Mines Branch Information Circular IC 120

SELECTION OF STEELS FOR THE AVOIDANCE OF BRITTLE FAILURE

by

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SUMMARY

The factors that have an adverse effect on the ductile-brittle transition include cold-work, strain-aging, quench-aging, large grain size, and increasing contents of carbon, phosphorus, nitrogen and silicon (over 0.4%). The factors that have a beneficial effect include fine grain size, deoxidation, heat-treatment, and increasing contents of manganese and nickel.

An understanding of the factors involved has led to changes in the type of steel selected for ship and land applications for which brittle failure might be apprehended. The Bessemer process has virtually disappeared, to be replaced by the open-hearth process, the L.D. (Linz-Donawitz) process, and others. Semi-killed steel is preferred to rimming steel. There has been a tendency to maintain the required strength in steels by increasing the manganese content to permit a reduced carbon content. For best properties fully deoxidized steels may be used, often in the normalized or quenched-and-tempered condition. As a last resort alloy steels may be used, usually in the fully heat-treated condition.

Proposals are in hand for the development of a series of Canadian steels with progressively increasing resistance to brittle failure. A similar series of British steels is already available.

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Direction des mines

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CHOIX DES ACIERS EN VUE D'ÉVITER LES BRISURES FRAGILES

par

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RÉSUMÉ

Les facteurs qui ont un effet défavorable sur le point de transition entre la ductilité et la fragilité comprennent l'écrouissage, le vieillissement mécanique, le vieillissement par trempe, la forte dimension du grain, ainsi que le relèvement des teneurs en carbone, phosphore, azote et silicium (plus de 0.4 p. 100). Parmi les facteurs qui ont un heureux effet, mentionnons la finesse du grain, la désoxydation, le traitement thermique, et le relèvement des teneurs en manganèse et en nickel.

Une connaissance des facteurs en jeu a permis d'apporter des modifications dans le type d'acier choisi pour certaines applications sur terre et sur mer où la brisure fragile est à craindre. Le procédé Bessemer a pour ainsi dire disparu et il a été remplacé par le procédé Martin, le procédé L.D. (Linz-Donawitz), ainsi que d'autres procédés. On préfère l'acier semi-calmé à l'acier effervescent. Dans le but de maintenir la résistance voulue, il s'est manifesté une certaine tendance à accroître la teneur en manganèse des aciers, afin de pouvoir réduire la teneur en carbone. Pour obtenir les meilleures propriétés, on peut utiliser des aciers complètement désoxydés, souvent à l'état de produit normalisé ou de produit trempé et revenu. En dernier ressort, on peut utiliser des aciers alliés, ordinairement après leur avoir fait subir tous les traitements thermiques.

On projette d'élaborer une série d'aciers canadiens doués d'une résistance de plus en plus grande à la brisure fragile. Il existe déjà une série d'aciers britanniques du même genre.

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INTRODUCTION

This review is divided into two parts. The first part covers the effects of composition and structure, with a few suggestions about why these effects should occur. In the second part an attempt is made to assess the commercial steels available from the point of view of avoiding brittle failure and also to examine the prospects of obtaining better materials.

EFFECT OF COMPOSITION AND STRUCTURE

(a) Possible Approaches

Cottrell[1] has given some thought to brittle behaviour in terms of dislocation theory, but it seems questionable whether it is possible yet to give a detailed description in atomistic terms. In these approaches, it is usually assumed that cleavage is initiated from dislocation pile-ups. Direct observation suggests that, in reality, shock twins and cementite cracks are the initiating points.

Figure 1 shows the application of fractography to cleavage facets, by Crussard et al.[2] The river-like markings are supposed to be deviations caused by structural defects. In time, this kind of work should make it possible to understand the effects of composition and structure on brittleness; at present the effects can only be described empirically.

At very low temperatures, around $-346^{\circ}F$, yielding disappears in 1020 mild steel, and it becomes brittle[(3)] (Figure 2). There are many factors besides temperature that can raise the yield stress, such as speed of stressing, effect of notches and change in section, multi-axial stresses, work-hardening, composition, impurities, strain-aging, quenching, quench-aging, and irradiation. The combined effect of these variables is to raise the temperature for the ductile/brittle transition for many commercial materials to temperatures comparable with the service temperatures.

Before examining the effect of individual elements, it is necessary to select a criterion of brittleness. Assessment by observations of brittle failure in service is an attractive possibility, but the information is insufficient and the conditions uncontrolled.

Unfortunately, as Figure 3 shows, the tests that have been developed do not always place steels in the same order of brittleness.[(3)] This might affect the importance assigned to any given element. For uniformity, the Charpy-Vee transition as given by the 15 ft-lb test will be mainly used here and in subsequent discussions unless otherwise stated. The justification for this is that it has been closely correlated with ship service failures, by Williams and others (working on ship failures), and that, because of this, the test has often been used as a standard in correlating other test criteria.

(b) Effects in Pure Iron

Work in the United States by Smith, Fostini and Brick has shown that carbon has a very considerable influence on the transition temperature in pure iron-carbon alloys.[3] A change from 0.02% to 0.22% carbon shifts the transition temperature from -33° to $161^{\circ}F$. This is several times greater than the effect of carbon in commercial steels. Figure 4 shows the results of some British work on a pure iron-carbon alloy containing 0.05% carbon, and illustrates the effect of heat-treatment.[4a] Again the changes are quite large, although similar to those that occur in steel. The sensitivity of pure iron to traces of oxide is similarly more acute, the resultant cracking being sometimes inter-crystalline, unlike that in steel.

