TEMPER-BRITTLENESS: PART I — UNALLOYED STEELS

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Abstract

It was until recently accepted that unalloyed steels were not susceptible to temper-brittleness and that alloying elements introduced temper-brittleness. A directly opposite view has been set forth in this paper, namely that unalloyed steels are not only susceptible to temper-brittleness but also temper-embrittle much more rapidly than alloyed steels based on the observations of brittle transition temperature ranges. Temper-brittleness and strain-age-embrittlement are discussed in relation to minor or residual chemical constituents like nitrogen, oxygen, etc. The role of stabilizing elements like aluminium, titanium, vanadium and of nitrogen in minimizing and often wholly suppressing temper-brittleness and strain-ageing is discussed at some length. The subject of blue-brittleness has also been touched upon. The observed phenomena are considered in terms of dislocations and certain gaps in the theory are pointed out.

IT has until recently been universally accepted that plain carbon steels are not susceptible to temper-brittleness and that alloying elements only introduce temper-brittleness. Zaffe and Buffum[1] have set forth a directly opposite view. They support the possibility that plain carbon steels are not only susceptible to temper-brittleness but are much more susceptible than alloy steels, in the sense that they embrittle much more rapidly. The criterion referred to earlier involved notched-bar impact tests only at room temperature, whereas the criterion now generally used retained the same heat treatments, but the impact tests were made over a range of temperatures covering the transition from ductile to brittle fracture. Based on their limited tests in accordance with the latter criterion, Zaffe and Buffum[1] arrived at two conclusions: (1) plain carbon steels are susceptible to temper-brittleness, (2) temper-brittleness develops so rapidly that even drastic quenching from a high tempering temperature is insufficient to suppress it.

The commonly accepted lower toughness of plain carbon steels compared with alloy steels may be partly due to their being more temper-brittle, as ordinarily heat-treated. Addition of suitable quantities of the proper alloying elements, to be determined by further research, may provide a method of retarding temper-brittleness to such an extent that it will be of practical importance.

It may be noted that the transition temperatures of alloy steels water-quenched from high tempering temperatures do not necessarily represent material entirely free from temper-brittleness; alloy steels may embrittle to some extent on quenching from the temper, though not as much as plain carbon steels. All steel parts and specimens tempered at moderate or high temperatures may be somewhat temper-embrittled. Temper-brittleness may thus be an almost universal phenomenon in tempered steels, superimposed on or competitive with the tempering, but in a sense slower.

Temper-brittleness in plain carbon steels is markedly influenced by aluminium deoxidation which decreases strain sensitivity and lowers the transition temperature. These effects are associated with the composition of nitrides present in steel. If there are iron nitrides, the steel is sensitive to cold-work and possesses a higher transition temperature than aluminium deoxidized steel. Although considerable thermodynamic and experimental data support the fact that aluminium nitride is present in aluminium-killed cast and wrought steels and that the presence of this compound is directly associated with much lower sensitivity to strain and temperature, the mechanism by which aluminium nitride brings this about remains unclarified and forms an improtant hiatus in our knowledge of deoxidation of steel and its low temperature properties in relation to temper-brittleness. The mysterious behaviour of aluminium nitride is further complicated when it is realized that in suitably deoxidized steels containing excess of 0·5 per cent carbon, aluminium deoxidation has no significant influence on low temperature properties and in general on strain-ageing and blue heat characteristics. The ultimate solution in case of low-carbon steels may revolve round the role of aluminium in fixing up the nitrogen as aluminium nitrides and throwing these out of action so far as their activity on temper-embrittlement and hardening is concerned. For carbon in excess of 0·5 per cent in steels, the effects of Al-N may be overshadowed by the influence exerted by carbon on temper-brittleness. Figs. 1 and 2 illustrate the effect of aluminium deoxidation in relation to transition temperature ranges.

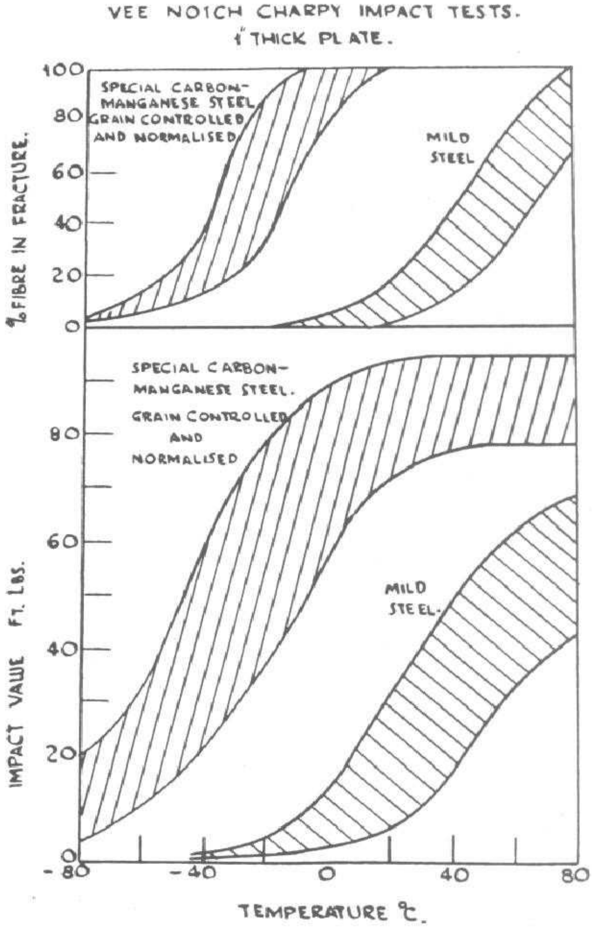

FIG. 1 (After W. BARR, West of Scotland, Iron & Steel Institute, Presidential Address 1950)

