

Part Three

The metallic tradition

Chapter 9 Ductility in metals

or the intimate life of the dislocation

'We will now consider iron, the most precious and at the same time the worst metal for mankind. By its help we cleave the earth, establish tree-nurseries, fell trees, remove the useless parts from vines and force them to rejuvenate annually, build houses, hew stone and so forth. But this metal serves also for war, murder and robbery; and not only at close quarters, man to man but also by projection and flight; for it can be hurled either by ballistic machines, or by the strength of human arms or even in the form of arrows. And this I hold to be the most blameworthy product of the human mind. In order that death may reach men the more speedily, we attach wings to it; we deck iron with feathers and thus the fault is not nature's, but ours. A few examples prove that iron could in fact be an innocent metal. Thus in the alliances which Porsenna established with the Roman people after the expulsion of the kings, it was established that iron should be used for no purpose except agriculture.'

Pliny, *Natural History*.

As we said in [Chapters 4](#) and [5](#), toughness, work of fracture and crack-stopping are very essential qualities in any useful strong material. To recap, 'toughness' implies, perhaps a little vaguely, a general resistance to the propagation of cracks; rather more precisely, 'work of fracture' is a measure of the energy which has to be consumed in propagating fracture through the material and thus of the length of a critical Griffith crack; 'crack-stopping' implies that the stress at a crack tip is reduced, usually by diminishing the stress concentration, to such an extent that the crack cannot proceed, even if the energy balance is in its favour. As we have seen, both natural and artificial non-metals rely upon a series of characteristic and highly ingenious mechanisms to provide these qualities. Metals achieve the same effects by a totally different method, basically by the dislocation mechanism – which scarcely occurs in nature. One effect of this mechanism is that many metals are 'ductile'.

If a metal possesses adequate ductility not only is the work of fracture high – which of course is a good thing – but the shape of its stress-strain curve is modified in such a way as to ensure large departures from Hooke's law. When this is the case one of the effects is that stress-concentrations are often very greatly and usefully diminished; in other words ductility tends to stop cracks. It will be realized that all calculations and assumptions about dangerous concentrations of stress assume that Hooke's law is obeyed. We speak of concentrations of stress but what the mathematical calculations really supply us with are concentrations of strain. Thus, if we calculate that the material immediately at the tip of a crack in a loaded structure is strained or stretched by 200 times more than the average for the structure as a whole then we assume that the local stress is also 200 times as high and we say that there is a stress concentration of 200. However, if Hooke's law is not obeyed by the local material at the tip of the crack then this is no longer true.

This is the classical metallurgist's way of crack-stopping but, since the local increase of strain at a crack tip is usually many hundredfold, it is of no use invoking minor departures from Hooke's law, such as might be caused by the shape of the interatomic force curve ([Chapter 2](#)). What is needed is a really whole-hearted lack of elasticity which is just what ductile metals provide. However, there is more than one way of departing from Hooke's law and it may be worth glancing at a mechanism which will *not* provide toughness.

Why viscous materials are no good

Viscous liquids will strain under a constant stress by any amount, if given sufficient time. In other words they flow. Like a quagmire, if you go on pressing, a viscous liquid will yield although it will resist a sudden load. All liquids are viscous but some are more viscous than others. The most viscous liquids are hard to tell from solids. In this class are pitch and tar, toffee and the baser sorts of plastics.

We have already remarked that a blow from a poker will shatter toffee which has resisted more adult and slower attacks and the same is true of pitch and the more deplorable plastics. These materials, given time, are very tough indeed because they can flow sufficiently at the crack tip to relieve the stress concentration. As structural materials, however, they combine the worst of both worlds. If they are subject to a sustained load they will flow in bulk and slowly run away from their responsibilities. Under a sudden load they are unable to yield in time and behave like solid glass. Once the crack is running it soon builds up to a speed to which the flow mechanism cannot possibly respond and so the material shatters.

Materials like wood and reinforced plastics creep a little, that is to say they behave in a slightly viscous way at high stresses and this, of course, is a bad thing. Quite apart from this creep however they are to a small extent non-Hookean so that the stress-strain curves generally look something like [Figure 1](#). The departure from Hooke's law, though, is far too small to cause a useful reduction in stress-concentrations and these substances have to depend on weak interfaces to stop cracks.

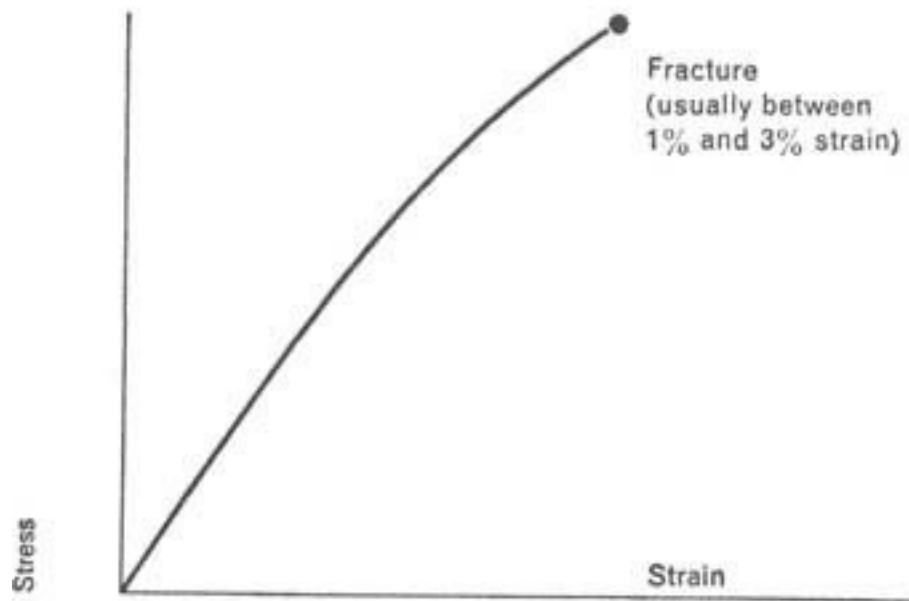


Figure 1. Stress-strain curve for typical non-metallic engineering material such as wood or fibreglass. The departure from Hooke's law is not in general due to the shape of the interatomic force curve but is more often due to small creep effects.

Crack-stopping by dislocations – stress corrosion

At its best the dislocation mechanism provides a very desirable combination of elasticity at low strains with rapid and extensive yielding at high strains. A typical stress-strain curve for a ductile metal is shown diagrammatically in [Figure 2](#). Such metals cease to behave elastically when they reach strains which are usually well under 1 per cent; thenceforth they behave much like Plasticine and extend at nearly constant stress to elongations of 50 per cent or more (in fact locally to a great deal more). During the state of 'plastic' extension, the material is not much weakened, the stress does not

rise with increasing strain, but on the other hand the metal is not seriously damaged. The mean working strains deliberately put upon engineering structures seldom exceed about 0.1 per cent and, as the metal may be able to yield locally by 100 per cent or more, local concentrations of strain at crack tips in the region of perhaps 1000 to 1 can be accommodated.

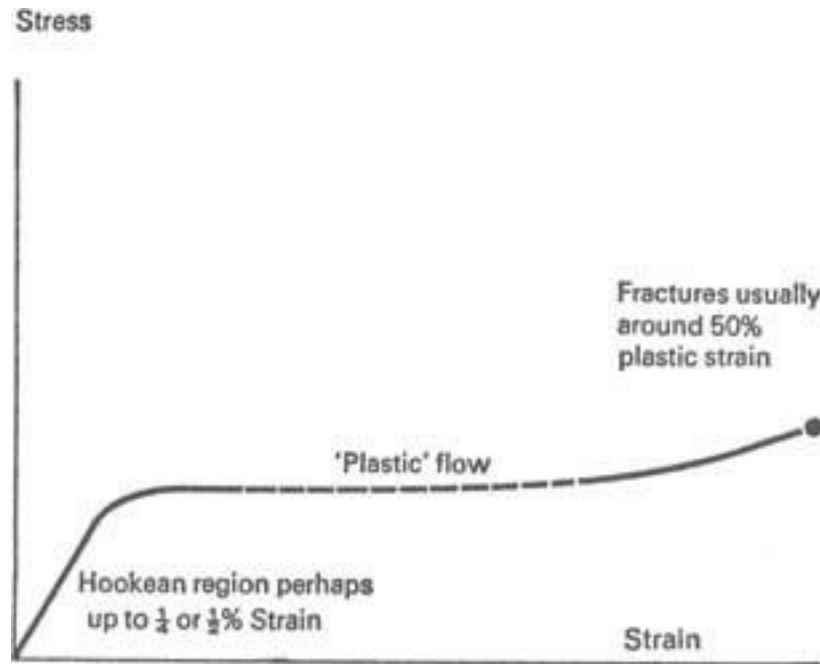


Figure 2. With ductile metals the stress-strain curve usually shows a very long region of plastic flow.

[Figure 3](#) shows that on either side of the actual tip of a crack there are small local regions of very high shear – shear stress

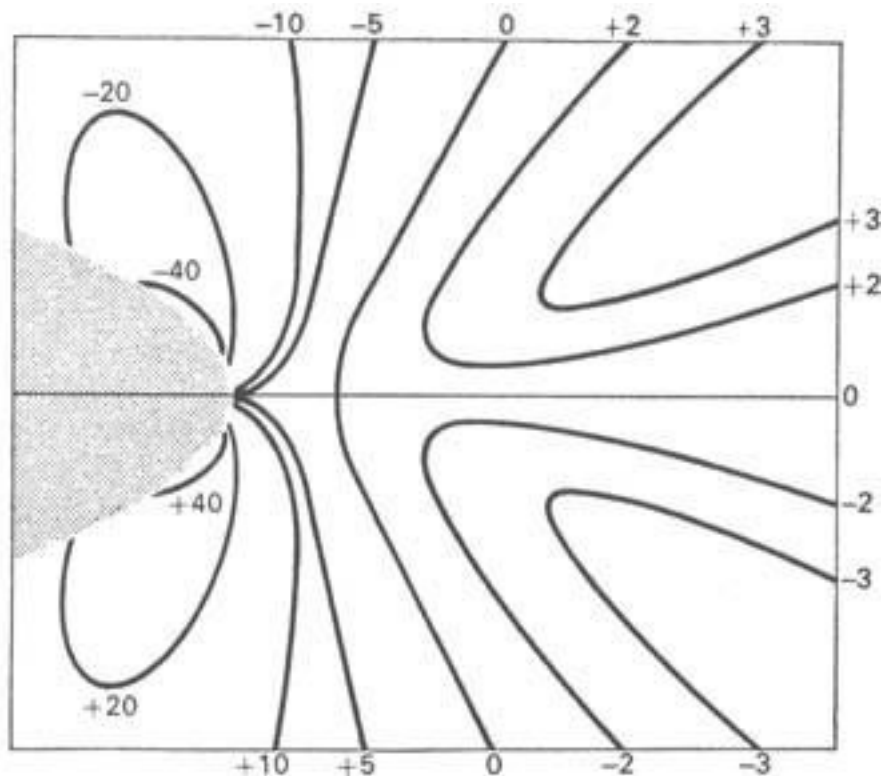


Figure 3. In addition to the concentration of tensile stress at the tip of a crack in a stressed material there are also concentrations of shearing stress which exist on either side of the crack tip. In a ductile metal these shear stress concentrations are able to nucleate hundreds of dislocations and thus help to relieve the stress concentration. This is a diagram of shear stress around a crack tip. Shear stress has a sign – positive or negative – either kind can nucleate dislocations.

concentrations. These are sufficient to initiate sources of dislocations in fairly soft metals and the new dislocations flow from these points in profusion. Slip occurs on two main planes, like ears, at forty-five degrees to the crack surfaces and so the worst of the stress concentration is relieved. This is roughly equivalent to rounding off the tip of the crack and thus, even if the Griffith energy balance ([Chapter 5](#)) is favourable to the propagation of the crack, the mechanism for implementing it may be frustrated for lack of a sufficient stress concentration.

The crack is thus not able to proceed under purely mechanical instigation and so the material is safe in perhaps ninety-nine per cent of practical cases. However, we have to remember in all materials work that there is no hard and fast dividing line between chemistry, physics and elasticity. Experts in their ivory towers like to make these distinctions but the bond between the atoms is not aware of them. A bond can be broken by chemical, physical or mechanical means or by any combination of these causes acting additively. A bond which is strained elastically is more susceptible to being dissolved chemically and physically. For this reason points of high stress are especially liable to attack by solvents or to corrosion by chemicals.

