the drinks can, the losses stack up to around 50% of the cast metal, and for the wing skin panel, the losses are an amazing 90%. As we saw in the previous chapter, weight is so important to the aerospace industry, that they will do anything to reduce it: so if we measure the outputs of an aeroplane manufacturer by weight their main product is swarf, the scrap of machining processes, and aeroplanes are a mere by-product!

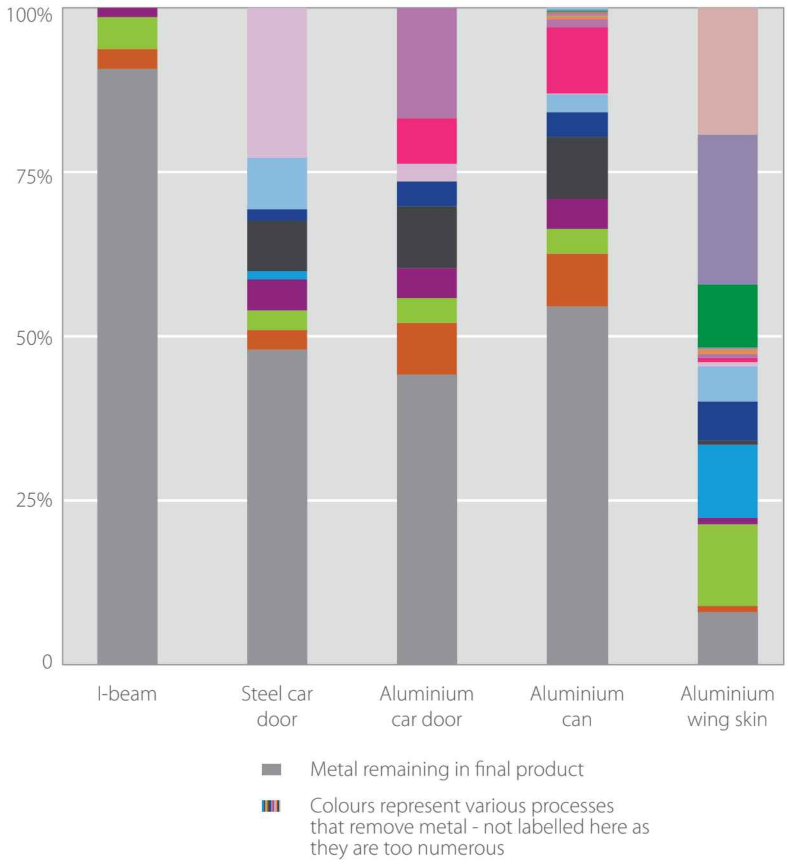


Figure 13.1—**Yield losses for the case study products**

Our case studies have confirmed the overall estimates of yield losses we saw in the Sankey diagrams of metal flow in chapter 4, and have drawn attention to the extreme losses in the aerospace industry. The overall yield ratios shown on the metal flow diagrams, are repeated in Table 13.1. Yield losses in forming components in aluminium are greater than those in steel, because cast aluminium ingots must be scalped, surface finish requirements for aluminium products are usually more demanding, and because more aluminium components are made by extrusion and direct casting which have higher yield losses than rolling. Yield losses in fabrication depend on the required change in geometry from stock to finished product, so depend on both product design and process route, but are remarkably similar for both metals.

The aim of the rest of this chapter is to explore how we can reduce these losses. However, before doing so, we can draw a further interesting insight from our case studies, by looking at the 'embodied' energy in each of the five components.

Table 13.1—**Global yield losses in steel and aluminium production**

Process	**Steel**		**Aluminium**	
	Output (Mt)	Yield loss	Output (Mt)	Yield loss
Liquid metal	1400		76	
Forming	1280	9%	54	28%
Fabrication	1040	18%	45	18%
Overall		26%		41%

The effect of yield loss on embodied energy and emissions in products

We discussed in chapter 2 the difficulty of attributing emissions to individual products or services. However, in the case studies of this chapter, having looked in detail at what physically happens at each process step, we can attempt an attribution. We have only collected data on processes, and haven't been told what else drives energy use at each site, so cannot correctly allocate all energy used in these factories to the products that they make: for example, managers who've talked to us informally about their energy use in downstream manufacturing businesses, have told us that around half of their energy purchases are to keep people warm or cool at work, and this energy is never allocated to products.