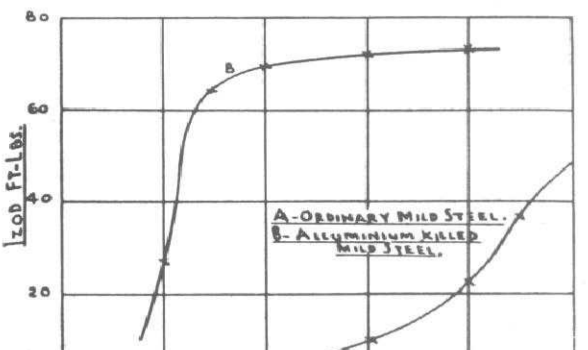

FIG. 2 — IMPACT VALUE ON TESTING TEMPERATURES (BARR AND HONEYMAN, *Institution of Engineers & Ship Builders*, 1948, 72)

Kruger[2] has recently investigated the subject of temper-brittleness of plain carbon steels. The quality of basic-Bessemer steels has improved considerably in recent years by blowing with oxygen-enriched air, or steam, oxygen and CO_2, or a mixture of these. Rimming and killed steels from the basic converter blown with oxygen-enriched air and a mixture of air, oxygen and steam were compared by Kruger[2] with ordinary basic-Bessemer, O.H. and electric furnace steels with respect to composition and mechanical strength before and after cold-working. The nitrogen and phosphorus contents were approximately the same in all the steels, but the oxygen content differed considerably. Tensile strength, necking, elongation and notch-impact data increased less after cold-working than those of ordinary basic-Bessemer steel. Ageing was also studied and the dominating influence of nitrogen and phosphorus was established. With high nitrogen and phosphorus there was a marked increase in tensile strength after cold-work. The effect of phosphorus alone appeared to be stronger than that of nitrogen alone. Steels blown with steam plus oxygen added to the blast were superior and very similar in all respects to O.H. steels. Thus Kruger[2] strikes a rather differing note concerning the role of nitrogen and phosphorus in strain-ageing of these steels.

Strain-ageing of Steel in Relation to Temper-brittleness

The second edition of Webster's *New International Dictionary* defines the verb 'age' as follows: 'AGE (verb intrans.): 1. To become old; to grow older; to show marks of age; to undergo changes with age or the lapse of time. 2. Specif.: (a) To suffer with lapse of time a diminution of essential qualities or faces; as, an incandescent lamp or a transformer ages; (b) To become mellow or ripe; to acquire a desirable quality by standing undisturbed for some time, as wine or varnish ages; (c) Metal. To remain or stand undisturbed after or during heat treatment, so that molecular or crystalline adjustments may occur; as, an alloy ages.'

There are two important points brought out by a study of this definition. The first is that time is the essential element in ageing; and the second, that the effects may be either deleterious or beneficial.

The phenomenon of strain-ageing in steels is closely linked with yield point phenomenon and it would be worthwhile outlining salient features thereof, in relation to chemical constituents present in steel of mild and structural varieties.

Various effects may be produced by ageing. For example, the material may become harder and have a higher tensile strength; it will correspondingly suffer a loss of ductility and ability to withstand shock; and the yield point will be more sharply defined. Ageing indicates a tendency in the direction of equilibrium after the disturbance caused by quick cooling as in quench-ageing or cold-working as in strain-ageing. Its cause is attributed to a breaking up of the supersaturated solid solution. Strain-ageing, in addition to rendering the steel harder and less ductile, eliminates the influence of temper rolling cycles designed to eliminate stretcher-strain markings. Hardness increase produced by strain-ageing is not by any means equal to the loss in ductility, which frequently far exceeds the relatively small gain in tensile strength and hardness.

Many aspects of the phenomena of strain-ageing are those to be expected of the age-hardening process. It has to be assumed that the solid solubility of a constituent or constituents is decreased by cold-working, providing a precipitation potentiality or that straining generally accelerated such precipitation. The nature of the ageing agents has been well argued for the last two decades and is still on the anvil. Strain-ageing has been observed in steels very low in carbon and it has been reasoned that the ageing agent may be oxygen; this point of view received ostensible support from the development of deoxidation techniques for steels with low strain-ageing sensitivity as in the case of Izett and stabilized steels. However, oxygen is not now believed to be directly responsible, although it may exercise secondary effects on the solubility of carbon and nitrogen in α-iron and their quantum needed to set up ageing. Strongly deoxidized stabilized steels do not exhibit strain-ageing — this may be due to the 'fixing' up of nitrogen by the deoxidants and its resultant inactivity thereafter. Thus while precipitation of ageing agent proceeds slowly at room temperatures and much more accelerated at higher temperatures, say at 300°C., this precipitation causes the crystal lattice of iron to be distorted and the metal offers increased resistance to movements along the slip planes. At temperatures above 300°C., the precipitated phases coalesce which, on being totally disentangled from the ferrite lattice, no longer exert any hardening effects thereby causing softening and over-ageing effects. The exact causes have yet to be finally established, and although of recent years stabilized non-ageing steels have been developed, their cost and yield factors are often prohibitive, so that the consumer tends to eliminate a proportion of his difficulties by, as far as possible, finishing the deep-drawing and pressings before the steel has appreciably aged or the influence of temper rolling has worn off.

Notable work has been done by Thomas and Leak[3], Jones and Owen-Barnett[4], and Hundy[5,6] on these subjects.