As we have said, there are many cases where the Griffith energy balance is usually still emphatically in favour of spreading a stationary crack. It is merely prevented from doing so by the reduction in the stress concentration at the crack tip which deprives it of a mechanism. Now although the stress concentration has been much reduced by the creation of numerous dislocations at the tip of the crack it has not been wholly eliminated and moreover the way of life of the local molecules has been considerably disturbed and all sorts of fine-scale strains remain. The bonds in this region are therefore more susceptible than elsewhere to attack by any aggressive solvent or chemical in which they happen to be immersed at the time. This is why metals which are tough in air or in other reasonably dry gases may crack when stressed for any length of time when wetted with sea-water or in chemical plants even though they may last for years submerged in the corrosive environment without a load. Some brasses are notorious traps for amateur constructors in this respect.

Ductility in crystals

The word ductility comes from the Latin *ducere* to lead, meaning, I suppose, that the material can be led by a stress to distort in a desired direction. In the engineering of metals it has two extremely useful consequences. It makes the metal tough so that cracks do not readily extend and, secondly, it may make the metal malleable (Latin *malleus*, a hammer), that is, able to be shaped, either hot or cold, by hammering, pressing or bending. Generally speaking, more capacity for flow is needed to obtain a useful degree of malleability than is needed to make the material reasonably tough. On the other hand a great deal of fabrication is carried out when the metal is hot when practically all crystals are much more ductile.

Ductility is exclusively a property of crystals for the reason that true dislocations can exist only as departures from the ordered crystalline state. Most solids are crystalline and dislocations exist in nearly all crystals. On the other hand, in the great majority of crystals, the dislocations are not

sufficiently mobile at room temperature or are not mobile in the right way. Nearly all crystals contain quite large numbers of dislocations which arise from the nature of the mechanisms by which they grow but these dislocations are dispersed throughout the body of the materials in a very roughly uniform way. However, the stress concentration at the tip of a crack is a very intense and localized affair and there are generally not enough dislocations available naturally in the immediate vicinity to provide enough slip to relieve the situation, even if the dislocations are very mobile. It is therefore necessary that many new dislocations should be born on the spot, nucleated by the stress concentration itself. Furthermore, this must be able to happen very quickly if the material is not to be vulnerable to a sudden blow.

In real life, cracks are not two-dimensional diagrams on a sheet of paper but are flat, wedge-shaped holes trying to penetrate a solid three-dimensional material. To relieve the stress concentration adequately, there has to be slip on five planes in all.

The number of crystals which satisfy all these conditions at once is very few: out of all the thousands of crystalline substances which exist, perhaps only something like a dozen metals. With the rather dubious exception of silver chloride, no non-metallic crystal at present can be considered as truly and reliably ductile.

Although an enormous amount of research has been done on dislocations during the last thirty years and there now exists a really frightening volume of theory and information, it cannot be said that all the causes which determine the mobility of dislocations in different substances are fully understood. However, it may be worth looking at some of the more obvious reasons.

First of all, bonds vary a good deal in the ease with which they can be broken and reformed, and, of course, every time a dislocation jumps a step bonds have to be broken and remade. In this respect the most mobile bonds are those which exercise their attraction symmetrically in every direction, most notably the metallic bond and after this the ionic. The worst is presumably the covalent bond which is often highly directional and has an all-or-nothing character. Unfortunately the covalent bond is also the strongest and stiffest and the most generally desirable of the chemical bonds. Dislocations in covalent crystals are never usefully mobile at ordinary temperatures.

Again, the crystallographic structure of the crystal is important; that is, the geometrical pattern according to which the atoms or molecules in the crystal are stacked. If the unit cell or repeating pattern in the crystal is large, then a dislocation jump will generally be more difficult. Even if the unit cell is small but the packing is geometrically slightly more complicated, then the number of directions of easy slip may be unduly restricted. On the whole, crystals with cubic arrangements of atoms are more easily ductile than hexagonal ones. Furthermore the size of the crystals and the impurities they contain all have an important effect.

Although the vast majority of crystalline substances have no useful ductility at ordinary temperatures, those which do have tend to be altogether too ductile. Pure crystals of iron, silver, gold and so on, are too soft to be of much practical use and the art and science of metallurgy consists very largely in making such crystals harder and stronger without making them too brittle. This has to be done by controlling and restricting the movement of dislocations without stopping it too much.

Engineers are very apt to talk about and to specify 'elongation' as a measure of ductility. This is a rough practical test of the amount by which the metal can flow before total fracture occurs and has nothing at all to do with the elastic breaking strain of the material which is usually somewhere below 1 per cent. Elongation is measured, quite arbitrarily, by seeing how far two marks on the stem of a test-piece, initially two inches apart, have separated when the broken halves of the specimen are fitted together after fracture. If the total distance between the marks is then, say, three inches, the elongation is called 50 per cent, and so on. As with most popular engineer's tests it is very difficult to relate elongation in any consistent way either to the flow properties of the material or to the end usage.

However, many engineers have an almost religious belief in the value of the test and if you tell them that wood and fibreglass will give an elongation of nil but yet are very tough, they will merely reply that that is why they do not use wood and fibreglass. As with most emotionally held beliefs this one presumably arises from fear, a very reasonable fear of brittle failure.

In practice, with most metal alloys, an elongation of about 5 per cent or 10 per cent is usually sufficient to ensure a tough material. The materials which are really popular, like mild steel, may have elongations in the region of 50 or 60 per cent even though the attainment of so much ductility implies the acceptance of quite low tensile strengths. This is partly due to an attitude of over-insurance against cracks but also to two other reasons. Many structures are fabricated from sheets and bars and tubes of metal and it is convenient and cheap to be able to bend these things to shape in the cold. One can also use rather brutal methods to make things fit. During the War I was told by one assembler of aircraft that the only way in which he could get the wings of his Spitfires to fit on to the fuselages was to bend the root fittings with a sledge hammer. I never saw this done with my own eyes so that I cannot guarantee that it is true but things of this sort certainly do happen on occasion though perhaps not in the aircraft industry in peacetime.

The second reason is that stresses can sometimes be relied upon to readjust themselves within the structure. In a complex structure it may be very difficult to calculate the loads in all the various members with any accuracy, or perhaps one is just too idle to do so. If the material yields and has a long 'plastic range', as it is called, then an overloaded member may stretch and be little the worse for it. Many engineers have a strong belief in the 'self-designing structure'.

These are very real benefits in an imperfect and commercial world and they go a long way towards explaining the immense success of mild steel, copper and soft aluminium. There are two drawbacks however. The ductility of even the softest metal is not inexhaustible and since there is generally no way of measuring how much of it has been used up in the manufacturing operations, one is left to guess how much of the initial ductility is left over to provide toughness in service. This is at the root of many complaints about failures in mass-produced goods. Annealing is a relatively expensive and troublesome operation, small components are costed and sold on tiny fractions of a penny and so the temptation to deform the metal in the cold as much and as often as possible may be irresistible. Perhaps it will not actually break until after the guarantee has expired.

The other drawback is that the requirement for maximum ductility necessarily implies a low tensile strength, because the metallurgist must arrange for dislocation movement to begin at a low stress. This has the consequence that structures are often much heavier than they need to be.

Dislocations, the edge and the screw

Dislocation theory is immensely complicated and, after all, perhaps mainly of interest to dislocation experts. We must however mention the two main varieties, the edge dislocation and the screw dislocation. The edge dislocation, which is that postulated by G. I. Taylor in 1934, is perhaps the easiest and simplest to think about. It has already been described in [Chapter 4](#) (see [Chapter 4](#), [Figure 5](#)). As we have said, it consists essentially of an extra sheet of atoms slipped into the crystal like a sheet of paper partially inserted between the pages of a book. Edge dislocations can be formed when the crystal grows, for instance at what are known as 'small angle boundaries'. That is, when two growing crystals meet at a fine angle so that they join up to form, effectively, one crystal, the join is marked by a line of edge dislocations, which may afterwards, of course, drift away.

Screw dislocations were postulated by Professor Frank, of Bristol, around 1948, not so much to explain the mechanical properties of crystals, as to explain their growth. For atoms or molecules to

come out of solution or out of vapour and to settle down, more or less permanently, in a solid crystal, requires an energy change. Whether it happens or not depends upon what is called the supersaturation; roughly speaking, on how badly the molecules want to come out of solution or out of the vapour. One can cool solutions of sugar or salt, for instance, well below the temperature at which crystals should be deposited without any crystals appearing unless some surface is provided which is to their liking.

For an ordinary plane, flat surface the supersaturation which can be attained without actually depositing material can be calculated and is found to be quite high. What worried Frank was that, in practice, many crystals grew healthily at supersaturations very far below those calculated for deposition on a flat surface. In fact, if we had to depend upon deposition on a flat surface very many crystals could hardly be got to grow at all. It can be shown that if the surface possesses an irregularity such as a step, even if it is only one molecule high, deposition is much easier.

The re-entrant part of the step provides a welcoming and comparatively cosy home for wandering molecules which tend to settle down there, just as a bricklayer lays a brick in an existing re-entrant in a course of brickwork. As with a course of bricks, the result is not to abolish the re-entrant but to cause it to move along the top of the wall as more bricks are laid. This mechanism had been observed in operation by Bunn and Emmett around 1946. It will be remembered from [Chapter 4](#) that this is the cause of the steps which mechanically weaken the surfaces of whiskers and other crystals (Chapter 4, Plate 10).

Frank's difficulty was that, admitting the existence of growth steps, what happened when a moving step came to the edge of the crystal? Presumably it would be extinguished, as the step in a course of masonry is extinguished when the bricklayer reaches the end of a wall. If so, then how could it be regenerated all over again for the next layer?

Frank's solution was brilliantly simple. Crystals are not built like a house out of level courses of bricks or molecules. The growth step was never extinguished at the edge because the crystal is built like a corkscrew staircase. Thus the crystal simply went on screwing itself into existence, using the same step indefinitely. Like G. I. Taylor's hypothesis of the edge dislocation, the screw dislocation is so intellectually satisfying that one feels it must be true and again, it turns out that it is. The screw dislocation was confirmed observationally by Forty and others not long after Frank conceived it ([Figure 4](#)).

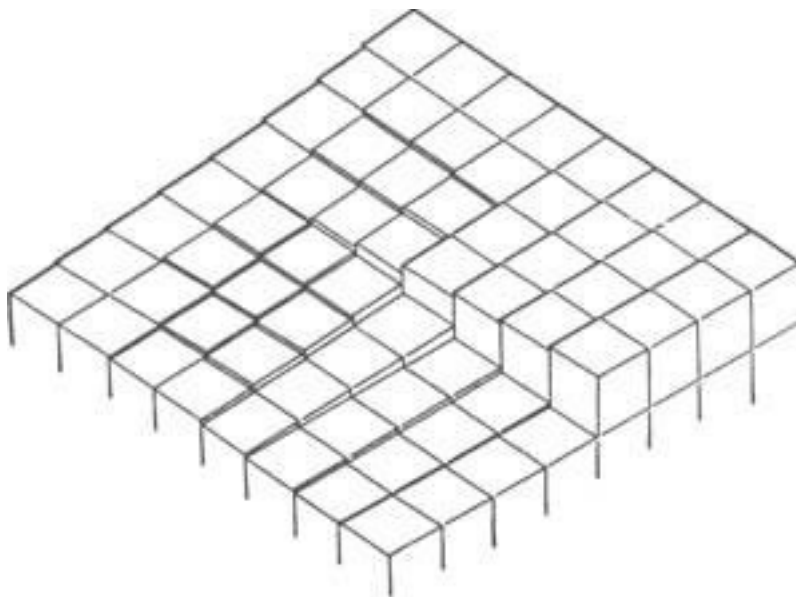


Figure 4. It is not very easy to visualize the arrangement of atoms in a screw dislocation. This diagram attempts to do so with rather moderate success.

The difficulty with corkscrew staircases is what happens in the middle. There is of course a hiatus or mismatch, in the form of a line of misfit up the middle of the screw and this is the actual dislocation. As with the edge dislocation the interatomic bonds are naturally highly distorted or strained at this point although in the normal way there is nothing one could call an actual hole. However it is not uncommon for whiskers to be hollow, like a tube. Possibly the reason is that these whiskers have grown with a screw dislocation of which the step is not one but several molecules high. If so, then the strain at the centre of the dislocation must be very large. The crystal may thus perhaps trade strain energy for surface energy, that is grow with a hole down the middle.

Like most successful hypotheses the screw dislocation has been rather overworked and almost every aspect of the growth of almost every kind of crystal has been attributed to it. It now seems that quite a number of crystals manage to grow without using the Frank mechanism but the fact remains that a very large number do use it and it is a very real and important phenomenon.

It is not necessary for dislocations to be wholly of the edge or wholly of the screw type. A single dislocation line can begin as an edge and end as a screw and vice versa. In between it partakes of the character of both and is spoken of as having a screw component and an edge component. However, the rules which govern the motion of the two types of dislocation are different and this is one of the reasons why the behaviour of real dislocations, which are usually lines curved in three dimensions, is very complicated.