Using just our process data, we can show how the cumulative energy required to complete a component builds up, at the same time that yield losses reduce the fraction of the original cast metal remaining in the component. We'll define the cumulative energy divided by the remaining metal as the energy embodied in the component. When metal is cut off as scrap, we won't attribute any energy to the scrap, because what concerns us is the total energy inputs required to make the component, and this is what we mean by 'embodied.' (The energy 'embodied' in the component is quite different from the energy 'embedded' in the product. The embedded energy is what we could recover from the metal, and as we know from chapter 8, this is its exergy, which is largely defined by its composition and uninfluenced by all other processing).

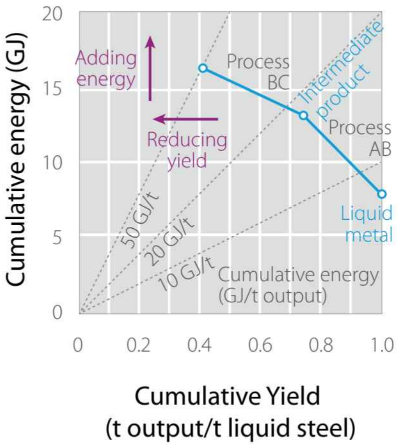


Figure 13.2—**Example graph of energy against yield**

To show how embodied energy builds up in our case study parts, we've invented a new graph. The x-axis of our graph shows the ratio of mass remaining in the component to the mass that was cast and is just like the column graphs of Figure 13.1. The y-axis of the graph shows the cumulative energy of all processes involved in making the component. We've also scaled this axis by the mass of metal cast (not by the mass remaining at each stage) so that both axes are scaled by the same fixed number. This allows us to plot contours of a constant ratio of the y-axis to the x-axis, equal to the cumulative energy divided by the mass remaining in the component, and these contours show the embodied energy in the component. The results of our cases studies are plotted on these new axes in Figures 13.3 and 13.4. In both cases making the liquid metal uses most energy, so we've truncated the y-axis.

The striking message of these graphs is that the liquid metal process dominates the cumulative energy, but yield losses dominate the embodied energy: in the most extreme case of the wing skin panel, the cast liquid metal required 100 GJ/tonne, but the embodied energy of the final panel is 1500 GJ/tonne because 92% of the liquid metal has been scrapped. More typically, the embodied energy for the sheet products (can and car panels) has nearly trebled mainly because of yield losses greater than 50%.

Liquid metal production is already highly optimised as we saw in chapter 7, so the graphs tell us that if we want to make a large reduction in embodied energy it will be more effective to try to reduce yield losses than to improve energy efficiency. To illustrate this message, in Figure 13.4 we've redrawn the graph for the aluminium door panel a further time, with axes of absolute cumulative energy against mass. On this graph efficiency improvements would reduce the y-axis height of the finished component. We've shown three lines on the graph: the aluminium car panel exactly as in the earlier graphs; the panel as if all downstream manufacturing processes were 20% more energy efficient; and the panel as if all