Strain-ageing and Yield Point

Strain-ageing and yield point phenomena do not appear so much to be directly related as to arise from the same cause, namely due to small additions of carbon, nitrogen and oxygen. Suppression of strain-ageing by removal of these or converting them to inert compounds also suppresses the yield point as illustrated by the 0·02 per cent C steel with Ti added (FIGS. 3 and 4). Further, as in strain-ageing, oxygen alone does not seem to produce a yield point, but acts indirectly by enhancing the effect of carbon and nitrogen. In unstrained irons, the yield point can be absent, even though strain-ageing properties are still detectable, e.g. for 0·003 per cent C, but in this case a yield point is observed after strain-ageing. Neither strain-ageing nor yield point is a property of pure iron but is due to carbon and nitrogen. Strain-ageing arises when these carbon and nitrogen are in supersaturated solid solution, while the yield point appears to be caused, under certain conditions, when these have been precipitated in a very finely divided state. The exact nature of these conditions and the mechanism by which the precipitate acts are quite unknown. At 300°C., which is above the optimum temperature for strain-ageing, the yield point disappears, presumably because the precipitate grows too coarse to play its effective role.

Early studies on the effect of hot-working and of tensile testing at these temperatures disclosed a characteristic brittleness in steel in the vicinity of 250°C. — the 'blue-brittleness phenomenon'. For tensile tests at

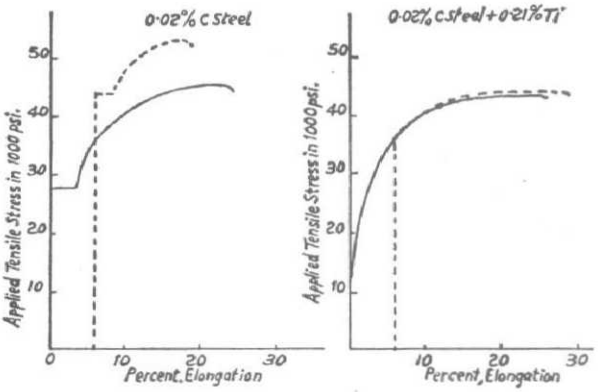

FIG. 3 — EFFECT OF ADDITION OF Ti UPON YIELD POINT AND UPON STRAIN-AGEING OF LOW-CARBON STEELS. Full line: Normal stress elongation curve. Broken line: Stressed to 6 per cent elongation, aged at 250°C. for 1 hr. and re-stressed

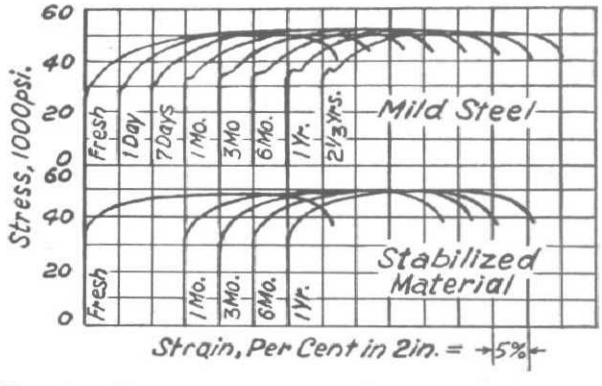

FIG. 4 — THE CHANGE OF THE STRESS-STRAIN DIAGRAM OF TWO STEELS ON AGEING AT ROOM TEMPERATURE FOR DIFFERENT PERIODS OF TIME SUBSEQUENT TO COLD-WORKING (KENYON AND BURNS)

elevated temperatures, the 'blue-brittleness' range is lower the slower the speed of of elongation — similar results were obtained on impact testing, where in 'static' notch-bar tests a brittle range was observed around 250°C., but in impact tests was observed to be shifted to 55°C. Strain-ageing and blue-brittleness are only different aspects of the strain-ageing process itself, i.e. at 250°C. the ageing process is rapid enough to occur concurrently during the test; at lower temperatures the time is not enough, whereas at higher temperatures it is sufficient for strain-ageing to occur which manifests itself through characteristic jaggedness in the tensile curve believed to be due to rapid strain-ageing on successively active slip planes. Non-ageing steels work-harden much less rapidly than ordinary steels at room temperatures and possess a much less marked blue-brittleness region, whilst highly purified iron free from strain-ageing is also free from 'blue-brittleness'. Optimum additions of aluminium (2-3 lb. per ton) to steels completely suppressed blue-heat hardening. In steels deoxidized with aluminium, titanium or zirconium, the nitrogen occurs as nitrides of these elements, and since the solution behaviour of these nitrides is radically different from that of iron nitrides, the ageing and blue-heat characteristics of such steels undergo material changes by the deoxidation practice. Although control of ageing is of great practical significance, it is not *ipso facto* an indication of unsatisfactory steel quality. Fig. 5 depicts the work-hardening characteristics of a Bessemer steel and a killed low-carbon steel. Fig. 6 depicts the 'blue-brittleness' characteristics of a mild low-carbon steel and stabilized non-strain-ageing steel.

The precipitation theory discussed above appears to offer a satisfactory explanation for the phenomenon of age-hardening. Mehl and Jetter[7] claimed that plastic deformation created loci of high energy content in the crystal lattice, and that these energy concentrations contributed to the formation of precipitate nuclei, thus increasing the rate of precipitation.

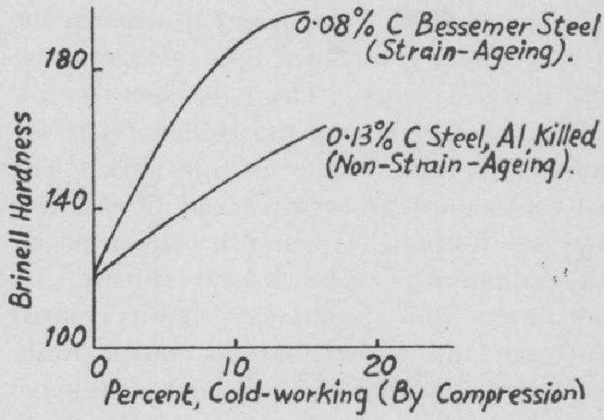

FIG. 5 — A 'NON-AGEING' STEEL, PRODUCED BY A DEOXIDATION WITH ALUMINIUM, WORK-HARDENS MUCH LESS RAPIDLY THAN ORDINARY LOW-CARBON STEELS