The study of dislocations is now an elaborate and well-supported science in itself which has undoubtedly thrown a great deal of light upon the behaviour of solids in general and of metals in particular; to a considerable extent we now understand why metals behave as they do. On the other hand it cannot really be said that the knowledge of dislocations has led directly to any radical improvements in the mechanical properties of materials. As far as metals are concerned it does seem rather as if most of the possible important improvements have already been made by traditional and empirical methods and that the role of dislocation theory has been to explain the reasons for the improvements afterwards.

The energy of dislocations and the work of fracture of metals

Although it often requires only a small stress to move a dislocation through the body of a crystal – so that the strength of highly ductile metals is often very low – yet it will be realized that both the screw and the edge dislocation involve the existence of very high strains and distortions among the atoms in their immediate neighbourhood. Thus a considerable amount of strain energy is necessarily associated with every dislocation; this is known as ‘the energy of the dislocation’. This energy, which does not differ very greatly between edge and screw dislocations, can be calculated quite easily and turns out to be about 10^{-9} Joules for each metre of dislocation length for most metals.

This amount of energy may not sound very much but it is to be remembered that, when a metal is extensively sheared, enormous numbers of new dislocations are created, in fact about 10^{16} per square metre. Thus the amount of energy stored in the dislocations in a cubic metre of highly strained metal is about 10^7 Joules. If we suppose the metal to be distorted to a depth of about one centimetre when it is fractured, which is roughly true, then this corresponds to a work of fracture of about 10^5 J/m²,* which is in fact the case for metals like mild steel. So everything adds up very nicely and that is where the work of fracture of a metal goes. Thus the dislocation mechanism not only acts as a crack-

stopper, it also provides a very high and useful work of fracture.

The observation of dislocations

However plausible and intellectually satisfying a scientific hypothesis may be it remains an abstraction without subjective reality to most people unless one can actually touch or see it. Indirect or mathematical proof is not enough. Heat is a case in point. Everybody knows, from elementary physics, that the temperature of a substance is due to the motion of its molecules which are in perpetual but highly irregular movement. However, since one is also told that molecules are far too small to see and since the sensations of heat and cold do not in any way resemble that of moving particles the idea of heat as molecular motion is usually not very real to us.

The botanist Brown discovered in 1827 that fine particles of pollen in certain flowers appeared under the microscope to be in perpetual dancing motion. The Brownian movement is most easily seen by making a suspension of fine scraps of solid in water. This can be done with ordinary Indian ink or with the water-colour gamboge. A drop of this can be put on a microscope slide, preferably covered with a cover-glass, and observed with a fairly high magnification in an ordinary optical microscope. The finer particles can be seen to be spinning and dancing in a most erratic jig for as long as one cares to watch them. What is happening is this. The particles themselves, which are perhaps a micron across, are a few thousand times larger than the molecules of the liquid which surrounds them. These molecules are rushing hither and thither in a thoroughly random way. The particles of ink or gamboge are therefore being jostled in a rough and irregular manner. For the smaller particles these jostlings do not necessarily cancel out, as they do for large particles, and so the little particles are pushed or kicked around in a fashion which is visible in a quite ordinary microscope.

Once one has watched the Brownian movement one's apprehension of the *nature* of heat will never be the same again. It is not that one can be said to have learnt anything in an objective scientific way but rather that one has come to terms with the kinetic theory of heat at a subjective level. It is the difference between having a sunset described and seeing one.

It is very much the same with dislocations. What began as an abstract hypothesis has become a very tangible phenomenon. What are the ways of observing a dislocation? Well, firstly one can etch it. As we have said mechanically strained bonds are more easily broken by chemical and physical means than unstrained ones. Thus one can prepare etches, usually acid brews, which will attack dislocations where they emerge on the surface of a crystal, in preference to the surrounding material. This produces a series of little pits which are usually easily seen in the optical microscope. This is a very common experimental technique and the expert can draw quite extensive conclusions from the series of pock-marks produced in this way on the surface of a crystal. One trick is to split a crystal in two. Any dislocations existing in the crystal before the experiment and which cross the cleavage surfaces will naturally be the same for both cleavage faces. One half of the crystal is selected as a control and etched immediately, thus showing up the pre-existent dislocations. The other half is distorted or otherwise experimented upon before it is etched. By comparing the etch-pits on the two surfaces one can see which dislocations were generated under the experimental conditions and also which have moved.

Etching is useful but it cannot be called a direct observation of the dislocation itself and so is perhaps not subjectively very satisfying. The next step in this direction was taken by Dr Hirsch in the Cavendish Laboratory, Cambridge. Very thin metal films are practically transparent in the electron microscope, but any distortion of the crystal lattice may show dark. The line of a dislocation thus shows as a dark line on a white background. So far so good, but one wants to see them move and it

takes a stress to do this. It is not easy to apply a direct mechanical stress to films thin enough to be transparent to an electron beam. Hirsch however used the heat of the electron beam itself to expand the film and thus to stress it. This worked very well and he was able to film dislocations in motion. The impact of this film is considerable. The dislocations give an uncanny impression of scurrying mice.

In Hirsch's pictures, however, there was no question of seeing individual molecules or the three dimensional chequer-board of the crystal lattice. Hirsch's dislocations were simply moving black lines of strain on a white or grey ground. What we really want to see, I suppose, is a layer of molecules coming to an end in the crystal lattice. After all, if one saw a course of bricks doing this in a brick wall one would be highly surprised. However, in order to see a dislocation in a crystal lattice one must first see the crystal lattice.

Now in metals and in the majority of ordinary crystals the lattice spacing is about two Ångströms. At the time I am talking about, around 1955, the very best resolution of an electron microscope was about ten Ångströms so, in the ordinary way, there was no hope of resolving the layers in normal crystals.

Jim Menter at Hinxton Hall, near Cambridge, got over this difficulty by making and using thin crystals of a substance called platinum phthalocyanine. This is a flat, roughly square, organic molecule about twelve Ångströms across. In the middle of the square is a hole, and in the hole, in the case of platinum phthalocyanine, is an atom of platinum. (Copper phthalocyanine is a first cousin, the synthetic pigment Monastral Fast Blue, familiar in the blue paint on innumerable front doors.) In the crystal the flat molecules stack so that the lattice spacing is about twelve Ångströms and in the middle of each row of molecules is a line of heavy platinum atoms, standing out from the light atoms of the surrounding organic molecule. There are thus lines of platinum atoms in regular crystalline array, but spaced twelve Ångströms apart instead of the normal two. The organic part of the molecule may be regarded as a transparent padding or spacer keeping the dense, opaque, platinum atoms separated.

By adjusting the microscope to give the best resolution it proved possible to resolve the lattice of the phthalocyanine crystal. The result looked like rather woolly charcoal stripes on a lighter grey background very like the lines on a television screen. The first impression was that of the incredible regularity of this tiny scrap of crystal. On big enlargements the innumerable fuzzy black stripes extended perfectly straight apparently for ever and there were an enormous number of layers, millions upon millions of molecules, each one perfectly in its place.

Many pictures were needed before, after diligent searching, an edge dislocation was found. It looked exactly like the diagrams people had been drawing for twenty years. One dark fuzzy stripe came to an end and the others came together to close the gap (Plate 14). Jim Menter was able to send this photograph to Sir Geoffrey Taylor in time for his seventieth birthday.

To those of us working at Hinxton at the time, these pictures, coming wet from the darkroom, had a numinous quality not far short of a religious experience. A visiting Russian scientist looked at them for a long time and then he said 'You are looking up zee trousers of God.'

Jim Menter's visual revelation of the crystal layers and their dislocations by means of the electron microscope is satisfying and has become famous. There is however another approach with a strong subjective effect. As we said in [Chapter 4](#), David Marsh devised a most sensitive tensile testing machine for whiskers and other fine fibres. This machine can detect extensions of as little as four or five Ångströms, which is about the resolution of a modern electron microscope. The shear slip movement caused by a single dislocation is about one Ångström and therefore cannot be measured by the machine. A dislocation source however releases sufficient dislocations to provide from one hundred to about five hundred Ångströms movement and thus can easily be detected by the Marsh machine.

Now if we take any ductile material, such as a soft metal, and pull an engineering-sized test-piece we shall get a load-extension diagram such as [Figure 5](#), a smooth curve of a type very familiar to engineers and metallurgists.

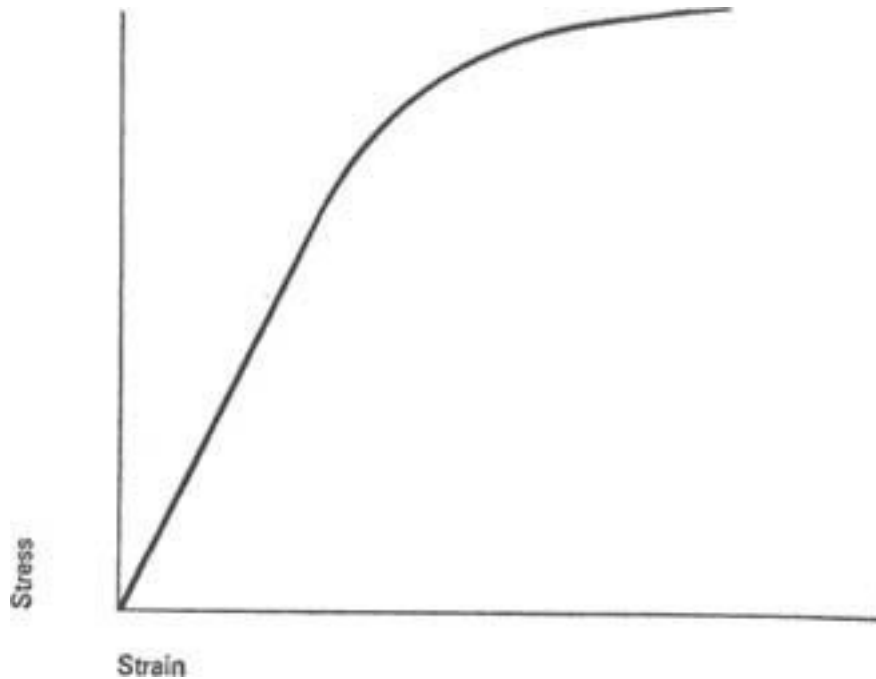


Figure 5. Normal macroscopic load-extension curve for a ductile substance.

If we now take a really thin but ductile test piece, such as a large whisker, and test it in the Marsh machine, we get a load extension diagram which is something quite different. A typical example is that in [Figure 6](#). Here we have an elastic extension interrupted by the sudden operation of sources. These sources operate quite erratically and the slip they produce is virtually instantaneous. The load extension diagram therefore has the form of a series of steps. What is happening is that, at each level of stress there are dislocation sources almost ready to give birth. What triggers them into doing so is a random thermal shove, just like the shove or jostle which pushes the particles around in Brownian movement. In a large specimen the same thing is happening but in so many places and so frequently that the gross effect is that of a smooth curve.



Figure 6. Similar material tested on a fine scale in the Marsh machine. Plastic extension is broken down into steps, each of which corresponds to the operation of a dislocation source.

With a small specimen in the Marsh machine the complete randomness and suddenness of the movements yet again impresses upon one the reality of dislocations.

Creep and temperature resistance

The consequences of this upon the behaviour of metals in service are fairly obvious. Well below the elastic limit or yield point, that is to say well within the Hookean region of the stress-strain curve, the elongation of the material is unaffected by time and we might subject it to a stress for centuries if need be without causing any change in strain or any deterioration. Near to the limit of elastic behaviour however the material becomes markedly affected by both time and temperature. As we have seen, even at room temperature random thermal pushes will activate dislocation sources so that plastic strain accumulates with time: the material gets longer and in some cases may break. Thus we cannot really specify the strength of such a material unless we also specify the rate of loading or say how long the load is to be left on for. Structures like suspension bridges which are loaded for many years on end must therefore be designed to lower stresses than structures which are only stressed rapidly and occasionally. In practical metals there is often *some* creep even at quite low stresses and this has to be watched where dimensional accuracy is important.

As we might imagine, the stress at which creep becomes serious is very dependent upon temperature and this is a factor which frequently governs the design of machinery and especially of heat engines such as gas turbines. On the whole the hotter the hot parts of an engine can be run the more efficient the engine is likely to be, especially in the matter of fuel economy. Since iron melts at over 1,500° C. and other metals at even higher temperatures it might be thought that there would be no great difficulty in running engines at temperatures of, say, 1,200° C. which are well below the

melting point. This is very far from being the case.

It is true that iron does not melt below $1,500^{\circ}\text{C}$. but then the concept of melting implies that the metal flows under its own weight which is usually a negligible stress. As soon as we introduce a mechanical stress, however, even a small one, flow and eventually fracture occur at far lower temperatures. Even for comparatively rapid loading, that is to say loading as rapid as can conveniently be applied in a testing machine, the strength is drastically reduced. Furthermore, when components are subjected to prolonged stress in one direction, such as the centrifugal stress in turbine blades, we have to be very careful indeed about the creep.