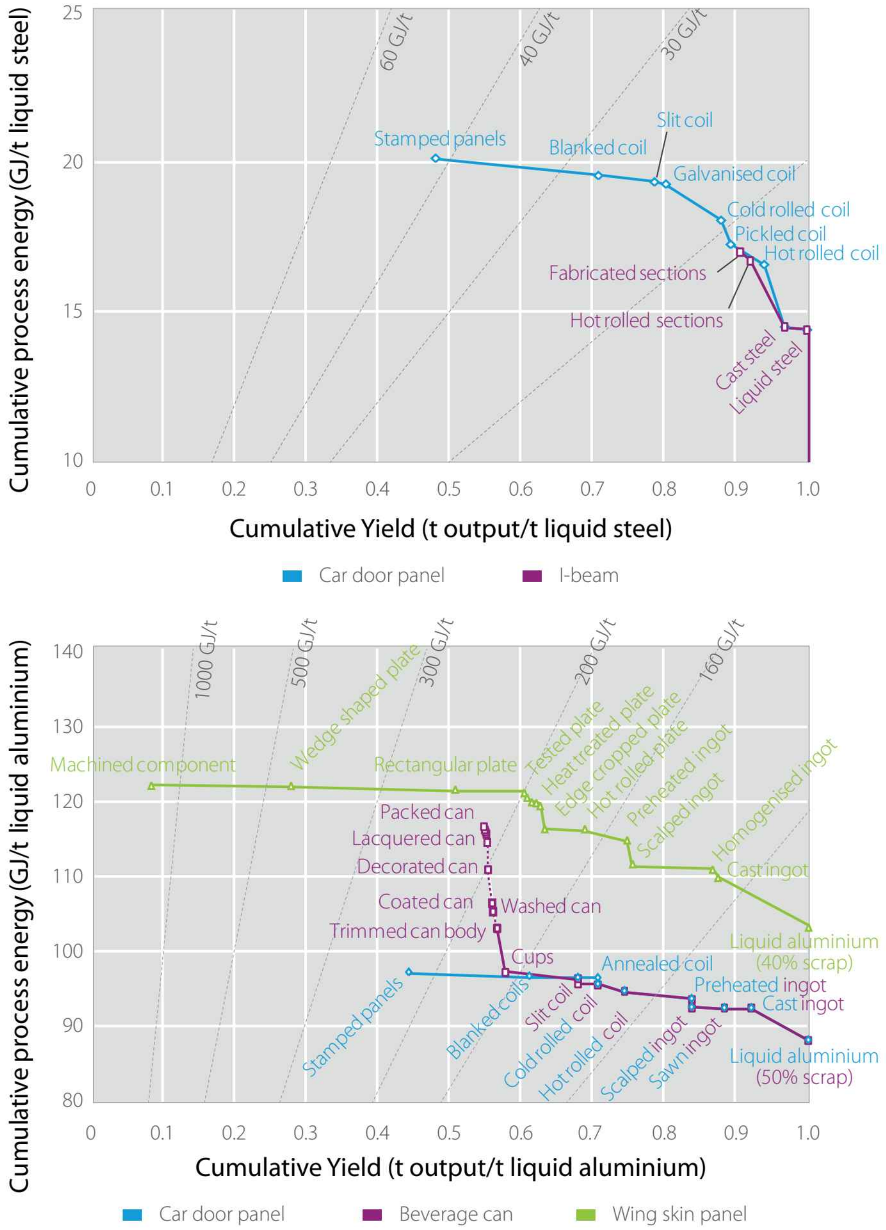


Figure 13.3— **Accumulated energy against cumulated yield for the metal products**

downstream processes had a 20% lower yield losses. The improvement in yield gives a much greater reduction in cumulative energy, because the panel required less liquid metal.

The energy embodied in the liquid metal depends on its recycled content. However, the graph for our aluminium case study parts, which includes two different starting

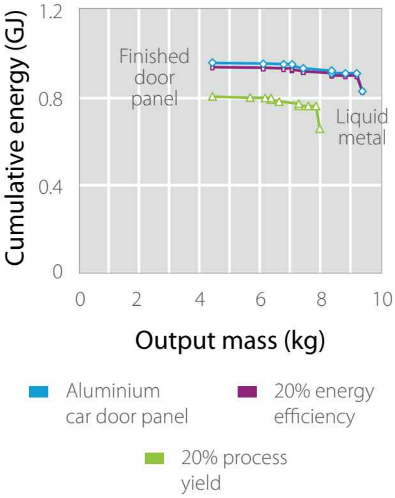


Figure 13.4—**Absolute values of cumulative energy against mass for the aluminium car door panel**

points, demonstrates that the strong effect of yield losses in driving up is similar in both cases. Without question we want to make the liquid metal with as much efficiency as possible —that's what our "one eye open" strategies were all about. But these case studies have shown that yield losses greatly increase the amount of liquid metal required, and therefore greatly drive up the embodied energy of final components.