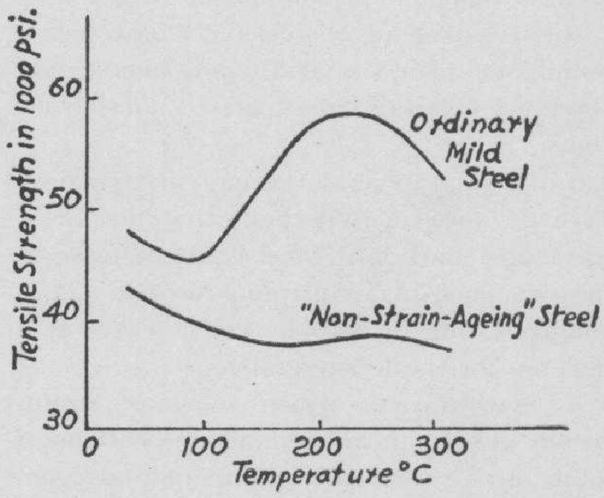

FIG. 6 — 'NON-AGEING' STEELS SHOW A MUCH LESS MARKED BLUE-BRITTLENESS REGION THAN ORDINARY LOW-CARBON STEELS

A radically different explanation of the mechanism of strain-ageing was advanced by Andrew and Lee[8]. They regarded that the strain induced localized allotropic transformation of alpha-iron to the gamma-phase so that some carbon was dissolved during the work-hardening process. The films of austenite thus formed at the slip planes will, under the quenching effect of the surrounding mass of metal, transform to minute crystals of alpha-phase and this reaction would result in an increased resistance to further slip along the gliding planes. The net effect is progressive strengthening of the ferrite in the course of time following cold-work. The age-hardening theory advanced by Andrew and Lee, although apparently supported by some dilatometric and X-ray evidence, did not receive wide acceptance. It was pointed out that this theory did not satisfactorily explain the work-hardening and ageing behaviour of austenitic steels and was not in agreement with the evidence that strain decreased the stability of austenite and the solubility of carbon in ferrite; further, it shed no light on the role played by nitrogen in the strain-ageing of steel and in any case it could not explain the yield-point phenomenon observed in certain face-centered non-ferrous alloys.

Nadai[9] and several German investigators have advanced a hypothesis that the yield-point phenomenon in steel is attributable to the existence of an ultramicroscopic grain-boundary film of carbide which serves as a skeleton for the ferrite grains.

A new theory, which explains strain-ageing by the anchoring and dislocations of solute atoms such as carbon and nitrogen, has been recently formulated. Evidence in support of this theory is given by Cottrell[10], Nabarro[11], Cottrell and Churchman[12], Bilby[13], and Harper[14]. Because of their distortion of the lattice, dislocations tend to attract the foreign atoms in a crystal, such as the carbon atoms in steel. A foreign atom that is larger than the lattice atoms will tend to move to the tension side of a dislocation, where there is more room between neighbours. Similarly, a smaller foreign atom will tend to migrate to the compression side of a dislocation. This effect was first pointed out by Cottrell and the concentration of foreign atoms is called a 'Cottrell' atmosphere. It is supposed to explain for the first time the phenomenon in metals known as the yield point. When a distorting force is applied to a metal, the deformation grows steadily greater as the force increases until the yield point is reached. Then the metal suddenly gives way, and the deformation continues to increase even if the force is reduced. The yield point marks the transition from elastic to plastic behaviour. The theory is that in the elastic range the forces are not large enough to pull the dislocations loose from the Cottrell atmospheres. At a certain critical value the dislocations are torn from their anchor, and may then be kept in motion by a smaller force. Metals without abrupt yield points are now being made simply by purifying them enough to eliminate the Cottrell atmosphere from all but a few of their dislocations. During ageing, the carbon and nitrogen atmospheres have time to move and anchor the dislocations and thereby introduce strain-ageing and strain-age embrittlement. Similar phenomenon is supposed to take place in quench-ageing. The simpler picture explaining the age-hardening after straining appears to be that when iron which contains no carbon or nitrogen is strained the metal undergoes plastic deformation like other pure metals showing no yield point or discontinuity in view of the position that there is nothing to prevent movement along the 110 slip planes. Interstitial atoms like carbon and nitrogen located at these slip planes increased the resistance to slip. Thus stress to initiate the slip is raised on these slip planes. Once, however, it starts, other planes follow likewise. On ageing after straining, carbon and nitrogen atoms diffuse back to their original relative position and then the phenomenon of yield point reappears.

Nitrogen in Steel

The iron-nitrogen system is of particular interest, since it provides several examples of a highly metastable equilibrium of considerable industrial importance. The solubility data for nitrogen in solid iron suggest that it obeys Sievert's law, i.e. the solubility varies as the square root of the pressure. A knowledge of the solubility relationships of nitrogen in both crystal forms of iron is of importance. An idealized version of the results of several investigators is shown in Fig. 7; two points are notable, firstly the markedly higher solubility of nitrogen in gamma compared to alpha-iron, and secondly, the solubility increases with temperature in alpha-iron.