For 'short-term' loading the strength of a metal varies with temperature much like [Figure 7](#), in other words the material dies with a whimper not a bang. As a very rough working rule, which is true for most metals, one cannot work a metal at a temperature which is higher than half its melting point in degrees Kelvin. (Degrees Kelvin = degrees Centigrade + 273. See Appendix.)

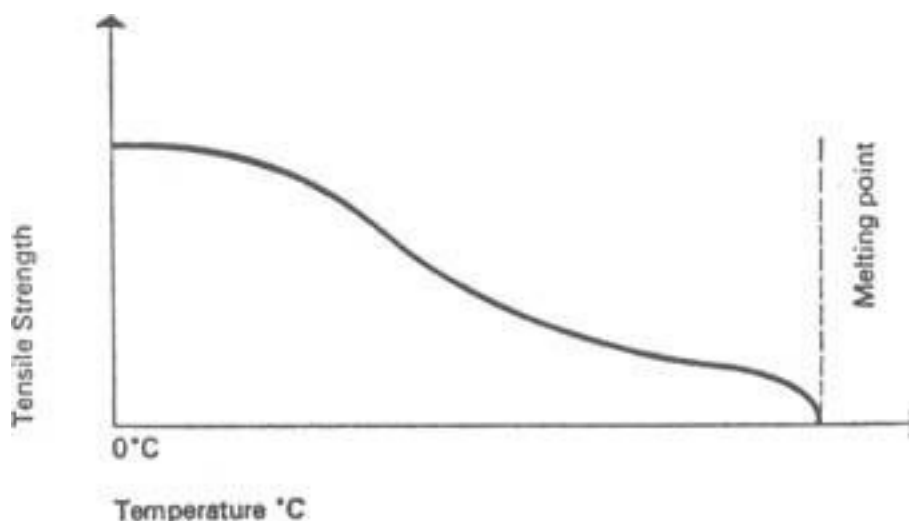


Figure 7. Most metals get weaker when they are heated and the weakening effect begins to operate surprisingly early. Thus although the melting point of iron is 1535°C . many steels cannot be used above about 300°C .

The way to get the operating temperature of an alloy up is, of course, to impede dislocation movement by one means or another. The difficulty is that most of the additions which one might use for this purpose tend themselves to become mobile. (Naturally one must avoid oxidation of the surface of a high temperature alloy but the additives introduced for this purpose may conflict with those intended to prevent creep). The subject is an extraordinarily difficult one and metallurgists have probably done well to achieve working temperatures as high as $950\text{--}1,050^{\circ}\text{C}$., which can just about be done with the recent very special turbine blade alloys. The normal run of engineering steels have to be operated far below this temperature.

It is true that dislocations are largely immobile in many ceramics at temperatures up to about $1,500^{\circ}\text{C}$. but then these materials are usually dangerously brittle at lower temperatures. Ceramics are very suitable therefore for static applications such as furnace refractories where they can be operated under load at temperatures surprisingly close to their melting points (this is important in steelmaking for instance) but they are usually unsuitable for moving applications such as machinery.

Note: for a discussion of 'creep' and 'fatigue' effects in metals, see *Structures*, Penguin Books, 1978.

Chapter 10 Iron and steel

Hephaistos among the Satanic Mills

'I will send them the locomotive to be the Great Missionary among them.'

George Stephenson (1781–1848).

Simply because wood and masonry have always been the commonest materials of construction and metals are relatively recent intruders in technology and engineering we are peculiarly conscious of the role of metals as innovators although, as we have seen, they are still in a minority on a tonnage basis. However, metals, especially iron, were remarkably well suited for making the sort of machines which were both the curse and the glory of the Industrial Revolution. It was the development of means of making and working iron cheaply and in quantity which made the spread of mechanization possible. Steel, as we know it, only came in as a cheap material in the second half of the nineteenth century when the main impetus of the revolution was over.

Important as iron was, it was only used to the smallest practicable extent in most of the early machines, even in steam engines. In Fulton's first steamship on the Hudson River even the boiler, incredibly, was of wood; the actual heating of the water took place in a separate arrangement of iron pipes. Even the Americans thought that this was going rather far, although the river steamers which carried the bulk of the American inland traffic until after the period of the Civil War used wood in their machinery, as well as in their hulls, to a degree which a modern engineer finds hard to credit.

Broadly speaking there are two problems with all metals – extraction metallurgy, the separation of the metal from its ores; and physical metallurgy, which is how to get the metal into the most useful condition of hardness, strength and toughness. As we have seen, a pure metal is usually very soft so that physical metallurgy consists, notionally, of impeding the dislocations to just such an extent that the metal is strengthened without being embrittled. Technologically however the processes of extraction metallurgy frequently do not yield the virgin metal in a pure condition so that both extraction and the subsequent processing have to be considered together.

In their chemical and technical details the treatment of the different engineering metals varies widely but in every case the physical objective remains the same – the control of dislocation movement by adjusting the size and structure of the metal crystals (dislocations can cross grain boundaries but they do so with some reluctance) and by adding other substances and 'impurities'. Complex alloy systems may ensue in which it is hoped that the diversity of crystal structures will impede the dislocations by just the desired amount. Very small particles, even single impurity atoms, will 'pin' the forward movement of a dislocation line wherever it meets them. The stress required to bow out and eventually to detach the dislocation line between the pinning points is calculable and depends upon the separation of the points and therefore this is a useful and powerful means of control. Almost anything which is added to a metal will affect its mechanical properties for good or for bad – sometimes for both since one has to be careful that an additive which is beneficial when dispersed does not end up concentrated around the grain boundaries where it may have a serious weakening effect as we saw in [Chapter 4](#).

When we consider the number of ductile metals and also the number of hardening mechanisms which are available the permutations and combinations of physical metallurgy are very numerous and the subject is a most complex one. To the non-specialist, however, who is chiefly interested in principles and in the end results, the consequences of these processes are very much to a pattern.

Many of the engineering metals are listed in [Table 1](#) of [Chapter 8](#) where it will be seen that –

although there is a very considerable range of specific gravities, from about 10·5 for molybdenum down to 1·7 for magnesium – for all the metals in that table the Young's modulus divided by the density of the metal comes out to an almost constant figure, namely $3\cdot9 \times 10^6$ p.s.i. (25,000 MN/m²); there are a few common metals not in the table, such as copper and brass, which have specific moduli which are a little lower than this. There is no ductile metal with a higher stiffness for its weight and thus nearly all the useful metals give one in stiffness exactly what one pays for in terms of weight, neither more nor less.

As has been said, all these metals are very soft and weak when in the pure state and it is the business of metallurgy to raise the strength and hardness without rendering them unduly brittle. Seen as *strain* the achievements of metallurgy are remarkably constant. Usually the maximum *elastic* strain which can be imparted without unduly embrittling the metal is around 1·0 per cent, give or take a little. However engineers generally regard metals in this state as having too little ductility for most purposes and for the majority of uses they are satisfied with a maximum elastic strain between 0·25 per cent and 0·5 per cent, when the elongation is likely to be around 50 per cent to 60 per cent.

Very, very roughly therefore all the metals may be taken as constituting a family with similar specific stiffness, specific strengths and elongations. This generalization is only approximately true and it is not quite fair to metallurgists who do, as a result of their labours, continue to attain rather better combinations of specific strength and toughness (specific stiffness they can do nothing about) although the limits are fairly narrow. What metallurgists have been more successful at is making metals retain their room-temperature properties up to elevated temperatures. For many uses of course this is more important than getting more strength at room temperature.

It is not necessary to describe here the special metallurgies of all the various engineering metals. There are innumerable books on the subject including an excellent general review of technical metallurgical processes in *Metals in the Service of Man* in the Pelican series. However, the great social and technical importance of iron and steel renders some account of these materials necessary. In attempting it I am only too well aware of the size and difficulty of the subject. Perhaps before doing so I should have sacrificed to Hephaistos, smith and purveyor of weapons to the Olympians, the only technologist to have reached the rank of a major God.

Iron

The elementary facts about iron and steel tend to be obscured by the jargon of the trade. First of all there is a confusion about what is meant by 'iron' and 'steel'. Naturally in both cases the predominant chemical element is iron. 'Iron' by itself usually means iron in the relatively pure chemical form. 'Cast iron' on the other hand means iron containing nearly as much carbon as it will hold, perhaps about four per cent. 'Wrought iron' is different again and is usually a special sort of fairly pure iron containing glassy inclusions. 'Steel' usually means iron with a little carbon in it, generally less than 1·0 per cent. The implication is that in steel the content of carbon or other alloying element is under fairly close control. Since the mechanical behaviour of iron is profoundly influenced by very small amounts of carbon and other additives the control which is exercised over steel is important. 'Alloy steel' is usually a generic term for steels which are alloyed with elements other than carbon. Alloy steels, incidentally, are generally a good deal more expensive than carbon steels.

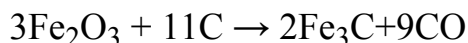
The strength of iron and steel is governed by the extraordinary sensitivity of dislocation movement within the iron crystal to quite small traces of carbon. Of course, dislocation movement was not understood until recently and even the comparatively simple chemistry of the extraction metallurgy of iron was not appreciated until fairly late in the Industrial Revolution. However, the practical

metallurgy of iron was worked out without benefit of these ideas and it remains today largely a traditional process. Just as, in the textile trade, spinning and weaving go back to prehistoric times and all that the most advanced factories have done is to mechanize and rationalize the simple hand process, so the steel trade operates techniques which are sophisticated versions of immemorial practices. On the whole therefore the iron and steel making processes are best understood in their historical contexts.

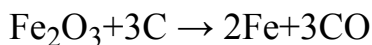
Apart from his scientific ignorance, the biggest difficulty that the primitive metallurgist had to encounter was that of getting a high enough furnace temperature. In a modern steelworks the availability of high and controlled temperatures enables short cuts to be taken which by-pass a number of ancient procedures. Naturally everything is on a much bigger scale and a modern furnace may produce a thousand tons a day where the medieval smith would have been content with a hundredweight.

Unlike bronze which can be melted at about 900° to 1,000° C. – which is just within the reach of an ordinary wood fire – pure iron melts at 1,535° C. which for long centuries was out of the range of human technology. However, the addition of quite small proportions of carbon lower the melting point of iron considerably and, of course, carbon is readily available when a carbon fuel, such as charcoal, is used to heat iron ore. The lowest melting temperature attainable in this way is about 1,150° C. which occurs when 4 per cent to 4½ per cent of carbon has diffused or seeped into the metal.* If a mixture of iron with excess carbon is heated to 1,150° C. therefore, it will melt. Such a temperature was not very easy for primitive people but it could just about be attained by a blown charcoal fire.

Iron ores are usually oxides of iron, typically haematite, Fe₂O₃, which is so called from its blood-red colour. The iron oxides, incidentally, are used as pigments in painting; Venetian red is largely Fe₂O₃. The first thing to do is clearly to get rid of the oxygen. When the ore is heated with charcoal or coke this occurs almost automatically:



The oxygen goes off with some of the carbon as carbon monoxide gas, leaving iron carbide or cementite, a compound containing 6·7 per cent of carbon. However in practice we also get the reaction:



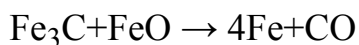
So some pure iron is produced as well as cementite and we usually end up with a mixture of iron and iron carbide containing, as a whole, 4 per cent or so of carbon. Iron and iron carbide are mutually soluble and it is this solution which forms the liquid whose low melting temperature was the key to the extraction of iron in primitive furnaces – it is also what the modern blast-furnace produces.*

Iron ores do not consist solely of iron oxide but contain various mineral impurities, mostly oxides of other metals. These have usually, by themselves, also a high melting temperature and if the ore were heated solely in contact with a carbon fuel there would be a danger that it would not melt properly. To ensure that it does so a ‘flux’ is added, usually lime or limestone. This lime performs exactly the same function as it would in glass-making, that is to say it reduces the melting temperature of the non-ferrous oxides by forming with them a glass with a lowish melting point. This is called slag. In commercial practice it is a dirty brown or grey substance which is nowadays

sometimes made into fibres and sold for insulating houses.

What we are apt to get at the bottom of the furnace is therefore a mixture of iron, iron carbide and slag. In the most primitive processes this mixture could hardly be melted and was extracted as a cake or 'bloom' containing bits of charcoal and other impurities. Apart from the question of these impurities, iron carbide is a brittle substance unsuitable for making tools and weapons. This is because, while crystals of nearly pure iron are held together by metallic bonds which favour the passage of dislocations, crystals of iron carbide are held together by bonds which are partly covalent in character so that dislocations do not become appreciably mobile until a temperature of 250° C. or so is reached. The metal in the fresh bloom is thus malleable when hot but brittle when cold.