We can draw one last lesson from these graphs. When we visited the can-making company for our case study, they gave us estimates of the process energy required to coat the can with external paint and internal lacquer. Both processes require a baking cycle, to harden the coating after it has been applied, and the aluminium graph above shows that these baking cycles are energy intensive. In fact baking adds as much to the cumulative energy axis as all the manufacturing stages required to make the can from liquid metal. We have similar estimates for the car body panels —the paint baking operation is the most energy intensive process in manufacturing car bodies from coiled sheet. Remembering back to chapter 2, where we looked at both global and Chinese total energy use, we found that manufacturing components from stock products used about 5% of industrial energy (compared to 25% for steel and 3% for aluminium). If baking cycles (and other furnaces) are a major driver of energy use in manufacturing, the contribution of metal shaping and cutting to total energy requirements must be relatively small. Therefore the development of shaping and cutting processes to support a more sustainable future should prioritise the reduction of yield losses.

The causes of yield loss

Why on earth are we making so much scrap? More than a quarter of all liquid steel, and nearly half of all aluminium never makes it into a component, and instead is perpetually cycling round an internal loop with each cycle costing us energy and creating emissions. What's gone wrong?

We've seen from our case studies that the losses arise from a combination of quality problems at metal surfaces, from the fact that the intermediate products made by the steel and aluminium industry are the wrong shape, from the need to grip metal components while shaping them, and from defects and errors. We'll look at each of those in turn.

When liquids solidify, they do so from outer surfaces towards their interior, and for liquid metal with complex compositions, during this process, the composition of the remaining liquid changes. As described in chapter 8, different cooling rates at the surface and centre of an aluminium ingot lead to a different, lower quality, microstructure and composition at the surface. As a result, 150 mm is currently sawn from the head and tail of each cast aluminium ingot and the outer 20 mm from the top and bottom surfaces is removed by 'scalping'. (Scalping, which is also applied to the hair of new army recruits, is a large scale machining process.) This problem does not occur for steel, although rapid growth of steel oxides (known as scale) causes some loss of steel when the brittle scale breaks away from the surface during rolling. After casting, most steel and aluminium is rolled at least once, and while rolling has tremendous throughput, it is most effective in the middle of each coil or plate—so the head and tail of any rolled material is always cut off, and the edges, which crack during rolling, are trimmed. Overall these problems at surfaces cause around 25 % of all yield losses in steel[1] and around 40 % of all yield losses in aluminium.

Blanking[6]

Cutting aluminium with a circular saw

Machining aluminium and making swarf

The second major cause of yield loss is that the stock products made by the steel and aluminium industry are the wrong shape. They are chosen as useful average shapes, so we can achieve economies of scale, but very few customers actually want the shape they purchase. The most extreme example of this in our case studies was for the aluminium wing skin where we saw the aluminium supplier producing a thick long rectangular plate of perfect proportions. But this perfect plate is machined into a wedge shape, because aircraft wings are thinner at the tip than the centre so much of the perfect plate is immediately scrapped. In reality, the aeroplane manufacturer never needed a uniform plate. However, this is merely an extreme. Can makers want circular disks of aluminium sheet to make cans, but instead receive 2 metre wide coils of sheet, from which they punch out circles and then send back 15 % of the coil for remelting. Car body panel makers also don't want continuous coils of sheet: they want cut-out shapes to form into panels, often with holes where the windows will be. They too return 10 % or more[2] of the coil after 'blanking' (cutting out the shape they really wanted). In fact all material removal processes applied to stock products cause yield loss, which occurs because the intermediate product was the wrong shape.

Sheet and plate materials are supplied flat, but usually are not flat in use, having been shaped in some way. The most common process for shaping sheets, 'deep drawing', illustrated in Figure 13.5, forms the flat sheet into shape, and can create incredible shape change, such as when forming a cup or box out of a single sheet without joining. If you form a sheet without firmly gripping its edges, you can only make a very shallow cup before the sheet tears. Equally, if you don't restrain the edges at all, as you begin to form the cup, the edges will wrinkle. So deep

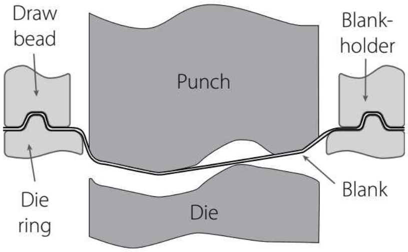


Figure 13.5—**Deep drawing**

drawing works using drawbeads to grip the edges of the sheet, which prevents wrinkling, but allows the sheet to draw inwards to prevent tearing. Deep drawing is a fantastic, efficient process but the material gripped by the drawbeads, about 25mm around every finished part, must be trimmed off. This leads to a yield loss of about 15 % for a typical deep drawn part[3].