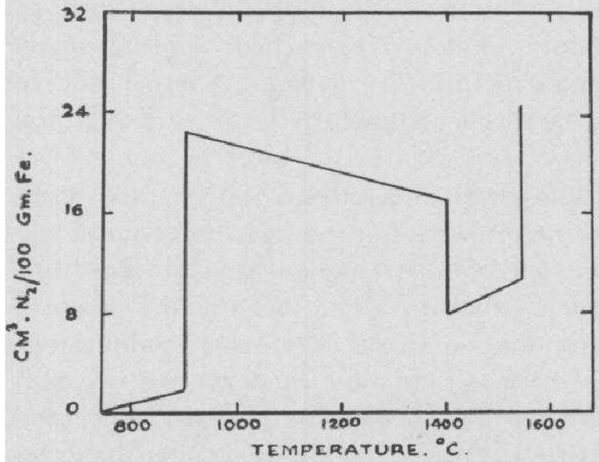

FIG. 7 — IDEALIZED SOLUBILITY CURVES FOR NITROGEN IN IRON FROM THE WORK OF VARIOUS INVESTIGATORS. NOTE (a) THE HIGHER SOLUBILITY OF NITROGEN IN GAMMA-IRON AND (b) THE SOLUBILITY INCREASE WITH TEMPERATURE IN ALPHA-IRON

More recent data by Paranjpe[15] and his colleagues express the solubility relationships of nitrogen in ferrite as shown in Fig. 8. A notable point from this curve is that there is a sharp reversal of solubility above about 600°C.

Darken[16] has investigated the solubility of nitrogen in austenite as influenced by various alloying elements and concluded that carbon, manganese, sulphur and phosphorus in amounts normal to low-carbon mild steels have negligible effects. Manganese contents up to 1·5 per cent were claimed to exercise no effect. Darken[16] further indicated that aluminium showed no influence upon nitrogen

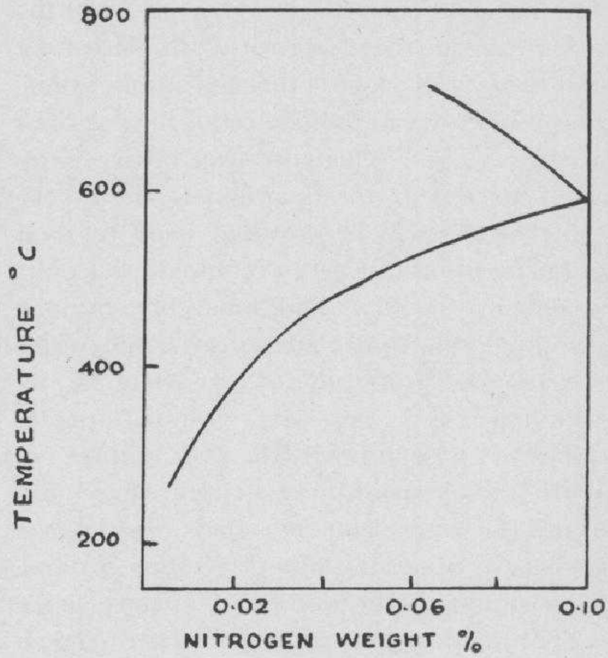

FIG. 8 — SOLUBILITY LIMITS OF NITROGEN AS A FUNCTION OF TEMPERATURE

absorption by austenite, until reaching a critical aluminium content which depended upon temperature. Above this critical concentration, the nitrogen content increased sharply, presumably due to the formation of a new phase, aluminium nitride. This critical aluminium content bears further relation to its role for austenitic grain refinement.

Concerning the effects of carbon and nitrogen on damping capacity of ordinary steels, only very small quantities (0·007 per cent of carbon and 0·001 per cent of nitrogen) of these elements can dissolve in iron at room temperatures; but the two different atoms occupy preferred positions in the iron lattice interstices. There is an alternative position, with actually more room, available within the lattice, but the other is the preferred position. On the average some kind of dynamic equilibrium is maintained and along any x, y or z-axis, taken at random, there will be in either position a statistically constant number of solute atoms at any given instant. If the iron lattice is extended along one axis, more room will be provided for the carbon and nitrogen atoms in this direction, and these will desert their positions along the y and z-axes in preference for the positions on the x-axis. When the iron lattice is allowed to retrun to its original length, the solute atoms will be crowded back to their former positions. Energy required for atomic movements of this kind must be obtained from the vibrational energy and will result in a reduced amplitude of vibration, i.e. by damping. Two opposing factors operate with rise in temperature; the number of solute atoms may increase, but there also occurs an expansion of the iron lattice. These two opposing factors combine to give a maximum in the damping capacity when plotted against temperature. It is shown that the peak in the damping curve is exactly proportional to the content of carbon or nitrogen present. Both elements have a deleterious effect on the toughness of steel in certain circumstances.

In the case of rimming steels Epstein[17] has claimed that the addition of 0·03-0·15 per cent of vanadium and/or 0·3 per cent of chromium to a rimming steel confers a high resistance to strain-ageing without seriously affecting the rimming properties of the steel. Epstein, Cutler and Frame[18] have supported this claim with vanadium-treated rimming steels.

In Great Britain, the subject has been studied on an extremely scientific and systematic basis, viz. to start with as pure iron as can be experimentally obtained and study the effect of trace impurities (with which iron is commonly alloyed in practice to yield steel) on it. This excellent work undertaken at the National Physical Laboratory, Teddington, has yielded valuable additions to our knowledge of this subject.

Perfectly pure iron has never been prepared. Realizing this the National Phsyical Laboratory workers have adopted a standard of purity which could be regarded as sufficient with the help of a special vacuum technique. They worked with pure iron containing: C, 0·002-0·004 per cent; Si, 0·002-0·003 per cent; Mn, 0·004 per cent; S, 0·0004-0·006 per cent; P, $<$0·001 per cent; Al, 0·001 or less; O_2 by wt., 0·001-0·002 per cent; N, 0·001-0·002 per cent; H-trace to $<$0·000005 per cent. This excellent work has thus been done with a purity of material that has rarely been exceeded[19-21].

Pure polycrystalline iron shows a brittle behaviour in a notched-bar test at about −15°C., but does not become brittle in plain tension until much lower temperatures of about −150°C. are reached, while a single crystal of iron at −196°C. is either ductile or brittle according to the direction of the stress.