(c) Carbon in Steel

Figure 5 summarizes the influence of carbon on fracture energy.[5] When the carbon is low, the transition is clearly marked and steep. A great deal of energy is required for fibrous fracture. As carbon is added, the upper energy level is progressively reduced. Also the transitions are shifted to higher temperatures, with the upper transitions being affected much more than the lower ones. It is clear from this that the effect of carbon will depend strongly on the criterion selected, the spread in temperature being successively increased for the 50% energy criterion, the 15 ft-lb energy level, and the 10 ft-lb energy level.

The effect of carbon content on the transition temperature is almost linear [6] (Figure 6). Three criteria are used: (a) the tear test, and (b)(c) the Charpy keyhole test with two different levels of energy. Keyhole transitions may be converted approximately to Charpy-Vee transitions by adding on about $30^{\circ}F$ or $40^{\circ}F$ to the keyhole values. There is a fair correlation between the two criteria. The illustration is taken from a paper by Boulger, Frazier and Lorig.[6] The work reported forms a part of a study of brittle behaviour at Battelle that is amongst the best to be found on compositional effects, because it was based on over 400 separate heats. Although fairly small heats of 200 lb were used, it was shown that the transition temperatures correlated with those of larger heats, for the basic A.B.S. Grade A and A.B.S. Grade B compositions on which the series was based.

(d) <u>Manganese in Steel</u>

The effect of manganese is also shown in Figure 6. Again there is a linear effect, though in the opposite sense. It may be noted that the tear test shows a less marked influence of manganese than the energy criterion of the impact test. This is a hint that manganese is less effective than is indicated by other tests in increasing the difficulty of crack propagation. It would be expected that the tear test would correlate with the propagation factor perhaps better than the impact test which includes both initiation and propagation energy fractions. According to Hartbower,[7] manganese is most influential in the range 0 to 0.8%, tapering off to some extent after this.

(e) Nitrogen in Steel

Figure 7 shows the influence of nitrogen.[6] The effect is again linear for the composition range examined. In this case the tear test indicates a greater influence of nitrogen than the impact test indicates, and again it is possible that this is reflected in a real effect on crack propagation. However, it must be remembered that most emphasis is placed on the 15 ft-lb energy criterion, which has a sound basis of correlation with actual service. It appears that the influence of nitrogen may be a little less when the manganese content is high.

(f) Phosphorus and other Impurities in Steel

No separate illustration is available for the effect of phosphorus, which has a linear and pronounced deleterious effect on the transition temperature. Phosphorus and carbon are the two worst elements in this respect. Phosphorus has a good strengthening effect, but not sufficient to offset its embrittling action.

Phosphorus (like the alloying element, manganese) is apt to promote banding. The effect of banding[8] is shown in Figure 8. The upper energy level is lowered, and in fact an effect is obtained similar to that of increasing carbon content. It may be that cracking in the high carbon bands controls the propagation of brittle fracture in banded steels.

McGeady and Stout, on the basis of notch bead bend tests, concluded that phosphorus was about twenty times as effective as carbon in raising the transition temperature. However, this figure seems high and is not now generally accepted.[3]

Recent British work[9] has shown that arsenic seems to have a similar effect to that of phosphorus, only less marked. The effect is variable and can vary from zero to, at maximum, about half the effect of phosphorus. The maximum effect occurs at 0.022% arsenic.

Sulphur appears to have little direct influence on the transition temperature, though because of its association with laminations when present in large amounts, it may, according to Parker,[3] result in an increased scatter in the results.

(g) <u>Alloying Elements in Steel</u>

Nickel has a beneficial influence. Figure 9 shows that with increasing nickel content in hot-rolled normalized steels there is a decline in the transition temperature.[3] However, the effect is exaggerated in the figure by the fact that the carbon content is declining as the nickel content is increased. Part of the benefit must be ascribed to this. Discounting the effect of carbon, the effect of nickel is still more pronounced here than has been found by other investigators. Rinebolt and Harris[10] have pointed out that the improvement depends on the criterion selected. Thus the addition of 3% nickel is equivalent to a 40°F drop in the average energy criterion, to a 45°F drop in the 50% fibrous fracture criterion, and to a 110°F drop in the 15 ft-lb transition, all criteria in connection with the Charpy-Vee impact test.

Of the other alloying elements, chromium and molybdenum have a slightly deleterious effect, and copper does not seem to have much effect.

(h) Deoxidation Effects in Steel

Rather complex effects are provided by the group of elements connected with deoxidation: silicon, aluminum, titanium, vanadium, zirconium, and niobium.

Figure 10 illustrates the effect of silicon on the transition temperature.[6] It appears that silicon has a beneficial influence when added in amounts up to about 0.3%, but that thereafter it has a deleterious effect. In most of the specifications for silicon-killed steels, an upper limit of about 0.3% or 0.35% is used. However, Figure 10 illustrates the fact that the deoxidizing elements cannot be considered in isolation.

The silicon reversal occurs at lower levels when the manganese content is high, as in the Type III steels. In other words, there is not so much deoxidation left to be done. Perhaps the silicon level should be restricted to about 0.2% for the high-manganese killed steels.