Finally, no manufacturing process is perfect, but customers only want perfect parts, so any error, defect or imperfection in manufacturing leads to yield loss. This is naturally an area where every manufacturing business is highly motivated to improve, but errors persist and around 5 % of all yield losses are due to defects and errors.

Options to reduce yield losses

When we began discussing yield losses with the various companies we visited in preparing this chapter, their immediate reaction was "well of course we wouldn't generate scrap if we didn't have to, so of course we can't improve." Strictly that statement should be "we wouldn't generate scrap unless it was cheaper for us to do so" because, as always with high labour costs in Europe, decisions are based on the balance between material costs and labour. But as we continued to explore the cumulative effect of yield losses along long production chains, we found that few if any of the companies we visited understood the yield losses of their suppliers or customers. It seems that current yield losses are as much a function of habit as necessity.

Convertible car doors often don't have frames surrounding their windows

We've therefore looked at three stages of the life of each metal component, to ask if a different practice at one stage could influence yield losses elsewhere: can component designers influence yield losses in manufacturing? can the design of cast geometries reduce the need for downstream yield loss? could we invent new manufacturing processes that reduce our need for trimming, cutting and machining?

...unlike conventional cars

We can start back at the Alhambra palace: designers of metal components at present are largely unaware of the implications of their geometric choices on yield losses, but potentially could design with tessellating or nearly tessellating shapes, and so radically reduce yield losses. This could constrain product geometry, which might be unacceptable to customers, but the issue is so little in the minds of designers at present, that some significant gains will be possible. A simple example is in the two photographs of car doors to the side: the door with an integrated window would require more than double the amount of metal than the door in the convertible car in which the window projects upwards. We've also been lucky enough to attract help from one of the UK's emerging new kitchen stars, Roseanna, who in the box story demonstrates the material efficiency of her hexagonal jam tart cutter.

Roseanna's hexagonal jam tarts

1. Roll out two identical sheets of pastry

2. Check that both sheets measure around 275x320 mm

3. Carefully position your hexagonal cutter in one corner

4. Continue cutting hexagons till you have filled the sheet

5. Cut out the other sheet with a circular cutter

6. Lift the cut tarts into a lightly greased patty tin

7. Check which cutter gave lower yield losses.

8. Fill both sets of tarts, and bake at 200°C for 15 minutes

9. Leave to cool, serve, and see which tarts your friends prefer.

Trimming the edge off a roll of paper

CNC machine cutting and perforating fabric

There are obvious limits to tessellation: at present we can't form drinks cans out of square, or hexagonal blanks, so in the short term we can't approach perfect yield in cutting sheets. But equally there is significant space in which to improve: paper makers, like sheet metal producers, produce long coils of constant width stock products, which are then cut to size according to customer preferences. Over years of development they have learnt to optimise the two-dimensional cutting of their stock to minimise waste. Arguably this is an easier problem than faced by metal sheet users, as most paper is used in rectangular shapes which naturally tessellate well. However, the clothing and textiles industry faces a challenge at least as difficult as that for the sheet metal makers and now use sophisticated computer algorithms to maximise the yield of clothing from rolls of fabric. In fact advanced clothing manufacturers now automate not only fabric layout but also cutting, with fast laser cutters to translate the optimised blanking pattern into action.

One of the lessons we've learnt from the mathematicians working on the 'two-dimensional cutting stock' problem, is that yields improve when the most possible shapes are tessellated. This is obvious: if you have a larger variety of shapes, you increase the chance that you can find small pieces to fit between the larger ones. At present, two features of metal product design mitigate against this: firstly, product designers tend to optimise material selection for each component, so the 200 sheet metal components in a typical car will be made of many different alloys, and many different thicknesses; secondly, the blanking presses used in cutting parts from coils of sheet metal are designed to cut one piece from the coil, then index forward the sheet, and cut the same piece again. This gives very little opportunity for tessellation. So if car designers used fewer alloys and thicknesses, they could improve yield ratios, and these would be realised if new approaches to blanking could allow more sophisticated tessellation. At present laser cutting of metal, while common in James Bond films, is relatively slow, so the approach of fabric cutting cannot yet be translated into metal sheets. However, there is great scope for innovation in blanking press design to cut more than one shape at a time.