The early smiths therefore took the crude iron from the extraction furnace and, after reheating to some temperature perhaps about 800° or 900° C, they hammered it. Originally the iron was 'wrought' or hammered by hand, with immense labour, but latterly this was done by water power, supplied by 'hammer ponds'. The hammering had two effects. It squeezed out mechanically most of the impurities and some of the slag and it also reduced the carbon content of the iron. This occurred in the following way. Iron heated in air to a moderate temperature forms an oxide scale, the commonest form of which is FeO. Iron which is heated and beaten out flat thus becomes covered with oxide and, when, after it has been beaten into an elongated form, the smith doubles it over like pastry and beats it out again, the film of oxide is included between the layers of hot metal with which it is hammered into intimate contact, so that the simple reaction occurs:



In high-grade work the beating out and folding over were repeated, sometimes for thousands of times. This is why swords show a delicate wavy pattern, each line corresponding to a thin layer of metal and to a beating operation. If the job was properly done almost the whole of the carbon was removed, leaving iron which was nearly pure except for a little silicon which was on the whole beneficial. This 'wrought iron' contained however streaks and strings of slag which again were to some extent beneficial. This was because the purified iron was now generally too soft and the glassy filaments limited flow to some extent. Furthermore, the rust resistance of wrought iron is generally excellent. This is partly due to the purity of the iron itself but many people hold that the initial film of rust is anchored to the surface of wrought iron by means of the slag inclusions so that it remains to form a protective skin instead of dropping off to make way for fresh corrosion as it generally does with steel.

Wrought iron direct from the anvil was too soft for weapons and cutting tools and therefore for these purposes it had to be hardened by putting back a certain amount of carbon, at any rate into the surface. This was done by a process almost identical with that which is still widely used, that is to say 'case hardening'. The sword or other weapon was packed inside a mass which consisted essentially of carbon but which often also contained a number of secret ingredients of dubious efficiency. It was heated in this environment for a period so that carbon diffused into the surface to a depth of perhaps half a millimetre to a millimetre.

This surface carbon hardened the metal considerably but, to get the best effect, the 'steel' might be quenched by cooling it suddenly in a liquid. The exact mechanism of this quenching is complicated. Briefly, the hot steel consists of 'austenite' which is a solution of cementite in iron which is unstable at room temperature. The way in which the austenite parts with the excess carbon when it is cooled depends on the details of the cooling process.

If cooling is comparatively slow the result will generally be 'pearlite', so called from its iridescent appearance in the microscope caused by its banded structure. Pearlite consists of alternate layers or

laminae of pure iron (ferrite) and iron carbide (cementite). In this form and because of its regular structure, the steel is tough and fairly strong but not particularly hard. However, if the austenite is cooled very quickly the result will be mainly 'martensite'. Martensite is yet another variant of the iron-carbon crystal which has the carbon atoms squeezed in in such a way that dislocation movement is impossible and so the crystal is extremely hard. On cooling, austenite transforms to martensite at a very high speed indeed, about three thousand miles an hour, and so to get as much martensite as possible, it is necessary to quench as quickly as one can.

Quenching can be done in water and it usually is but, historically, there seems to have been a preference for using urine and other biological liquids.* It turns out that this practice really was beneficial for two reasons. The first reason is that the cooling was rather quicker. When water is poured on hot metal a film of steam is formed so that the liquid water does not actually touch the metal and the heat transfer is consequently bad. This is easily demonstrated by dropping water on the hot plate of an electric cooker. With urine, however, crystals are formed on the surface of the metal as the water evaporates and these tend to bridge the steam gap and improve the heat flow. Furthermore, urine contains urea and ammonia both of which are nitrogen compounds. There was therefore some degree of nitriding of the surface, that is nitrogen diffused into the iron. This formed hard needle crystals of iron nitride, Fe_2N , and, also, individual nitrogen atoms insinuated themselves into the iron lattice as what are known as interstitials. Interstitial atoms pin dislocations. As a matter of fact the degree of nitriding effected during quenching is very small. In modern commercial practice periods of two or three days in urea or ammonia are needed, for this reason it is a rather expensive treatment, used where only the best will do.*

It will be noticed that the preparation of iron and steel consists of a series of approximations, each process going too far and being in turn corrected. Thus we first make cast-iron or pig iron which is too hard and contains too much carbon, then we generally remove all the carbon and find that the iron is too soft so that we have to put some carbon back again. This iron or steel, as has been explained, is generally 'quenched' by cooling suddenly in a liquid when we want a hard tool or weapon. Quenched carbon steel (or carburized iron) is often too brittle and so yet another and this time final process is often needed, that is tempering.

For tempering, the quenched metal is reheated to some temperature between about 220°C . and 450°C . and allowed to cool naturally. This softens the steel to some extent by transforming some of the martensite into a softer, more ductile structure. The higher the tempering temperature the greater the effect. Traditionally the temperature for tempering was judged by the colour of the oxide film found on the surface of the metal which varies from yellow through brown to purple and blue. It will be obvious that simple carbon steels of this kind cannot be operated at high temperatures without spoiling their properties.

Cast iron and pig-iron

As we have said, the earlier extraction furnaces could barely melt the iron which they made and this iron was usually removed from the bottom of the furnace as a rather messy cake or bloom. By the middle of the fifth century B.C., that is about the time of Pericles, Greek furnaces were able to melt the iron properly and so run it out into moulds as 'cast-iron'. Although cast iron was available through the classical period, the uses for such a brittle material were limited and it does not seem to have become economically important. Most classical iron is wrought iron.

With the dark ages the temperature of furnaces fell and cast iron does not seem to have been made again in Western Europe at least until the thirteenth century. It really found its métier however after

the invention of gunpowder. The earliest cannon (the word comes from *kávva*, a reed or bamboo, and is connected with the ecclesiastical sort) were made from wrought iron staves bound with iron hoops, like a barrel. However, as the capacity of furnaces and the skill of ironfounders increased cannon began to be cast. The early cast guns burst nearly as often as the built-up wrought iron ones but they must have been much cheaper. * In its traditional form cast iron is not only very brittle but it also contains little layers or veins of carbon in the form of graphite which act as built-in cracks. As a result, cast iron was both weak and unreliable in tension. It was therefore really a very unsuitable material for a pressure vessel like a gun barrel. However until about 1860 it was the only economic one available, brass or bronze being usually too expensive. In consequence, guns were extremely heavy; one throwing a thirty-two pound shot, such as the main armament in H.M.S. *Victory*, weighed between three and four tons. The weight of the guns therefore formed about ten per cent of the displacement of a warship. Because of her age, *Victory* can no longer bear the weight of her own guns and they have been replaced with wooden replicas.

At one time it was usual to cast iron directly from the blast furnace but this is not very often done today. This is partly because blast furnaces have become much bigger and it would not be economic to cast iron from them in penny packets, and partly because iron cast straight from the blast furnace is hard, brittle and weak. Nowadays, it is usual to cast the whole of the production of the blast furnaces as pig-iron. Part of this goes on to be turned into steel and part is remelted and its composition modified so as to produce cast iron with more acceptable properties. By taking thought, it is now possible to produce cast irons which are reasonably tough and have quite good tensile strengths. As it is generally cheaper to make a complicated shape by casting it in iron than by forging it in steel there is still a considerable incentive to improve cast iron which is nearly always used for the cylinder blocks of car engines, for instance, because of their elaborate shape.

In England iron was originally extracted with charcoal in the forests of the Weald and later in Shropshire, but during the first half of the eighteenth century the problems of using coke in place of the increasingly scarce charcoal were gradually solved. The change to coke was fairly complete in England by about 1780 although it did not take place on the Continent until much later. This not only enabled more iron to be extracted more cheaply but it was one of the reasons why the iron trade gradually migrated to what we now call the 'Industrial North'.

Thus, by the late eighteenth century large castings, up to about 70 feet long, were available in England quite readily and cheaply and they could generally be transported by water. These castings however were very weak in tension by modern standards and so they had to be used in applications where the stresses were predominantly compressive. An obvious use was bridge-building. Here the iron could be used in compression to make arches, much like stone arches. A stone arch is built up from wedge-shaped stones called 'voussoirs' each of which has to be cut laboriously by hand. The early iron bridges were made from cast voussoirs in the form of open or lattice frameworks which fitted together like a stone bridge.

The famous Iron Bridge, erected over the Severn at Coalbrookdale in 1779, was the first large iron structure and is more or less of this type. It has a span of just over 100 feet, a total length of 196 feet and rises 50 feet. It contains 378½ tons of iron and was built in three months. It cost £6,000 to build and, even at the values of 1779, this was much cheaper than such a bridge could be built in any other material.

Although the Iron Bridge was successful, it gave trouble from its very virtue. An arch bridge, like an arch in a cathedral, thrusts outwards at the base, and whereas in a church this thrust may be opposed by buttresses, in a bridge the outward forces are balanced by the opposite push of the masonry and earthwork approaches. We are not apt to think of cast iron as a lightweight material, but

compared with traditional building materials it is so. As a result, the arch at Coalbrookdale showed, perhaps for the first time in history, the opposite fault to that of stone arches and domes. It was too light to oppose the inward thrust of the approaches whose weight, tending all the time to slide into the river, forced the iron arch inwards and upwards. For this reason the conventional approaches had to be replaced by cast-iron subsidiary arches. This must have been an early case of that difficulty of putting new wine into old bottles which constantly troubles materials engineers.

Puddled wrought iron

After coke began to be used in mechanically blown blast furnaces crude cast iron became relatively cheap and plentiful though its uses in this form were limited by its brittleness and low tensile strength. For most purposes the stronger and tougher wrought iron was needed and as long as this had to be hammered out laboriously, wrought iron remained, even with water-driven hammers, a scarce and expensive substance. If one had to pick upon any one material as being the key to the Industrial Revolution, then that material must surely be puddled wrought iron. Steel in its various forms did not appear in quantity until much later and its social and economic implications were less important.

Puddling, at least in any practical form, seems to be due to Henry Cort (1740–1800) who patented the process in 1784. Cort invented a coke-fired furnace in which the chimney ran for a short distance horizontally before turning upwards in the usual way. On the bottom surface of this horizontal section was a basin shaped hollow in which could be melted a pool or puddle of pig-iron. This puddle of molten iron could be stirred through ports in the side of the furnace by long iron tools called ‘rabblers’, shaped rather like a hoe.

When the pig-iron was molten the puddler stirred iron oxide into it with his rabble. This oxide, often the scale from the rolling mills, when well stirred reacted with the carbon in the pig-iron in much the same way as it did in the hammering process, removing most of the carbon as carbon monoxide. The evolution of gas agitated the bath into a ‘boil’ which drove most of the slag out of the furnace. As the carbon was removed, so the melting point of the iron increased, and, as the furnace temperature was around 1,400° C, the iron began to ‘come to nature’ or to grow pasty. It was then rolled up into a ball weighing about a hundredweight and removed from the furnace. Although puddling was very hard work a puddler could puddle about a ton of iron a day which was perhaps a ten-or twenty-fold increase on the hammering process. Puddling was a very skilled trade and for many years after the Napoleonic wars English puddlers earned good money by travelling around on the Continent giving instruction in puddling.

When puddled, the hot pasty iron was usually passed through rollers which, after many passes, squeezed it into plates or rods. In the process the hot surface oxidized and the resulting scale fell off as the iron cooled and was fed back into the puddling furnace. As will be seen, the whole process was chemically equivalent to beating out the iron in the old way but was considerably more productive. Nowadays puddling is almost extinct because, even with mechanization, the output of a puddling furnace can only be raised to about a hundred tons a day whereas, by blowing air through the iron in a Bessemer converter, such as is used for making steel, an output of about 800 tons per day is possible. In any case the market for wrought iron nowadays is limited since steel is both cheaper and stronger.

Many of the problems of engineering are really concerned with how much strength and how much toughness one can get for how much money. The whole of the Industrial Revolution has to be seen and judged against a background of the gradually falling price of wrought iron and mild steel. This is very clearly illustrated in the history of the railways.

Railways began as colliery tramways in which wooden rails were laid to ease the passage of horse-

drawn waggons. Towards the end of the eighteenth century many of these wooden rails were replaced by cast iron ones which lasted longer and showed less rolling friction than wood, so that a horse could pull four or five loaded waggons on the level. For the transport of minerals this was considered quite satisfactory and probably no further modifications would have been made had it not been for the sharp rise in the cost of horse fodder at the time of the Napoleonic wars. This turned the minds of colliery owners to the possibility of using the coal which they produced themselves at 3/9d. per ton as a source of tractive power. The pit owners, of course, already used steam engines extensively for both pumping and winding but these stationary low-pressure (3 p.s.i.) engines were far too large and heavy in relation to their power output ever to become mobile.