In a similar way, the effect of aluminum is bound up with the manganese and silicon contents. Amounts of aluminum up to about 0.2% seem to be beneficial, so long as the silicon content is fairly low - around 0.1%. The use of aluminum makes it possible to make steels of fine grain, which is well known to have a favourable effect on the transition temperature. Apart from the effect on grain size, even small amounts of aluminum seem to lower the transition temperature, provided that silicon is used in conjunction. This is because aluminum is a more effective deoxidant than silicon and so removes a little more of the harmful oxides, but in addition combines with nitrogen, fixing it as relatively harmless aluminum nitride. It appears that aluminum is more effective in combination with silicon. The addition of about 2 lb per ton, giving about 0.03% residual aluminum, will have a helpful effect if silicon is present in the range 0.15 to 0.30%, though larger amounts would be required if silicon were absent. Aluminum tends to be less effective in the small amounts used in semi-killed steels, because the oxygen combines with the available aluminum, leaving the nitrogen free.

Figure 11 shows the progression that occurs to lower transition temperatures, as the extent of deoxidation is increased from rimmed steels through semi-killed[7] to fully-killed steels. It is not necessary to rely on small specimens to establish the effect. A similar effect has been reported in testing full-size, wide-flange rolled beams at Columbia University, the transition being 24 to 40° higher for beams made of semi-killed steels compared with those made from killed steel.

(i) The Effects of Cold-Work and Aging in Steel

Figure 11 shows another effect of great practical importance, which tends to exaggerate the differences due to deoxidation. This is the effect of aging. There are two kinds of aging: quench-aging and strain-aging; and the results given are for aging after quenching. There is a wide spread as the result of aging for the rimmed steel, though there is a narrower spread for the semi-killed steel and a still narrower spread for the killed steel. In other words, aging has a bad influence on the transition temperature, with the killed steels being least sensitive and the rimmed steels most sensitive. This was illustrated for quench-aging but parallel effects are obtained for aging after cold-work, that is, for strain-aging.

Figure 12 illustrates the effect of aging on the impact energy of a group of basic Bessemer steels.[7] The effect of aging is given after rolling, after normalizing, and after full heat-treatment. In all cases the killed steel (K in Figure 12) is superior to the rimmed steel (R in Figure 12) in showing higher individual values for impact energy, and for reduced sensitivity to aging.

Straining or cold-working alone, even without subsequent aging, has an undesirable influence.[3] This is illustrated in Figure 13, which shows the effect of cold-working by drawing on impact energy. The lower left-hand curve is a semi-killed steel and shows a high strain sensitivity. The upper curve is for a steel from the same blow, deoxidized with 2 lb per ton of aluminum. Both steels are in the normalized condition. The right-hand curves are for a silicon-killed steel (bottom), with progressive additions of aluminum (middle and top). The effect of cold-work is quite undesirable. In the worst cases, a small amount of cold-work, 1 to 2%, is sufficient to bring down the impact energy from a high value to something around 15 ft-lb. This would happen at every location where the steel was shaped by cold-work--that is, punched, rolled, hammered, bent, and so on. After aging, which would occur slowly at normal temperatures, the condition would get worse with time.

Acker,[11] in his review of welded ship failures, mentions a case of two deformed plate specimens from welded ships, for which the transition temperature of the bent area of the plate was 20°F higher than that of the flat area of the same plate. He considers that the same effect would be significant for the cold forming of mast tube plates, which involves an outside fibre strain of 3 to 4%.

The effect of irradiation is analogous to that of cold-work, increasing strength and decreasing ductility. One investigation by the General Electric Company (using a fast neutron flux, 4.3 times 10^{20}) showed substantial loss of impact energy absorption in A201 steel. This loss was, however, substantially recovered by annealing at 600°F. The same investigation showed that steel A-302B was much less affected. Other investigators agree on the direction of the effect, though not always on the extent.

Of all the elements to be considered for reducing the effects of straining and strain aging, vanadium and aluminum are the most potent, followed by zirconium, with titanium trailing.

(j) Other Effects on Steel

The effect of grain size is important, and if the number of grains is doubled the transition temperature is decreased by 20 to 30°F; equivalent to killing with silicon, or alloying with 2% nickel.

Aluminum is helpful in obtaining fine-grained steel, as will be explained.

The effect of aluminum is complex and includes these effects: (a) deoxidation, (b) denitrification or fixing nitrogen, (c) redistribution of sulphides and inclusions, (d) reduction of grain size, and (e) alloying effect.

Some interesting microscopical work by Bruckner has thrown some light on the effect of deoxidation on the ductile-brittle transition.[12] Specimens of steel were given sub-critical impact blows and examined microscopically. Figure 14 shows a brittle cleavage crack in cementite that has extended into the neighbouring ferrite. The illustration is actually from British work by Hopkins,[4a] but Bruckner shows many similar instances. He found that in rimmed and semi-killed steels this happened very frequently, and the composition, condition, and distribution of the cementite may therefore be an important factor for the initiation of brittle cracks in these materials.

Bruckner also found that twinning usually precedes failure.[12] Figure 15 shows cleavage cracks in shock twins. In the case of fully-killed steels, the first sign of cracking often occurs in twins or twin-deformed regions. The transition temperature is therefore likely to be affected by the ease of twin formation; the number of twins; the ease of cleavage formation by twins; and the ease of twin propagation. Bruckner shows that the less thoroughly deoxidized steels have a higher twin nucleation temperature; easier twin formation presumably implies easier crack initiation.