Phosphorus exercises a detrimental effect on the properties of iron because it raises the temperature of transition from a tough to a brittle fracture. The behaviour of polycrystalline material is further complicated by the fact that some elements, e.g. oxygen, nitrogen or phosphorus in iron, reduce the brittle fracture stress by weakening the grain boundaries to such an extent that brittle fractures may take place partly or wholly along the grain boundaries. The sensitivity of this effect to heat treatment is illustrated by the remarkable grain-boundary weakness that can be developed in iron-nitrogen alloys. Steel differs from pure iron principally in containing carbon and manganese. The effect of carbon on iron depends upon the heat treatment and on the quantity present, and when slowly cooled from the austenitic condition, steels of all carbon contents are brittle at −196°C. while steels of very low carbon content (below 0·05 per cent carbon) are much improved both in strength and toughness at low temperatures by being cooled rapidly. Steels containing enough carbon to be hardened are embrittled by this treatment. Excellent properties can be obtained at −196°C. for steels containing 1-2 per cent manganese and 0·05 per cent carbon suitably heat-treated.

It is considered worthwhile to further elaborate the excellent work of National Physical Laboratory investigators. Under the conditions employed in their work, the addition of more than about 0·003 per cent of oxygen to pure iron causes failure in the brittle condition to occur increasingly along the grain boundaries, with a consequent pronounced decrease in brittle fracture strength in plain tension at −196°C. and a progressive increase in the transition temperature in impact. The effect of oxygen on impact transition temperature was most marked between about 0·003 and 0·011 per cent oxygen. The rise in impact transition temperature with increasing oxygen content was largely due to a decrease in brittle fracture strength. At the higher oxygen levels, however, because of the small temperature dependence of the yield stress and possibly also of the brittle fracture strength above, say, room temperature, a rise in impact transition temperature could be accounted for by a small change in either.

No intergranular phase has been found to explain the grain-boundary weakness conferred on iron by oxygen, so that the precise mechanism of the embrittlement is not known. Definite evidence of iron oxide inclusions was first obtained with 0·007 per cent of oxygen; raising the oxygen content above this level increased the number of oxide inclusions, which were randomly distributed.

The addition of manganese was found to counteract very largely the embrittling action of oxygen, but some grain-boundary failure remained. Brittle fracture in a normalized mild steel occurred partly along grain boundaries, and its transition temperature range of 10°-85°C. in the Charpy impact test was higher than it would be otherwise because of this intergranular weakness.

Concerning the important effects of small quantities of carbon on the mechanical properties of high purity iron, with particular reference to the transition from the tough to the brittle state, it is pointed out that the great toughness, with increased yield stress, that can be conferred on iron by retaining as little as 0·04 to 0·05 per cent of carbon in the ferrite by quenching, is diminished by ageing at room temperature. Ageing is accompanied by the precipitation from the supersaturated ferrite of carbon-rich areas and can be substantially prevented by the addition of about 0·75 per cent manganese. These results obtained at Teddington render intelligible the effects of manganese content and heat treatment upon the susceptibility of mild-steel plates to brittle fracture and indicate how the susceptibility may be controlled in practice.

Nitrogen is often considered to be similar to carbon in its effects on iron, but in an iron containing 0·01 per cent of nitrogen a number of effects quite dissimilar to those of carbon have been found. In particular, the grain boundaries appear to be greatly weakened by the presence of nitrogen in solution in ferrite, and the precipitation of iron nitride appears to be less effective in decreasing the ductility of iron than is the precipitation of iron carbide. The degree to which the grain-boundary embrittlement occurs is strongly influenced by the rate of cooling through certain ranges of temperature.

Phosphorus has long been known to reduce the ductility of iron. Its effects prove to be in many ways similar to those of nitrogen. Grain-boundary embrittlement is produced to a degree that depends upon the quantity of phosphorus and the rate of cooling. Some of these results obtained by National Physical Laboratory workers have been depicted in Figs. 9-13.

The problem of brittle fracture of mild steels is such a *bête noire* in the design of large welded structures such as ships, bridges, etc. General features of the problem are now so well established that further elaboration of the subject-matter would be largely redundant. One characteristic which should be recalled is that brittle fracture has a