A completely different strategy to reduce yield losses, is to start by forming the liquid metal to a shape nearer to that of the final component. We've found three approaches: continuous thin strip casting where the liquid metal is cast into the nip between two chilled rollers into a continuous strip; direct casting in a mould;

Direct casting of a steel part in a sand mould

and additive manufacturing. The aim of these approaches is to make components with fewer processing steps and reduced yield losses. But unfortunately, none of them are as good as existing process routes. Thin strip casting saves the need for reheating prior to hot rolling, and for aluminium can also avoid yield losses in scalping, sawing and hot rolling. However, it is difficult to control, and the resulting sheets often have poor surface quality, unless they are rather pure alloys. Cooking foil, which is a nearly pure form of aluminium, is made by thin strip casting, rolling and coiling, but as yet this approach is not used for alloys with more complex compositions. The geometry of components made by direct casting must be simple enough to ensure complete filling of the mould, and as we saw in chapter 3, the properties of steel and aluminium depend on both composition and processing. Without deformation it isn't possible to increase the strength of direct cast components by breaking up large grains or work hardening. As a result the properties of direct cast components cannot match those achieved by conventional process routes involving deformation such as hot rolling.

A part made by additive manufacturing (selective laser melting)[5]

Many additive manufacturing technologies are under development, and the whole area of "3D printing" has attracted great excitement in research over the past twenty years. It's a very easy topic to "sell", because the dream that we might in future somehow not just order our goods over the internet, but have them magically appear in our domestic 3D printer is a compelling media image: all we need is the magic powder that can be James Bonded at home! Some parts of this dream are quite real: the photo shows a part made additively, and the aerospace industry is pursuing the technology for making complex parts in titanium. In one common process, 'selective laser melting', a bed of powder is placed under a scanning laser which 'draws' the pattern of a layer of the product. The laser melts and bonds the powder then a new layer of powder is laid and the process repeats. Unfortunately, there are several drawbacks: the process works with powdered metals, which must be made from liquid metal in an energy intensive process using spraying and freezing; lasers are themselves energy intensive; production rates are low because each product is built up in layers; as with direct casting, the properties of the product are limited by the absence of deformation; and surface finishes are poor and must be improved by subsequent operations.

Our interest in additive processes was motivated by energy efficiency, related to yield losses. Figure 13.6 compares the energy embodied in a part made by a conventional process chain (with yield losses) against one made by the selective laser melting process (with no yield losses). The graph shows results for mild steel, stainless steel and titanium because aluminium parts cannot currently be made with the required density[4]. The graph shows that for steel parts, the additive

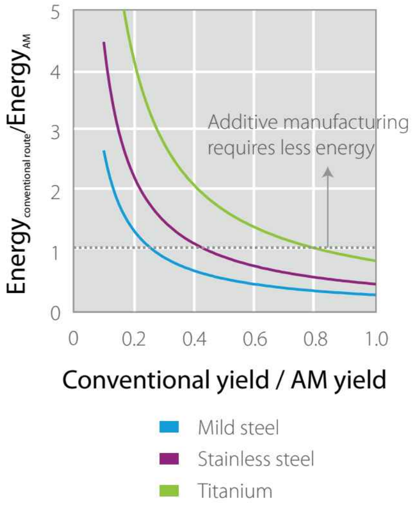


Figure 13.6—**Comparison of energy use in conventional and additive manufacturing processes showing a dependence on process yield**

process leads to lower embodied energy if the conventional process has yield losses worse than 75%. In contrast, the yield losses need be only 20% before selective laser melting saves energy for titanium components, because this method produces parts with acceptable properties, it is commercially attractive. For steel parts, there would be no energy saving, and it is not currently possible to overcome the other drawbacks listed above.