Niobium has not received much attention. Its effects are at least as complex as those of aluminum. In addition to the effects described for aluminum, niobium affects the composition of the carbides and the response to heat-treatment.

Figure 16 summarizes the effects of the various elements on the transition temperature.[3] It appears at once that carbon and phosphorus are the worst; that manganese is consistently good up to about 1.5%; and that nickel is similar to manganese but proportionately less effective. Vanadium has a maximum deleterious effect at about 0.15%. The data refer to killed steels with about 0.3% carbon, 1% manganese, and the diagram is due to Parker.[3]

COMMERCIAL STEELS

In the second part of this review, it will be shown how the effects of composition and structure are reflected in steel-making practice, and in the steels and specifications available.

(a) The Steel Process

Of the structural steel used in the United States in 1957, 87% was made by the open-hearth process and 10% by the electric-furnace process. The remaining 3%, from Bessemer output, is mainly used for tubing, piping and bars. It is characteristic of the open-hearth process that the sulphur is not more than about 0.025%. This low value is normally advantageous but it is of little consequence for brittle failure. It is more important that because of the heavy slag blanket, the nitrogen content can be kept low, usually below 0.006%. With the electric furnace, higher nitrogen contents are usual, and with Bessemer steel it would be normal to have around 0.015% nitrogen and also high phosphorus in the range 0.07 to 0.12%, the highest values being for the acid Bessemer process. The Bessemer process is the worst for brittle failure, and this may account, in part, for the virtual disappearance of the process in its original form.

However, the position with regard to steel manufacture is beginning to change with the introduction of the Linz-Donawitz (L.D.) and related processes. The use of pure oxygen, particularly in the L.D. process, seems to offer possibilities of increased production, and a very acceptable product, that may well bring a complete resurgence of the Bessemer-type process. The results of a one-year examination showed that in spite of the fact that the raw pig-iron contained an average of 0.175% phosphorus, the L.D. steel contained phosphorus in the range 0.013 to 0.040% and mostly around 0.026%. Sulphur is reduced from 0.045 to around 0.021%. Nitrogen is low, usually better than 0.008%. On the basis of composition, this is as good as, and often better than, can be produced in the open-hearth. It is not to be wondered that the L.D. steel is finding its way more frequently into specifications as an alternative to open-hearth and electric steels. This trend will probably continue. The Austrian steel specified to Grade 44KA is a non-aging steel with guaranteed weldability and guaranteed resistance to brittle fracture as measured by the weld bead bend test. This specification can be met by the L.D. steel. There is also an interesting new steel from Luxembourg, designated L.D.A.C., which uses oxygen and lime in combination, and for which characteristic figures of 0.002% sulphur and 0.025% phosphorus are given. There are so many permutations of the various improvements in steel-making, such as the use of oxygen injection in the open-hearth for instance, that it is becoming increasingly difficult to keep definite boundaries between the various processes or to maintain a running balance of their rival merits.

(b) Deoxidation and the Steel Product

The product of the steel process may be rimmed, semi-killed or fully killed, and without entering into detail it is worth taking a glance at the differences in composition involved. Rimmed steel should contain about 0.35% manganese and only traces of other deoxidants. In semi-killed steels the manganese is usually a little higher, and silicon is added though less than 0.15%. In fully-killed steels, the manganese content is about the same or higher, but the silicon content is in the range 0.15% to 0.30%, and aluminum is sometimes added. The total nitrogen content of rimmed, semi-killed and killed steels will vary as a result of the steel process rather than the extent of deoxidation. Moreover, in steels killed with aluminum, part, at least, of the nitrogen is fixed as aluminum nitride and may be so distinguished by analysis. The extent to which the nitrogen is fixed is partly determined by the heat-treatment.

(c) Plate Thickness, Grain Size and Heat-Treatment

If a steel is purchased to "fine-grain practice", it does not mean that the steel supplied necessarily has a fine grain. The steel is only potentially fine-grained as a rule. It is not necessarily fine-grained in the hot-rolled condition, the condition in which it is normally supplied, but will have a grain size similar to a semi-killed steel of the same composition. It must be normalized at low temperatures (1600 to 1700°F) to develop fine grain, or, for low-thickness plate, it must have been finish-rolled at a similar temperature. Each time the steel passes through the rolls it recrystallizes, so that the final grain size depends on the temperature of the finishing pass. Figure 17 shows that aluminum added in critical amount, around 0.05%, elevates the grain-coarsening temperature.(6) Even so, the grain-coarsening temperature for a killed steel similar to the Navy Grade C may be around 1760°F. Thick plates require few roll passes and have a high finishing temperature. In addition, they cool more slowly and there is usually some time for grain growth. The advantages of steels made to fine-grain practice can usually only be realized by normalizing at least the thick plates. The roll finishing temperature for thin plates is lower, say around 1750°F, so that the benefit of normalizing is consequently less. Figure 18 shows the effect of controlling the roll finishing temperature, and a change from the more normal 1850 to 1650°F has an obviously desirable effect.[6] These curves were obtained by taking commercial $1\frac{3}{4}$ in. plates from three sources and re-rolling to 3/4 in. thickness with different finishing temperatures. This reduction of 200°F in the finishing temperature is equivalent to changing the manganese/carbon ratio from 2:1 to 5:1. The control of the reheating temperature for the final pass is quite common in the lighter sections, but control of finishing temperature for thick plates does involve some difficulties, though the method has been used rather successfully in Sweden. Some improvement may be obtained by accelerated cooling after the last pass in the thick plates.