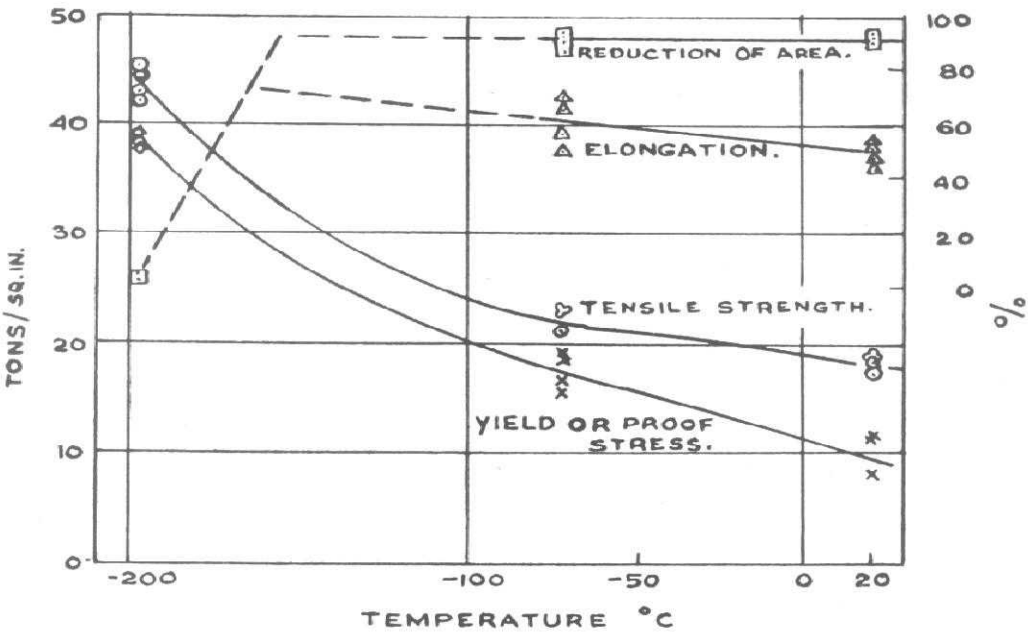

FIG. 9 — TENSILE PROPERTIES OF PURE IRON OVER A RANGE OF TEMPERATURE

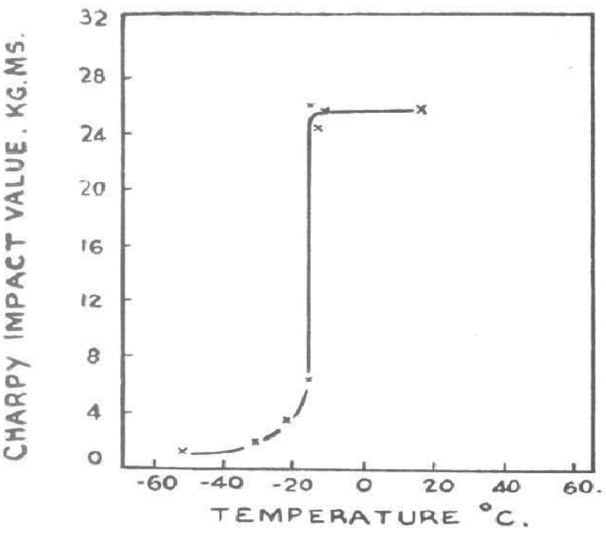

FIG. 10 — THE IMPACT TRANSITION TEMPERATURE IN PURE IRON

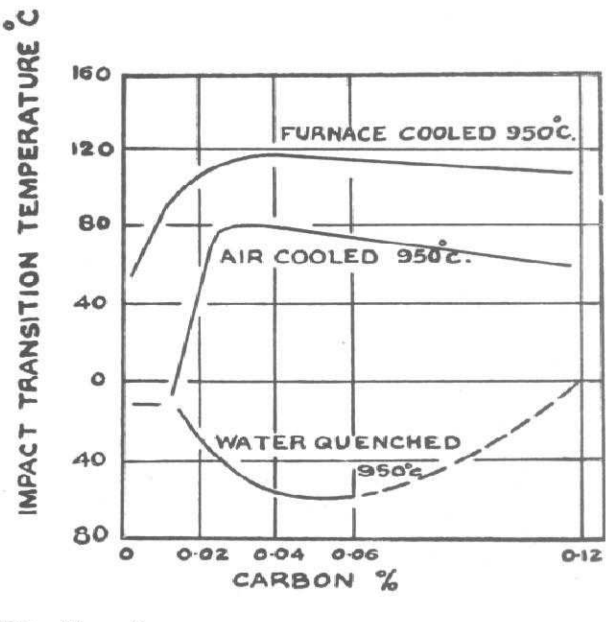

FIG. 11 — CHARPY IMPACT TRANSITION TEMPERATURES OF IRON-CARBON ALLOYS

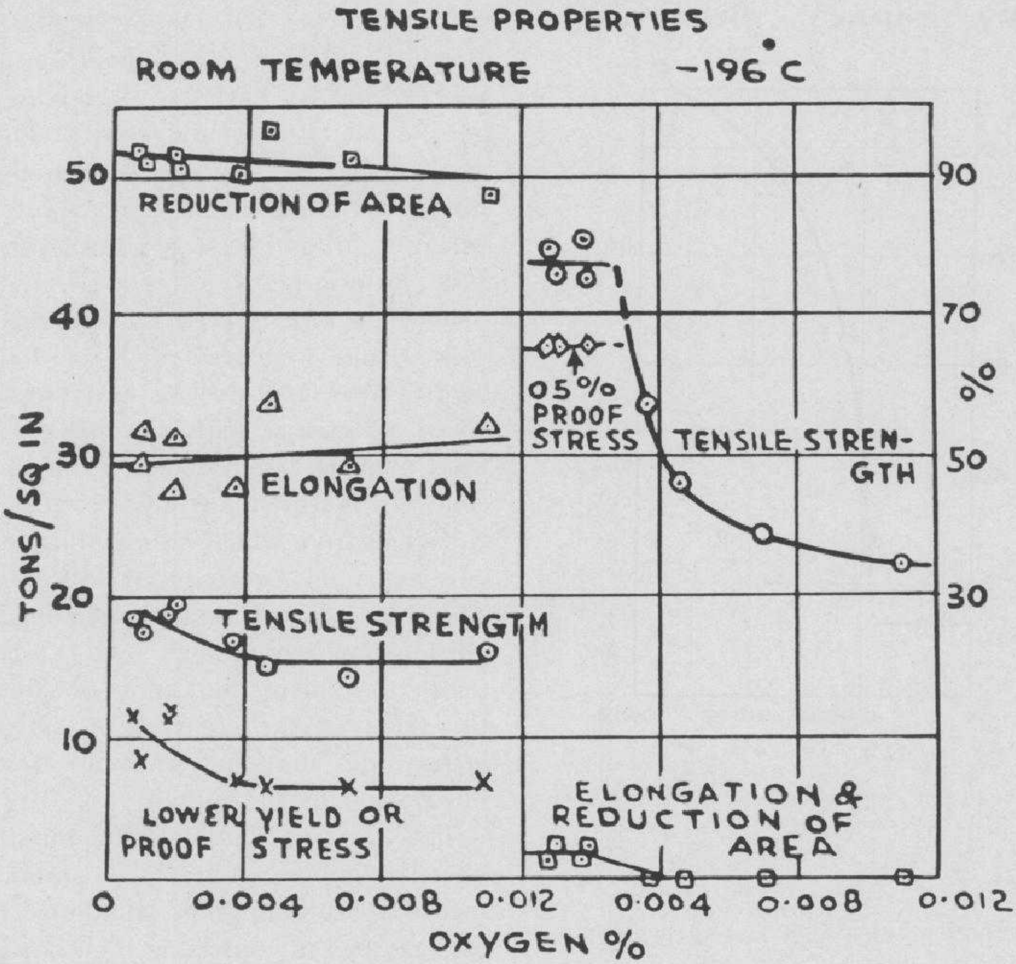

FIG. 12 — EFFECT OF OXYGEN IN IRON ON TENSILE PROPERTIES

distinct crystallographic connotation, in the sense that the fracture path follows the (100) planes or the cube faces of the iron lattice, while normal ductile failure appears to possess no crystallographic preferences. The term brittle fracture can be a misnomer since it may be preceded by considerable plastic flow before cleavage of the grains follows. In ordinary structural steels cleavage fracture appears at about 0°C. in notched-bar impact tests, and about −160°C. in tension. In studies of brittle fracture, therefore, it is not surprising that an acceptable theory of notch brittleness will command attention. The hypothesis which Orowen[22] employs to account for this property postulates the existence of a cleavage strength which is less dependent on temperature or strain than the yield stress or flow stress. In general, the cleavage strength is greater than the shear fracture strength of the material, and obeys Sohncke's normal stress law. When a notch is present, larger sections on either side of the root constrain the material thereby generating a hydrostatic tension. The ratio of normal stress to shear stress is, therefore, raised relative to the plain bar. By this means the cleavage strength of the material may be attained before the onset of ductile failure. Recent evidence[23] rather suggests that in the special case of single crystals Sohncke's normal stress law is not obeyed, although the unique crystallographic identity of the cleavage plane is retained.

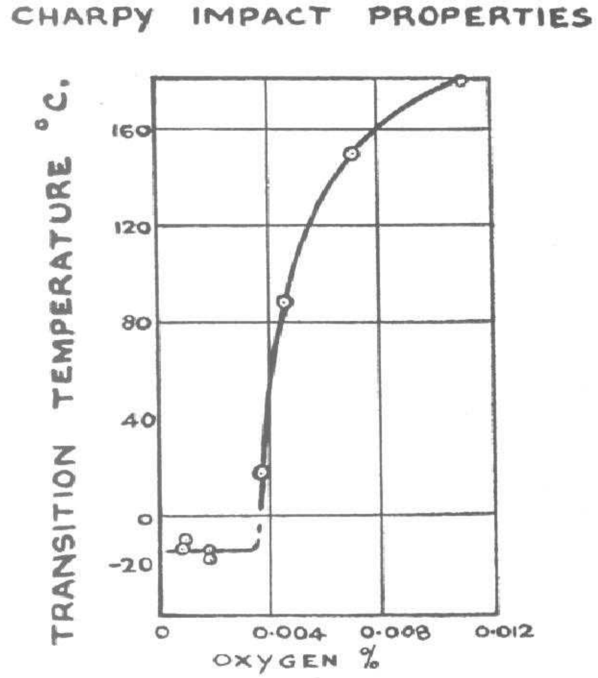

FIG. 13 — EFFECT OF OXYGEN IN IRON ON IMPACT PROPERTIES

A characteristic cleavage strength seems to exist, however, for certain polycrystalline metals.

Physical Concepts

It is not the purpose of this paper to discuss the phenomena of temper-brittleness or strain-ageing in terms of dislocations. However, some gaps tend to define themselves with a view to present the metallurgical standpoint. The physical approach very often in proceeding to explain the observed behaviour of metals tends inevitably to include a number of pure speculations, some of which are not unoften short-lived. Some may feel concerning the role of the theory of dislocation in explaining well-established phenomena, like strain-ageing, yield point, work-hardening, etc., that