The inventor of the high-pressure locomotive, and therefore the true father of railways, was Richard Trevithick (1771–1833), a genius who died in poverty, unlike the Stephensons who both lived and died in the odour of great prosperity. Trevithick produced a high-pressure (50 p.s.i.) locomotive in 1804 and another in 1805 (Plate 15). Both were successful as locomotives. It was the track which let them down.

In spite of the relative costs of hay and coal, locomotives were expensive both to build and to run. The annual running costs of an engine, including capital charges and so on, were estimated at a little under £400, which of course was far more than that of a single horse, even if the cost per horse power was less for the engine. To be economic the locomotive must therefore either draw a greater load than the horse or else draw the same load faster. Since horses were already working along the line it was impracticable to increase the speeds very much and hence the engine must be made to pull more trucks.

As we know there is no particular difficulty about getting enough adhesion between smooth metal wheels and rails to draw any desired load, always provided that the weight on the driving wheels is sufficient to prevent them from slipping and this was where the real impediment lay. The existing cast-iron rails were just sufficiently strong to support reliably the three-ton trucks in use but an engine weighing only three tons itself could not be made to draw thirty or so trucks of the same weight without slipping. If the engine were made heavier then it broke the cast-iron rails so frequently as to be uneconomic. The failing of Trevithick's engines was that they broke rails in a wholesale manner and so they had to be converted to stationary uses.

After this the story of the development of the early locomotive is that of a struggle for adhesion without breaking the rails. Part of the trouble was that the early engines were not sprung because no strong enough steel springs could be made. In consequence the load on the rails was multiplied at every jolt. Engines were built with eight driving wheels in order to spread the load (Plate 16), but one of the most popular solutions was to cast the rails with teeth which meshed with cogs on the engine like a modern mountain railway ([Plate 17](#)). These devices were troublesome and never worked really well.

George Stephenson met the spring difficulty by providing his engines with 'steam springs', that is by supporting the axles on pistons floating in cylinders filled with live steam, a suspension exactly similar in principle to that recently introduced for motor cars. However, because of the problem of sealing the pistons properly Stephenson abandoned steam suspension as soon as steel springs became available.*

In 1821 John Birkinshaw of Bedlington near Morpeth patented a method of rolling puddled wrought-iron rails of I section and one of his early customers was George Stephenson who was thoroughly worried about the track for the Stockton and Darlington line at the time. Birkinshaw quoted £15 per ton for his wrought-iron rails and, although this was more than twice the cost (£6–15) of cast iron, the effective cost per mile turned out to be the same because, the wrought-iron rail being

stronger, a lighter rail could be used. The length of Birkinshaw's rails was 15 feet which, it will be remembered, was the length of the forged bars made at Akragas in 470 B.C.

The American approach to the same problem a few years later was different. In many cases they seemed to have reverted to a system which was used in Scottish colliery lines about 1785. This involved laying a flat strip of wrought iron on top of a substantial wooden rail. This was used in America for some years and worked fairly well. The iron strip was however merely nailed or spiked to the wood beneath and from time to time the butt joints worked loose. When this happened the end of the strip might curl upwards under the weight of a train wheel and when this happened it could penetrate the floor of a carriage above it, sometimes with fatal results to the passengers.

Such tracks were replaced by the usual wrought-iron rails but for a great many years the American practice was to use rails of much lighter section than in Europe, supporting them by very closely spaced wooden sleepers. This habit of course reflected the cheapness of timber and the high cost of iron in America.

Although cheap steel became available about 1860 it took nearly thirty years to oust puddled wrought iron. In 1883 some seventy per cent of the pig-iron produced in Great Britain was puddled, and it is doubtful if more than ten per cent was turned into steel. By the 1890s these proportions were roughly reversed. The real reason why puddled wrought iron hung on for so long was that, although weaker, and sometimes more expensive than steel it was considered, with some justice, to be more reliable.

The first sensational success for the new Bessemer steel occurred when fast paddle steamers, such as the famous *Banshee*, were built in the early 1860s to run the Northern blockade into Southern ports during the American civil war. This they did with almost contemptuous ease, having a speed of twenty to twenty-two knots compared with the fifteen or so of the fastest ships of the Northern navy. Some of these vessels ended their days, comparatively recently, as passenger steamers on the Clyde. Although the saving of weight, by the use of steel, was very great, accidents occurred quite frequently and the British Admiralty would not build hulls in steel until about 1880. The use of steel for really large and important structures could not be said to have become established until the Forth railway bridge was built of open-hearth steel in 1889.

Steelmaking

The making of steel, especially under modern conditions, is an extraordinarily complicated business and only quite a brief outline can be given here. What we now call mild steels and carbon steels consist of iron having between 0.1 per cent and 0.8 per cent carbon content, little or no slag inclusions and with or without controlled small amounts of other elements such as silicon and manganese. What the traditional producer of wrought iron made however was iron almost free from carbon but containing extensive slag inclusions and also small but uncontrolled amounts of other elements. As we have said the biggest difficulties faced by the early ironmasters arose from the fact that, as they removed the excess carbon from the pig-iron, they also raised the melting point from about 1,150° C. to around 1,500° C., a temperature beyond the capacity of their furnaces. Thus slag could not be removed by melting and carbon could only be put back, to give the necessary strength and hardness, by carburizing the hot but still solid surface of the iron by blacksmith's methods.

However, throughout the eighteenth century the temperature of furnaces was slowly rising and about 1740 Benjamin Hunt found that he could melt wrought iron with a little added carbon in small batches of up to about 90 lb. in covered clay crucibles in a furnace. When this was done, the slag also melted and separated and rose to the top (because it was lighter), leaving molten iron containing a

little carbon, but still with its original quantities of impurities, underneath. The carbon content could be adjusted to give the desired strength and hardness and the resulting steel could be poured off, free from slag, into moulds.

Crucible steel was expensive, partly because it was made from the already expensive wrought iron, and moreover, since no purification or control of impurities – other than slag – took place, its quality was variable. Even so, it was generally cheaper and better than most of the smith-made ‘steel’ used in swords and it was used extensively in small quantities for tools of high quality.

Crucible steel had the advantage that, instead of making a tool or a weapon dead hard outside and soft inside, any required strength and hardness could be achieved right through. For some purposes however the steel was still carburized or ‘case-hardened’ to give a more durable cutting edge, as indeed is still sometimes done. Nowadays nobody would try to make plain carbon steel in this way, except experimentally, but small batches of expensive alloy steels are usually made in crucibles.

Bessemer or Mushet steel

Until the middle of the nineteenth century crucible steel remained the only steel available and the metals of large scale construction were still cast iron and puddled wrought iron. The production of cheap steel in large quantities was originally due to Henry Bessemer (1813–98) and Robert Mushet (1811–91). Bessemer was a prolific inventor with a strongly developed business sense. After doing well with a number of inventions such as the manufacture of ‘gold’ paint and the consolidation of graphite for ‘lead’ pencils, Bessemer was drawn to steelmaking by the publicity given to the weaknesses of cast iron guns during the Crimean war.

After various experiments Bessemer had the revolutionary idea of blowing air through liquid pig-iron to remove the excess carbon and other impurities. He took out his master patents in 1855 but, in its original form, Bessemer steel was of poor quality because it contained excessive oxides and sulphur. However, in 1856 Mushet took out his own series of patents for a very similar process which differed from Bessemer’s mainly in that the impurities which had not been burnt out by the air blast were controlled by the addition of something called ‘spiegeleisen’, a special cast iron from Germany containing manganese. It was the addition of manganese at the end of the blowing operation which ensured the success of the Bessemer process.

Bessemer steel is made in a contrivance called a Bessemer converter which consists of a pear-shaped crucible or container mounted on trunnions so that it can be tipped. It has no external means of heating. At the bottom of the converter are a series of holes or tuyeres through which air can be blown.

To operate the converter, the vessel is tilted so that its spout is under the outlet from a blast furnace and a charge of from five to thirty tons of molten pig-iron (that is iron at perhaps 1,200° C. containing about 4½ per cent of carbon and small amounts of silicon and manganese) is poured in. Since the converter is on its side the charge lies in the belly of the vessel and does not block the tuyere holes. Air is now blown through these holes and the converter is allowed to swing upright so that the air is forced to bubble through the molten iron. Under the conditions in the converter the air first oxidizes the manganese and silicon in the iron to form a slag which floats on top of the charge. The process is traditionally controlled by watching the colour and character of the flames produced in the mouth of the converter. At this stage they are short and reddish brown.

After a few minutes the manganese and silicon are fully oxidized and the air begins to remove the carbon; at this stage the flame changes to whitish yellow and becomes longer and more alarming. Finally, when all the carbon is eliminated, the flame drops and the blast is turned off. During the

blowing period the burning of the carbon, manganese and silicon, which together amount to about six per cent of the charge, produces a great deal of heat; enough not merely to raise the temperature of the charge to keep pace with the increase of melting point due to loss of carbon, but so much that it would be overheated were not a little scrap steel added to cool it – otherwise the furnace refractories would be damaged.

By the end of the blow we have what is called ‘blown metal’ or approximately pure iron in the converter and it is usually desired to put back some carbon and manganese and also perhaps silicon. This is done by adding solid carbon and the special form of cast iron – spiegeleisen – which contains a high proportion of these elements. Manganese is wanted in steel both for its own sake as an alloying element and also because it controls the sulphur which is not removed from the iron during the Bessemer process.

Sulphur is a great nuisance in steelmaking because it does not oxidize to SO_2 as one might expect, but forms iron sulphide, FeS , and this has the peculiarity that it is soluble in molten iron but not in solidified iron. As a result, on cooling, the iron sulphide separates out at the crystal boundaries and weakens the steel ([Chapter 4](#)). The addition of manganese changes FeS to MnS , which is insoluble in liquid steel and so passes into the slag. Manganese also reduces the solubility of oxygen in steel which again is beneficial because oxide particles also tend to end up at the crystal boundaries.

Bessemer described his process to a meeting of steelmakers in 1856 in a paper called ‘On the manufacture of malleable iron and steel without fuel’. Such was the enthusiasm of the audience and such was Bessemer’s reputation that £27,000 was immediately subscribed in advance patent royalties, after which the steelmakers went home to build themselves Bessemer converters.

As it turned out none of them could make satisfactory steel, for the original Bessemer process was sensitive to the kind of pig-iron which is used and moreover it requires some skill. Not unnaturally, Bessemer became exceedingly unpopular. He then built a complete working model of his converter in his laboratory in St Pancras and used it to demonstrate steelmaking to his licensees. As these demonstrations did more to show up the incompetence of the licensees than to improve Bessemer’s popularity, the agitation against Bessemer continued and no steelmaker would operate his process. In consequence, in 1859 Bessemer set up his own steelworks in Sheffield and made steel which sold extremely well, notably to the French and Prussian governments for the manufacture of guns.

The palpable success of Bessemer steel led steelmakers all over the world to seek licences and Bessemer received about one million pounds in patent royalties over and above the profits of his own steelworks. Those of Mushet’s patents which were connected with blowing air through iron were probably anticipated by a few months by Bessemer but Mushet’s patent on ‘spiegeleisen’ should have been valid and immensely valuable. Unfortunately Mushet forgot to pay the stamp duty when renewing the patent and thus extinguished his legal rights. In consequence Bessemer always refused to pay any royalties to Mushet and a long quarrel ensued. Towards the end of his life Bessemer paid Mushet an annuity of £300 a year.

It is difficult to quote representative figures to illustrate the economic effects of Bessemer steel. However, while in the 1850s steel fetched from £50 up to £100 per ton, by 1900 steel rails were being sold for less than £5 per ton. Although shipbuilders’ tons are different from anybody else’s it was possible to build steamships in the 1890s for around £10 per ton. (Nowadays, in spite of technical improvements, the price of steel is around £50 a ton and ships cost upwards of £200 a ton.)

Part of Sir Henry Bessemer’s fortune went into building a cross-channel steamer, the *Bessemer*, in which the first-class saloon – which was large and luxurious – was hung, like a Bessemer converter, on trunnions and was intended to remain level at sea. Seasickness was further discouraged by blowing fresh air vigorously among the passengers by means of an ingenious arrangement of pipes in the

floor.

In practice, the swinging cabin never worked properly and after a few voyages the ship was scrapped. The original saloon of the *Bessemer*, firmly fixed, is still in existence, as a conservatory, in a garden somewhere near Dover.

Nowadays, although straight Bessemer steels probably only account for a few per cent of the gross steel production, modernized and more sophisticated versions of the Bessemer system are making headway. In the Kaldo process, for instance, the converter is blown with oxygen instead of air and the extra heat which is produced is used to melt a flux for removing the sulphur directly and also to consume more scrap. What is gained in extra efficiency in such processes can however be lost by damage to furnace refractories and by the cost of the oxygen.