Normalizing, in addition to refining the grain, reduces the magnitude of the variations. Normalizing offers a bigger potential advantage for killed steels. Thus it might lower the transition temperature by about 65°F for the Navy Class C steel, but only 30 to 40°F for the Class A and B steels respectively. Even better, from this point of view, is full heat-treatment. Quenching-and-tempering results in a fine grain size and also a dispersal of carbides.

(d) Economic Aspects

Taking as a starting point the semi-killed steels, there are certain disadvantages of killing. Production is reduced because control is more difficult. In addition, a larger portion of each ingot must be scrapped. Concern has been expressed about hot-top capacity for the large-scale production of killed steels in the event of an emergency. In these circumstances, it makes good economic sense to make the best use of semi-killed steels, by securing the maximum advantages to be gained from control of composition. In simple terms, this means reducing the carbon content, and maintaining the strength by increasing the manganese content. It is common sense to take a long step in this direction, as has been done in Europe. So far, Canadian and American steelmakers have seemed reluctant to follow in this direction. To obtain further benefit from semi-killed steel, the next obvious step would probably be to normalize it.

There is an obvious limit to what can be done with semi-killed steels, and when the possibilities have been exhausted it is necessary to consider as-rolled killed steels, normalized killed steels, and heat-treated killed steels. The effect of some of the variables is shown in Figure 19, the information being due to Mackenzie.[4b] Finally, there are the alloy steels, and especially the nickel steels, though from the point of view solely of resisting brittle failure the use of alloy steels is a last resort. Of course, in practice, the picture is complicated by other requirements.

(e) United States Navy Steels

It is worth looking at the use of steel by the United States Navy, because not only have they had the greatest problem in the history of brittle failure, but they have instituted the largest and most elaborate investigations, and have provided answers that may prove at least the basis for something permanent.

When it was realized that more than design was involved, a fairly thorough examination of the fractured wartime ship plates was undertaken, and this revealed that the transition temperatures were in the range 0 to 155°F, with a large number in the range 30 to 90°F. The American Bureau of Shipping therefore drew up new specifications in 1948, which were modified in 1957, and which may be found in modern form in the parallel A.S.T.M. specification A131 (Structural Steel for Ships). Figure 20 shows the shift to lower transition temperatures of the three grades A, B, and C, from the original single grade.(11) Before 1948, the steel used was bought to tensile requirements, with composition limitations only on sulphur and phosphorus. Grade A is not very different from the original, but is now used only in thicknesses of less than 1/2 in. Grade B, used for thicknesses of 1/2 to 1 in. inclusive, has a maximum set for carbon of 0.21%, and manganese must be in the range 0.80 to 1.10% by ladle analysis. Grade C, used for all plates over 1 in. in thickness, is a silicon-killed steel made to fine-grain practice with a carbon limit of 0.24% and intermediate manganese of 0.60 to 0.90% by ladle analysis. It is considered good practice to normalize when the plate thickness exceeds 1-3/8 in., though this is not mandatory.

Fairly extensive comparisons of present steels with pre-1948 ship steels have shown that, as a result of these changes, the average transition temperature has been reduced by over 40°F for plates of intermediate thickness (1/2 to 1 in.) and over 100°F for thick plates (1 to 1½ in.). A recent report of the Ship Structure Committee(13) has revealed that, since these steels have been in use, only 68 dangerous brittle fractures have been recorded in ships over the period April 1952 to December 1958. A remark from the report is worth quoting: "The smaller fractures, even in important locations, must be accepted as routine in welded ships."

(f) Available Steels from All Sources

Figure 21 shows the range of Charpy-Vee 15 ft-lb transition temperatures for a number of ship steels and also structural steels for non-ship structures. The vertical scale for temperature (°F) is inverted so that progression upwards indicates a fall in transition temperature, and an improvement in the steel.

For this chart, specified or measured temperatures relating to the Charpy keyhole test have been converted to Charpy-Vee 15 ft-lb values by the addition of 35°F.

In the lower left corner, the ship steels are again illustrated. Curve A represents the estimated air temperatures to which the wartime ships were exposed, with a peak frequency at around 68°F. The smaller distribution curve F represents the failure temperatures and has a peak frequency at around 40°F; the failure temperatures are spread over the lower half of the ambient temperature range. It is interesting to compare the range of brittle/ductile transition temperatures for the ship steels used. The block T indicates that most of these fell in the range 90 to 30°F. As explained before, the complete distribution covered 155 to 0°F, but most fell in the range shown. Most of the welded ships made at this time must have been at least partially brittle every winter. The progressive improvement in Grades A, B, and C is clear. The block for Grade C is in two parts, the upper being for experimental values obtained on re-rolling to 3/4 in. thickness. The adjacent shaded blocks represent the effect of normalizing. It is an experimental observation that rolling thick plates in C Grade to 3/4 in. thickness slightly improves the transition temperature, but this has no practical implications. It is of interest to note that normalizing produces a considerable improvement, particularly for Grade C which is a fully-killed steel made to fine-grain practice. It is apparent that there is no complete security, since the transition temperatures of all grades except normalized Grade C can extend to higher temperatures than the range where the failures of the wartime ships occurred. However, in combination with improved design, the failures may be reduced to manageable proportions.