All three routes to nearer net shape production will continue to develop, but we do not have a clear winning technology to replace existing production routes for steel and aluminium components. The steel and aluminium industries will therefore continue to sell intermediate stock products requiring subsequent shaping.

If we are largely restricted to existing stock products, can we look downstream and find new manufacturing processes with lower yield losses? We discussed above the need for trimming after deep drawing: but is it possible to replace deep drawing with a different process that does not require trimming? The older and slower process of metal spinning can make parts with geometries similar to deep drawing but without trimming, so maybe in the future, novel derivatives of spinning processes will be able to take over from deep drawing. The whole class of machining processes, those which remove material by cutting chips from it (drilling is the simplest version), is used in manufacturing only because the geometry or quality of the parts made by upstream forming processes is insufficient. In the companies we've visited where machining removes a substantial fraction of purchased metal, we've identified opportunities to remove less metal by forming metal closer to final shape. For example, with modern control systems, the rolling mill used to make thick aluminium plates as part of wing-skin manufacture could be adapted to roll a variable thickness, eliminating the machining step.

It appears that we have many options for reducing yield losses. Although we need more development before net shape casting can replace existing processes, we have seen opportunities both for designers to reduce losses by tessellation, and for process innovations to reduce scrap. How would these savings influence emissions and does it make business sense?

Emissions savings from reducing yield losses

When we explored embodied energy earlier in the chapter, we found that the embodied energy in a product is significantly increased by yield losses. In most cases, yield loss is a greater driver of embodied energy than the energy of downstream manufacturing. So reducing yield losses should have a significant effect on emissions overall.

It does, but the scrap metal which arises from yield losses is mostly recycled at present. The effect of reducing yield losses is therefore to reduce the supply of metal sent for recycling by exactly the same amount that we reduce our demand for liquid metal. In other words, yield losses create a permanent loop of recycling in the two metal flow Sankey diagrams of chapter 4, and reducing yield losses reduces the size of this loop. The strategy of designing goods with less metal that we examined in the last chapter leads to an overall reduction in demand for all liquid metal. But in contrast, the strategy of reducing yield losses simply reduces the mass of metal that is permanently cycling round the secondary production route as production scrap. The table shows how the elimination of all yield losses would reduce total energy requirements and associated emissions in the steel and aluminium industries.

	Steel	Aluminium
Energy savings	17%	6%
CO_2 savings	16%	7%

Table 13.2—**Global energy and emissions benefit of eliminating all yield losses in steel and aluminium**

The business case for better yield

The initial reaction of businesses to our exploration of yield loss was 'if we could save it we would.' However, our work in this chapter has revealed that collaborative design and process innovation would exploit further opportunities for reducing yield losses. Collaborative examination of yield losses along long metal production chains would not be expensive and we anticipate that some of the resulting opportunities will be cheap and may be immediately profitable. The business case for others will depend on the trade-off between economies of scale and increased variety in product specification. Generally a loss of economies of scale in production can be compensated by development of more flexible equipment and we've shown that this could occur.

The ideal target in this chapter has been to reduce yield losses to zero. This would eliminate production scrap, so would reduce recycling at the same rate that it would reduce demand for secondary production. However, it will take time to do this so before we reach the 'paradise on earth' of the Alhambra's mosaic artists, we'll look in the next chapter for opportunities to make use of the scrap before we send it off for recycling by melting.

Notes

The causes of yield loss

1. Based on data collected by Worldsteel (2009). Yield improvement in the steel industry.
2. Depending on the part being made, blanking losses may be as large as 80 %, though for most mass produced car parts, the losses will be considerably lower (Tata Steel Automotive, 2010).
3. The draw bead dimensions and exact yield loss due to edge trim after deep drawing depends on the geometry of the part and tooling, so the figures of a 25mm edge trim and 15 % yield loss are quoted for a typical automotive drawn part.

Options to reduce yield losses

4. We've assumed that making the metal powder requires 40 GJ/tonne for steel and stainless steel and 45 GJ/tonne for titanium. Data from Cambridge Engineering Selector software, CES (2011).

Images

5. Image courtesy of Renishaw Inc.
6. We would like to thank Tata Steel for their picture of the blanking process.