mathematical developments of the theory have run far ahead of the knowledge of the values denoted in the equations. The piling of dislocations behind an obstacle, function of grain boundaries acting as barriers to moving dislocations, explanation of the sharp yield point on 'avalanche' basis under the stimulus of the clustering atmospheres of solute atoms anchored around dislocations, similar to the ionic atmospheres of the Debye-Huckel theory of electrolytes, though reasonably argued and well presented, all tend to be highly speculative. The metallurgist is allowed to escape with the impression that what is being attempted in terms of physical concepts is the tendency to create master equations from which all metallurgical observations could be deduced or manoeuvred. These physical theories including that of 'dislocation' move fast — Mott's recent attempt to explain the fatigue phenomenon on the basis of the creation of extra vacant lattice sites under alternating stresses is an illustration of the mobility.

There are often other characteristics introduced by micro-additions of stabilizing elements like aluminium, vanadium, titanium, etc., to steel in conferring high impact notch toughness, reducing strain-ageing effects in steel; micro-additions of boron in improving hardenability, etc., that have yet to be fully accounted for in modern physical theories. The writer may perhaps illustrate this with a specific case, viz. the influence of carbon in relation to 'blue-brittleness' in steel. In the regions of 250°-300°C. the mobility of carbon solute atoms is assumed with the result that a moving dislocation is surrounded by an incomplete carbon atmosphere which causes a viscous drag on it. Thus the drag is smaller faster the flight of the dislocation, but at the same time higher the temperature, greater is the mobility of carbon atoms and thus larger is the stress required before the dislocation breaks away catastrophically. However, at temperatures higher than the 'blue-brittle regions' the whole phenomenon changes since the 'blue-brittleness' itself disappears. Here it is assumed that each dislocation is accompanied by its atmosphere, but the carbon atoms are then so mobile as not to appreciably retard the flight of the dislocation. One looks in vain for the effects of stabilizing elements like aluminium or titanium in eliminating 'blue-brittleness' to be explained in terms of the flight of dislocation vis-à-vis mobility of carbon solute atoms. Similar remarks can equally hold good for other phenomena, such as non-strain-ageing of stabilized steel to be accounted for in terms of dislocation theories.

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