The position for non-ship structures is not so well known. The range of ambient temperatures to which they are exposed will evidently extend to lower temperatures (curve A, lower left of centre, Figure 21). The range of failure temperatures given by Shank [12] in his study of brittle failure in non-ship structures shows that in the past failure has occurred in the temperature range $+41^{\circ}F$ to $-40^{\circ}F$, with a peak frequency value at $-4^{\circ}F$ (curve F, lower left of centre, Figure 21). The transition temperatures of steels which failed varied from 0 to $100^{\circ}F$, with a peak frequency at about $32^{\circ}F$ (curve T, bottom centre, Figure 21). Two rather general conclusions may be drawn. First of all, on average, non-ship structures have in practice failed at much lower temperatures than the ships, around $65^{\circ}F$ lower, and this suggests that for a wide range of different structures the conditions are much less severe than for ships. Secondly, for brittle failure, a differential between the transition temperature for the ship steels and the ambient temperature of about $30^{\circ}F$ has seemed to be necessary - that is, ships have usually failed at temperatures about $30^{\circ}F$ below their transition temperature. This is an approximate figure. From the few figures available so far, there is a similar differential between the transition temperature and the ambient temperature for failures in structures other than ships. However, longer experience may show that the differential temperature required is larger for structures other than ships, in line with the suggestion that the conditions are less severe than for ships.

There is little reason to suppose that the transition temperatures for A7 would be very different from those obtained for the A.B.S. Grade A steel and the pre-1948 ship-hull steel, since it is made to a similar specification. The transition temperatures for A7 are therefore shown extending from 0 to +150°F. Some points are shown within the A7 block (bottom centre, Figure 21) for the transition temperatures of structures made in A7 that have failed by brittle failure. It would certainly be anticipated that for bridges, storage vessels, and pressure vessels made in this material, there would be an appreciable risk of brittle failure.

The weldable structural steel A373 should be better from the viewpoint of brittle/ductile transition temperature. There is little direct information, but it is estimated (on the basis of composition) to be in the range from -10 to +60°F (right of lower centre, Figure 21).

The next three blocks, derived from extensive data by Mackenzie,[4b] show the transition temperatures for the plates produced from a Scottish mill using open-hearth, semi-killed steel (right of lower centre, Figure 21). It is interesting to note that there is a marked increase in transition temperature when the plate thickness is over one inch. The reason for the A7 temperature range being placed a little higher than the Scottish steel is that the carbon content for A7 typically averages around 0.26% compared with less than 0.20% for the Scottish steel. Mackenzie[4b] describes the steps that were taken to analyze, using statistical methods, the reasons for the variations in transition temperature. It was concluded that variations in carbon content, manganese content, phosphorus content, and residual nickel content, combined with variations in roll finishing temperature, accounted for 72% of the variance in transition temperature. The analysis presumably provided some of the ground work for the development of Coltuf, which is a high-manganese, low-carbon, fully-killed steel made to fine-grain practice, and supplied in the normalized condition. The small blocks (marked Colvilles, right side, Figure 21) represent typical figures for such a steel in the as-rolled and normalized condition.

At the present time, one of the best available unalloyed carbon steels is A201 (right side, Figure 21). This is a silicon-killed steel with up to 0.8% manganese content and up to 0.20% carbon content for Grade A, with minimum tensile strength of 55,000 psi. Grade B specifies a maximum carbon content of 0.24% and should comply with a minimum tensile strength of 60,000 psi.

When required for pressure vessels for service at low temperatures, the ceiling on manganese content is raised to 1.0%, and the A201 steel can be supplied under specification A300 with guaranteed 15 ft-lb Charpy keyhole impact energy at temperatures down to -50°F. The best properties can only be obtained by normalizing, or by control of roll-finishing temperature. A203 is a higher strength pressure vessel steel, but contains $2\frac{1}{2}$ to $3\frac{1}{2}$% nickel depending on grade and thickness (centre, Figure 21). This steel can be supplied also to A300 with guaranteed 15 ft-lb Charpy keyhole impact energy at temperatures of -75°F and -150°F. A410 (right of centre, Figure 21) is a chromium-copper-nickel-aluminum pressure vessel steel (about 2 to 3% total alloy content) which can similarly be supplied with guaranteed Charpy keyhole impact values at temperatures down to -150°F.

Typical values for T-1 steel are given for comparison (right, Figure 21). T-1 contains a variety of additions which add up to about $2\frac{1}{4}$% total alloy content. This is supplied in the quenched-and-tempered condition, and it is only fair to say that the better known structural steels would also be much improved by full heat-treatment. A353 (top right, Figure 21) is the 9% nickel steel which can be supplied with guaranteed 15 ft-lb Charpy keyhole impact value to temperatures as low as -320°F.

It is interesting to compare, with the commercial steels, the results of some laboratory investigations (upper right, Figure 21). A normalized $2\frac{1}{2}\%$ nickel steel ($2\frac{1}{2}$ NT in Figure 21) is further improved by quenching and tempering ($2\frac{1}{2}$ QT). An as-rolled $3\frac{1}{2}\%$ nickel steel ($3\frac{1}{2}$ AR) shows remarkable improvement after normalizing and after full heat-treatment ($3\frac{1}{2}$ NT).