Open-hearth or Siemens-Martin steel

In a sense the Bessemer process was a cause of its own obsolescence because, as steel became cheaper and commoner, so did steel scrap and the availability of scrap began to exert an important influence on the economics of steelmaking. Nowadays about fifty per cent of the steel manufactured finds its way back to the steelworks as scrap. The Bessemer process, however, in its traditional form is essentially a process for converting pig-iron from the blast furnace into steel and it only makes use of scrap in trivial quantities so as to get rid of a small excess of heat.

In the open-hearth process much of the charge consists of scrap steel which has the advantage, not only of being cheap in itself, but of already having most of the excess carbon and other impurities removed. Moreover it is rusty. As we have said, the Bessemer converter cannot use very much scrap because to melt it would need more heat than is produced by blowing the charge.

In 1856 the German-born Frederick Siemens (1826–1904) and his brother Charles William Siemens (1823–83), both of whom, like Bessemer, were prolific inventors with a strong business sense, developed the regenerative furnace. This is a furnace whose outlet and inlet are reversible and are both furnished with extensive labyrinths or honeycombs of firebrick through which the gases have to pass. Much of the heat in the outgoing gases is therefore stored in the outlet honeycomb. The furnace, however, is arranged so that the gas flow is repeatedly reversed and thus the incoming air is always being drawn over heated bricks and so picks up some of the heat which was in the exhaust gases. These furnaces are usually gas-fired and, as a consequence of their design, the temperature could be raised as high as the refractories would stand, in practice to something over 1,500° C. which was sufficient to melt pure iron.

In steelmaking the Siemens furnace was originally used simply as a convenient and economical way of melting crucible steel. Later, the Siemens brothers applied the regenerative principle to the traditional puddling furnace and made steel by melting pig-iron with iron ore. The addition of large quantities of scrap is due to a Frenchman, Pierre Martin, and dates from 1864.

In operation, the open-hearth furnace is charged with a flux – usually limestone – about equal quantities of scrap steel and pig-iron and some iron ore, perhaps Fe_2O_3 . On heating, the whole charge is melted and the iron ore removes the carbon present in the pig-iron. The flux converts not only the non-ferrous oxides present in the iron ore to slag but also the sulphur present in the steel. For this reason it may not be necessary to add manganese. One of the advantages of the open hearth process as compared with the Bessemer converter is that much closer control is possible over the composition of the steel and until recently about eighty-five per cent of plain carbon steels were made in this way. However the open hearth furnace is slow and rather expensive to operate and it has therefore been losing ground to the oxygen blown converter processes such as the Kaldo which are quicker, rather

cheaper and can take liquid iron directly from the blast furnaces. In consequence only about half the steel in the country is now made by the open-hearth process which seems to be declining rather rapidly.

For still closer control over cleanliness and composition it is usual to employ electric furnaces and a comparatively small, but significant, tonnage of high grade steel is made in this way.

Chapter 11 The materials of the future *or how to have second thoughts*

'In fact we have to give up taking things for granted, even the apparently simple things. We have to learn to understand nature and not merely to observe it and endure what it imposes on us. Stupidity, from being an amiable individual defect, has become a social vice.'

J. D. Bernal, *New Scientist*, 5 January 1967.

Before the first edition of this book was published in 1968 I was persuaded, rather against my judgement, to add a final chapter called 'The materials of the future' with the defensive sub-title 'or how to guess wrongly'. Much to my relief there do not seem to be any real technical clangers in the original chapter and, in the present edition, it has been possible to transfer most of these prophecies, as accomplished factual information, to their appropriate places within the body of the book.

The weakness lay, I think, not in the facts but in the emphasis. Much of the discussion was about what it is now fashionable to call 'High Technology' and we are less inclined to be impressed by this kind of thing than we were a few years ago. Getting to the Moon has turned out to be, perhaps, just a little boring and that enterprise was, in any case, a very expensive way of developing non-stick frying pans. Students tell me that space-fiction keeps its popularity but surely its appeal is no longer chiefly technical, it is simply the fairy-story or the fable in modern dress.

More and more one comes to see that it is the everyday things which are interesting, important and intellectually difficult. Furthermore the materials which we use for everyday purposes influence our whole culture, economy and politics far more deeply than we are inclined to admit; this is, indeed, recognized by the archaeologists when they talk about the 'stone age', the 'bronze age' and the 'iron age'. It is significant that, from very soon after the introduction of bronze for tools and weapons, there was a sort of polarization between the metallic and the non-metallic technologies.

Although the ductile metals have their limitations and they are by no means infallibly tough or even particularly strong yet, for a number of purposes in peace and war, they were so much superior to the other solids which were available that a whole range of popular beliefs and superstitions and emotions have become associated with them and especially with iron and steel. In one shape or another these emotional situations have continued down to the present day and, because they still influence many people's thinking, it seems to me that it may be worth spending a little time on the historical and psychological background of the subject.

Because of their interest in tools and weapons the early civilizations were inclined to have smith-gods. The Norsemen had Thor and the Greeks had Hephaistos, who is also the Roman Vulcan after whom volcanoes are called. The stories about Hephaistos are many and not always edifying. Hephaistos, be it noted, was an Olympian god and the Olympians were not indigenous to Greece but came, as it is sometimes said, with the Dorian invaders from the North, who may have conquered the Greek world with iron weapons – possibly at the fall of the Minoan kingdoms around 1200 B.C. At any rate Hephaistos looked after the supply of iron and of weapons and was regarded by gods and men with rather mixed feelings. Hephaistos was rather a big-wig as gods went and he has a magnificent temple in Athens which stands to this day. It is interesting that there was no god of any consequence specifically connected with any of the non-metallic materials; one or two scruffy little low-class demons were associated with pottery works – where they sometimes caused the pots to crack in the kilns – but these hobgoblins were of no real importance in the world.

In the middle ages Wayland Smith, who is Wieland, who is Voland and who lived in Heligoland,

or possibly near the White Horse in Berkshire, was continually turning up in improbable circumstances. There were magic swords almost innumerable, Miming, Flamberge, Excaliber and so on; some of these were quenched in Dragon's Blood. If he was not too busy with a magic sword Wayland Smith would shoe your horse for you for a very modest sum. Again, I do not think that there was any real non-metallic equivalent to Wayland.

Although this sort of thing died out – or was suppressed by the Church – the strength of the feeling about the special nature of iron and steel continued and was reinforced rather than diminished by the Industrial Revolution. The Victorians could not really be said to have had smith-gods but they did everything they could with iron – short of affording it actual formal worship – and iron and steel became synonymous with industrialism and technical progress. Everything done with metal was important and to be taken seriously; it followed that anything done with non-metals was old-fashioned and quaint and unimportant.

About 1912 an ex-theological student called Joseph Djughashvili (1878–1953) changed his name to Stalin* since 'Iron out of Calvary is master of men all'. He proceeded to live up to his name and, incidentally, spent much time later on in building up the steel industry throughout the Soviet Empire. Actually it looks as if he may have rather overdone it since most Communist countries now seem to be suffering from a surplus of steel.

Of course, from Boulton and Watt down to Henry Ford, iron and steel have been, above all other materials, the agents of development, industrialization, enrichment and 'progress' and, historically, we could not have done without them; the question is whether we ought now to be growing out of that kind of thing. Everything has its bad side and the bad side of metal technology did not come to an end with the Factory Acts. What really made the industries which were based on iron and steel so successful in modern times was that they lent themselves best to disciplined mass-production and to the dilution or elimination of skill and individual judgement at the bench level. All the worthwhile decisions were taken at the top and imposed from the top. Such manufacturing systems placed enormous power in the hands of managers and accountants and, eventually, in the hands of governments and trades unions. Governments and trades unions are no more enthusiastic about giving up this power than the managers and accountants and they are even more apt to talk about the economies of scale and the benefits of 'rationalization' and centralized control.

What is left out of account is that most ordinary people don't like this kind of thing and nowadays they find ways of not standing for it and of being bloody-minded which more than nullify the economies of scale. A factory may be an accountant's paradise but if it is on strike it is not producing anything at all and surely it would be better to have a less 'efficient' system which did produce something?

These large and highly interdependent organizations presuppose a willing and disciplined labour force of a kind which is most unlikely to exist for long under any political system. In my opinion nationalization and high wages or even 'workers' control' do not really improve the situation because they do not deal with the roots of the trouble which are to a large extent inherent in the size and in the inhuman nature of so many manufacturing processes.

The difficulty has been that, until recently, no economically practicable alternative to bigness has existed and, on the whole, the economists from Marx to Keynes seem to have taken the economies of scale for granted; indeed most of them have rather welcomed bigness, partly because it appeals to tidy minds, but also because bigness puts more power into the hands of the Children of Light. But the Children of Light are few in this world and people furiously disagree as to who they are; also all power corrupts and ought to be diminished.

But then what shall we do to be saved? There is nothing like Leather, says the cobbler; nothing like

Sound Management, says the business man; nothing like Taxation, says the politician; nothing like Equality, says the trades unionist; but I think that the problem might very well be a technical one. Although about twice as much timber is used as steel, it is interesting that the woodworking industries in the Western world are seldom in the news, whether for good or for bad and they do not seem to be especially plagued with troubles or dissention. Somehow steel and its dependent industries is never out of the headlines and nobody associated with it ever seems to be really happy. Whether we are concerned with making swords or making motorcars steel somehow remains the material of power and politics. It has been the fashion, especially on the Left, to regard steel as being in some way a 'People's material', a key to all sorts of enlightenment and progress. Of course steel is extraordinarily useful stuff, we cannot get on without it and it is wrong to take too simple a view, yet there is a strong case that steel is the agent of a sort of faceless industrial oppression, the life-blood of the Dark Satanic Mills. Indeed steelworks are gloomy places.

The differences between the social records of the industries based on wood and those based on metals is unlikely to be due to pure chance and can probably be traced, however indirectly, to the physical characteristics and properties of the materials themselves. For one thing, speaking comparatively and in a very general kind of way, people seem to *like* working with timber; for another, the very manufacturing limitations of wood impose constraints upon the sociology of the industry which may well be salutary. If this is true, then it might be a good idea to study the whole question of how materials affect the happiness of the people who work with them in much more depth. Now that we can design new industrial materials to suit ourselves we ought surely to bear this psychological element in mind much more than we do. At present nobody seems to care.

Designing materials to suit ourselves

All this brings us to the question of designing new materials and we might begin by harking back just a little. Materials science – the study of materials as a whole rather than in their special chemical, physical and engineering aspects – is a fairly recent development. Indeed it has only lately become respectable. However, in spite of its youth, the new discipline has been rather successful and I think it is fair to say that we now understand a great deal more about the reasons for the mechanical behaviour of solids than we did only a very few years ago. This may be because many of the raw materials of understanding were lying to hand already. There was a great body of orthodox physical and chemical knowledge and there was also, although in different hands, an accumulated mass of engineering experience and tradition. To fit them together and to make one explain and confirm the other required only a moderate amount of original experiment and fresh thinking – once a sufficient number of workers had considered it worthy of their serious attention. As so often, the real difficulty about the solution of a problem is to recognize that the problem exists.

Naturally enough, the first task was one of understanding the observed phenomena – why solids in general, and especially the familiar materials, behave in the way they do. Although there are still a good many loose ends, this stage can broadly be said to be accomplished. The problem now facing materials scientists is what use to make of their knowledge. The possibilities are not unlimited – one of the things which has been learnt is that there are a considerable number of things which cannot be done even if we wanted to do them. A cognate aspect of our knowledge is that many lines of improvement had already been exploited, almost to the full, before the scientists got there. Some of our knowledge is useful simply in telling the engineer what to avoid – what sort of stress-concentrations are dangerous, for instance.

However, when all due reservations are made, the ambitious will want to apply materials science in

radical ways, either by making substantial changes in the older materials or else by inventing new and perhaps better ones. However, the more intelligently we examine traditional materials like wood and steel the more we ought to be impressed by how cunningly they are made. What is wanted is not one property in isolation but rather a balanced combination of properties and this is provided in such materials by means of exceedingly subtle and complex mechanisms such as dislocations and hollow helical tubes. Modifications to the older materials of construction are more likely to spoil them than to improve them.

If we are going to set out to invent entirely new materials then we had better watch our step because the requirements for any really successful material are likely to be very complex indeed. Nevertheless, it is probably worth trying and the eventual rewards, both economically and socially, may be very great. As Academician Rabotnov remarked in his introduction to the Russian translation of this book ‘this is a noble task to which young people might well devote their lives’. Although I might not have expressed the sentiment in quite those words, I cannot but agree with Professor Rabotnov.

Before we can discuss the subject of new materials intelligently we have to begin by asking ourselves the question – ‘What do we really mean by a *better* material – better for what?’ The answer to this is anything but obvious and the question is really the central one in materials science at the moment. As we have already said, the whole problem is made more difficult by the extraordinarily complicated way in which the technical, social and economic aspects are interwoven.