There is a temperature limit at about -50°F, below which it is not possible to obtain guaranteed satisfactory impact values without normalizing or equivalent treatment, and a limit at about -75°F, below which it is necessary to use alloy additions as well. These limits are indicated at the appropriate temperature levels on the left side of Figure 21. However, the experimental work suggests that if maximum use were made of the composition and heat-treatment, smaller amounts of alloy would be necessary than are used in present steels.

There is a region of uncertainty extending from a temperature of $+25^{\circ}$F to -75°F. To obtain guaranteed satisfactory impact performance for minimum temperatures within this range, it is not clear what control methods should be used. There is some disagreement about the technical and economic merits of various improvements, and good data are rather scarce.

It is useful, therefore, to consider the British notch-ductile steels ND1, ND2, ND3 and ND4, which are now commercially available (14) (right, middle, Figure 21).

The specification permits high manganese content up to 1.5%, with a maximum carbon content of 0.20% for ND1 and ND2, and 0.17% for ND3 and ND4. The two lower grades ND1 and ND2 are semi-killed, and the upper grades ND3 and ND4 are killed steels to fine-grain practice, with some use of normalizing for Grade ND4. They are sold with the following Charpy-Vee notch energy acceptance limits: ND1, 20 ft-lb at $0^{o}F$; ND2, 20 ft-lb at $-15^{o}F$; ND3, 20 ft-lb at $-30^{o}F$; and ND4, 20 ft-lb at $-50^{o}F$. There is considerable interest in the steels, particularly among the fabricators of oil-storage tanks, and it was partly as a result of a demand from this source that the requirements for the ND steels were drawn up. Figure 22 shows typical curves for the British ND steels.[14] The results are for 1 in. plate.

Something similar will probably result from present deliberations on a proposed series of five Canadian notch-ductile steels (labelled A, B, C, D, E, on Figure 21, right centre). Discussions are still going on, and at the time of writing, preference has been shown for having only three steels instead of the original five. These steels would probably be sold with tight compositional control, and though they would have no specific impact energy requirements, the composition and treatment of the steels would give reasonable assurance of expected performance.

(g) Steel Prices and Steel Selection

The following prices are approximate and are quoted for 100-lb lots. The basic price of A7 is $5.85. A373 and Navy Grade C would be around $7, since this includes silicon-killing. Fine-grain practice would be another extra and some grades of A201, involving this treatment, would go up to around $8, or even $12 if supplied to A300. It is difficult to be precise, because there are so many different premiums, depending on the particular circumstances such as size and shape of plates, thickness, deoxidation, composition, miscellaneous specification requirements, additional tests (especially if low-temperature properties are involved), heat-treatment, and so on. The cost of alloy steels is often very high, sometimes several times as high as for unalloyed steels; in spite of this they are occasionally preferred because of the additional safety factor. The cost of importing steel with guaranteed impact properties may sometimes be worth considering. For example, the premium for the British Grade ND4 is about $3 per 100 lb, including normalizing. For premium quality, and until there is some equivalent here, this might be a possibility. The corresponding premium for the British Grade ND1 would be about 80¢ per 100 lb. With regard to the proposed Canadian notch-ductile steels*, the cost of Grade I will probably be a little higher than that of A131 Grade B, while Grade III is expected to be a little more expensive than A131 Grade C. Grades IV

* Since this circular was prepared, the Canadian Standards Association has issued Specification G40.8 covering three grades of notch-ductile steels. Prices may be obtained from manufacturers but are less than were first expected.

and V should be cheaper than the present alloy steels that they will replace. All grades will cost more than A373.

It is difficult to assess the cost of failure in non-ship structures, especially when the danger of loss of life must be reckoned. Success and failure can be evaluated only in statistical terms. Experts may provide contradictory answers, even if it is possible to decide exactly how much assurance is required. This is a hinterland of opinion and uncertainty. Many will say that there are thousands of structures made in A7 steel which have not failed, and draw the conclusion that nothing better is required. On the other hand, 20% of the non-ship failures reported by Shank were made in A7; another 20% were in steels similar to A7. All told, that makes 40% of past failures in steel of this type. In these terms, the performance of A7 seems questionable. Moreover, in the future, there are likely to be more exacting requirements: higher stresses, greater thicknesses, lower temperatures (for building programs in the northlands and in the Arctic). Evidently, better steels will be needed, but no one can say exactly how much better they must be. Few can question the wisdom of making available better steels, such as the ND steels. This provision will make it possible for constructors to choose from several steels for their different requirements. This choice will usually involve a compromise between technical and economic considerations. Such decisions have always been part of the burden of practical men. It may be asserted with confidence that an alert, empirical approach will help to overcome difficulties in the future as it has with those of the past.