Many business men however seem to have no serious doubts about what they want – theirs is a simple Faith and they want the stuff to be cheaper. For this reason a high proportion of materials research is directed towards getting the cost of production down. There are, of course, some materials which are unduly expensive and which could and ought to be made more cheaply. However, I do not think that this is true to any important extent of the engineering materials of construction in general, such as steel. The cost of steel was reduced very greatly during the nineteenth century and it is now fairly cheap; on technical grounds it seems unlikely that such marginal economies as are likely to be made in future can really justify the investment of any large scientific effort.

Even if it were practicable to achieve large reductions in the cost of constructional materials it is worth asking who would benefit. In many finished products the cost of the materials, as such, is only a few per cent of the cost of the finished article and so, even if the material were to be supplied free, the benefit to the consumer would be small compared with other changes which might be introduced.

Secondly, the very cheapness of materials may actually have a bad effect upon design and performance. When materials are unduly cheap the designer has too little incentive to economize in using them and the result may not only be heavy, clumsy design (involving waste of fuel and damage to roads) but it may also, in the long run, lower the professional standards of engineers. The reason for much bad, heavy, ugly design is partly to save fabricating costs but as often, I am afraid to save the designer from the trouble of thinking. Economists tell us that, in a given context, there is generally an optimum price for both land and labour which results in efficient social development and I fancy that the same reasoning might apply to the price of materials.*

There is another aspect of the price of materials which is also important. The cost of the various fabricating processes is frequently very many times higher than the cost of the bare material. For instance it is cheaper to buy a plastic at 20p a pound which can be moulded into its final shape for a further 5p than to buy steel at 5p per pound which needs to have 50–100p spent on it in pressing, machining and finishing operations.

Cheap fabrication is, at root, the reason for the commercial success of plastics which are always expensive raw materials compared to most metals. It is not only that, from the economic point of

view, such materials can offer large savings in processing, manufacturing and finishing but also many of these processes can be carried on competitively upon a very small scale. I have seen the extrusion of plastic tubing carried on as a village industry in Hungary and indeed, all that is needed is two or three extrusion machines and a shed to house them. It is difficult to see how the process could benefit, economically or otherwise from being done in a big factory. When I was on the Board of a large plastics company I was able to watch our extrusion business being run off the market by little back-street firms whose overheads were lower and whose thought-processes were quicker than ours.

Very much the same sort of thing applies to the injection-moulding of thermoplastics; an industry which makes millions upon millions of toys and kitchen gadgets and useful what-nots at an incredibly low price. Given a suitable (and rather expensive) mould, injection moulding can be carried out in almost any barn or garage. It may suit the convenience or the vanity of administrators or business men to group these activities in large factories but there does not seem to be any compelling reason for doing so. Though I find it difficult to go all the way, politically, with either William Morris or Dr Schumacher, there can surely be no doubt at all that Small is Beautiful?

Extrusion and injection-moulding are very well as far as they go and they enable jobs which are inherently dull and repetitive to be carried on by smaller groups of people in pleasanter surroundings – which is all to the good and, after all, some people like repetitive jobs – but, of course, it does not give much scope for initiative and variety in the design of the product.

This is achieved, to a considerable extent, in the woodworking industries, making products like furniture in comparatively small numbers and to comparatively individual designs. By using modern machinery and adhesives and finishes the cost can be kept competitive with the big factories. The same thing applies to a still greater extent in the fibreglass industry where all sorts of shell-like products, from swimming-pools to boats to car bodies to flowerpots, can be produced in little factories with very low capital costs.

Naturally, there are plenty of small industries which are based on metals but these people generally find it more difficult to compete with the big boys and it is the non-metallic small industries which are going ahead much the faster. This is probably an area where a moderate amount of materials research could do a great deal of good.

Energy conservation

Latterly it has become very fashionable to talk about energy conservation and, quite apart from political questions about oil-wells, it is probably high time that we gave this aspect of technology more consideration and respect. When power had to be provided, in very small quantities, by men or horses, vehicles were generally made from wood and other light materials. It is most instructive to look at sedan chairs and horse carriages in museums and to see how light and robust some of these things were.

Traditionally, railway trains were drawn along smooth and level rails by engines burning lots of cheap coal and a railway carriage is an interesting example of just how heavy and clumsy one can make a moving structure. To some extent the prodigal use of material in railway rolling-stock arises from the nature of trains themselves; that is to say trucks and carriages have to be constructed to resist what are called 'buffing loads' which occur because of the mutual impact of strings of vehicles during shunting and manoeuvring. Light, modern rolling-stock has usually to be worked in conjunction with older, heavy vehicles which are liable to smash anything near them and, in my experience, it is difficult to save very much weight or fuel in trains by advanced structural design. In any case, I doubt if the real problems of the railways are the technical ones.

Nevertheless, the whole tone of traditional engineering was set for many years by railway and by marine engineering and by bridges and stationary engines and all these things were generally constructed as if weight were no object. 'The English think that weight means strength.' The requirement for weight saving arose with the invention of the motorcar and the aeroplane but even here engineers were generally more interested in increasing the power of the engine than in saving weight in the structure. It used to be said that 'a tea-tray will fly if only you put enough power into it'.

By running internal combustion engines at very high speeds on high-octane fuel it was possible to increase their power output very dramatically indeed. Much of this power output has been needed to cope with the large increase which has taken place in the tare weight of cars during the last fifty years, mainly due to the introduction of the pressed steel body. As long as oil was comparatively cheap and plentiful I suppose that this did not matter very much. In fact the fuel consumption of a car is roughly proportional to its weight and so nearly half the petrol which is imported into this country is used or wasted in propelling heavy rusty steel shells along the roads.

The only real argument in favour of pressed steel bodies for cars is the safety one. These steel shells are in fact very good at absorbing impact energy during an accident – due to the high work of fracture of mild steel – and so each of us drives about inside his own private tank. However, according to my sum, the extra fuel needed to move all this armour around costs about £1,000, at present prices, taken over the life of each average car. One would think that there would be cheaper forms of protection than that. The total cost to the country in imported oil is enormous and, of course, the extra weight does no good to the tyres or the roads.

Fibreglass car bodies save a great deal of weight and, in fact, they are already quite widely used. The trouble is that such bodies have barely enough energy absorption and they are probably distinctly less safe than steel bodies. What is needed is a large increase in the work of fracture of the material and also, perhaps, some increase in stiffness. As we saw in [Chapter 8](#), tougher, stiffer composites seem to be only just around the corner and, if so, we may see a large swing to plastic car bodies together with a saving in fuel which might well be as high as 30 per cent. Since such bodies do not rust cars would probably last longer.

Lightweight car bodies are one good way of saving energy; improved building methods and house insulation are probably another. Unfortunately development in building materials is a good deal handicapped in this country by conservative building regulations and by the Building Societies. It does, however, very much look as if a new approach to the whole question of building materials and insulation is overdue.

The new materials might perhaps be sophisticated ones based on polymers or other 'advanced' substances but they might equally, and perhaps preferably, be based on traditional local materials, modified where necessary in the light of modern knowledge. Professor Biggs tells me that if one looks at housing from the total energy point of view – that is to say, if one considers the energy needed to make and to transport the materials, as well as the energy consumed during the life of the building in heating it – then the traditional English thatched and half-timbered cottage is probably better than anything else. Rather predictably, this is just what one is not allowed to build under the present regulations.

A variant of the same problem exists in connection with overseas developments. In many tropical regions, such as parts of Africa, it is difficult to improve upon the traditional construction of mud and reeds which can be put up cheaply and quickly and which is cool to live in. Most of the drawbacks of these buildings can be got over by making use of various forms of modern technology. I am told however that the inhabitants reject this construction with scorn and insist on building with concrete and corrugated iron which are both hot and expensive. As long as such attitudes prevail it is difficult to see what science can be expected to do.

So far we have talked about saving energy; however, if we are going to go out and actually collect energy from primary sources, such as the sun and the wind, then we shall probably need to invent and to make use of a whole new range of materials. For something like 200 years engineering 'progress' has consisted of making machinery and other engineering devices more and more compact, of working at higher and higher stresses and of 'processing' more energy in less space. A modern ten horsepower engine is at least a hundredfold smaller and lighter than it would have been in the eighteenth century. This has been possible because of the concentrated nature of fossil fuels. Primary energy sources such as the sun and the wind are not concentrated and have to be collected in dribbles, as it were, from over a wide area. Plants are superbly good at collecting the energy of sunshine but the structures and materials which they use are different from those which are popular with the modern engineer.

If we want to revive the sailing ship and the windmill, under modern conditions, as I am fairly sure that we should, then we shall have to devise ways of reaching out and collecting small amounts of kinetic energy from quite long distances very cheaply and simply. One has only to sit down and study the problem from the economic and structural point of view to see that this probably cannot be done with existing materials and we shall probably have to go about the job in some more intelligent way and, again, this will undoubtedly call for new kinds of materials and structures.

The disposable technologies

There is no doubt at all that the introduction of 'disposable' materials, such as cheap paper and plastics, has been, on the whole, decidedly beneficial. It has reduced the incidence of infectious disease and dramatically diminished the less attractive kinds of domestic chores. The question is, how far ought we to go in this direction? What do we really mean by 'disposable' anyway?

It is all very well to throw away things like towelling and packaging and it is probably an excellent thing to throw away your morning paper, but what about refrigerators and motorcars? It is perhaps possible – just possible – to exaggerate the cynicism of manufacturers and shopkeepers about 'planned obsolescence'. Of course, Nature arranges for all her creatures to die and there is no good reason why the works of man should last for ever. A paper towel is very cheap – much cheaper than one made from cotton or linen – and furthermore the cost of washing a durable towel is probably greater than that of throwing away many paper ones. But all this is not true of motorcars or refrigerators. In such things a small addition to the first cost would result in a much longer life and in reduced maintenance costs.

One of the biggest contributions to the total economy would be to make 'consumer durables' durable. After all, if such things last twice as long, that is roughly equivalent to doubling the production of the article; in other words one need only make half as many. This does not necessarily cause unemployment because one can use the money which is saved to buy something else – or else perhaps just save it.

Many products wear out – or rather go out of service – for silly, shoddy reasons (Oh no, sir, we don't stock spares for out-of-date models). However, the biggest single reason for throwing things away is probably rust. As we have seen the introduction of plastics in place of pressed steel shells is one way of getting over this and very often these plastic shells can be manufactured on a 'Small is Beautiful' basis.

I suppose that industries which deliberately live by 'planned obsolescence' ought not to be surprised if they become obsolete themselves; perhaps we need some form of euthanasia for declining industries. At present the policy is to pension them off so that they can continue to exist comfortably

at the taxpayer's expense. One does see that there are political and social problems about lame ducks and disposable industries but it is seldom pointed out that it is precisely those industries who, in their hey-day, were most ruthless in superseding the stage-coachmen, the canal boatmen, the coastal seamen, the sailmakers, the millwrights and such other excellent people who now call most loudly for subsidies on social grounds. Times have changed since the nineteenth century but are they changing fast enough today?

If 'consumer durables' wear out too quickly, do houses and other buildings last too long? Very possibly more houses have been built during the last thirty years than were put up in the whole span of previous history; most of them are ugly, or at any rate commonplace, and our grandchildren may well want to get rid of them. Also it would perhaps be better if our houses could be altered quickly and cheaply to suit our changing requirements and better still if we could take them with us when we wanted to move to another part of the country.

Unfortunately the local authorities have joined with the Building Societies to ensure that houses shall be as expensive and as immovable as it is possible to make them and also very difficult to modify. It is quite true that both caravans and also most temporary buildings, in their present forms, are nearly always ugly and shoddy and to be discouraged. But is this necessarily so? We have got it firmly into our heads that anything temporary or disposable has to be ugly but, after all, one could hardly have anything more temporary or more disposable than a crocus or a daffodil and it might be worth giving some thought to the way in which Nature does these things.

We have, I suppose, the biggest aesthetic opportunity in the whole of history and what are we doing with it? Nothing, or rather we are producing miles and miles and miles of the dull and the commonplace. Does everything really have to be Fabian grey? By making use of modern ideas and modern materials I suppose that we could all of us be pavilioned in splendour – quite comfortably and cheaply – if we really gave our minds to it.

Because the influence of materials and structures upon almost every aspect of our lives is so great, the fact that we now at last understand, pretty well, how materials work and have some idea of how to invent new ones, is very important indeed. So far the implications of this new knowledge have not been sufficiently widely appreciated. Our modern understanding of materials has been brought about by getting engineers and physicists and chemists to talk to each other, which they were rather reluctant to do. What is wanted now, I think, is to bring materials science together with economics and aesthetics. If this can be done in a really imaginative way then the opportunities are enormous and surely the challenge is great enough to satisfy the most able and the most ambitious?