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Figure 1 - River markings on cleavage surface in iron. (Ref. 2)

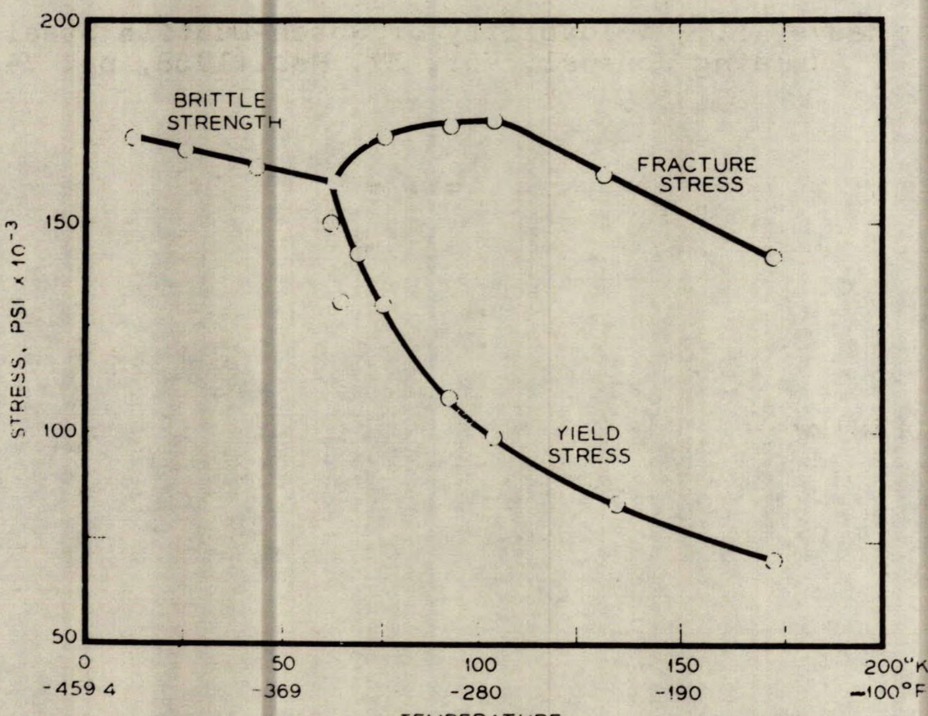


Figure 2 - Disappearance of ductility in iron at low temperatures. (Ref. 3)

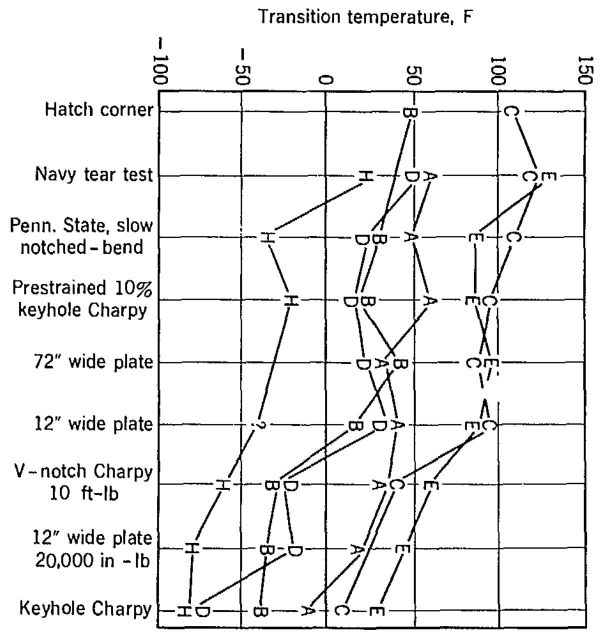


Figure 3 - Plot of various transition temperatures for six project steels. (Ref. 3)

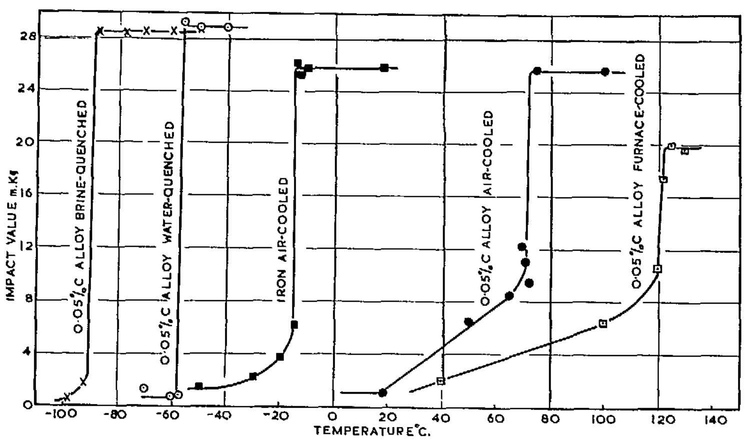


Figure 4 - Impact values at various temperatures of iron-0.05 per cent carbon alloys cooled at various rates from 950°C and of a high-purity iron air-cooled from 950°C. (Ref. 4a)

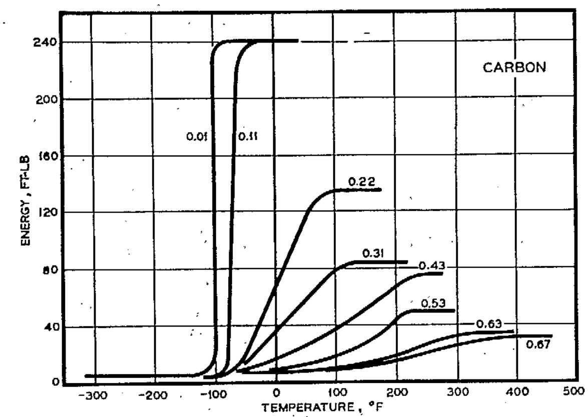


Figure 5 - Effect of carbon on the shape of the Charpy-Vee transition curve. (Ref. 5)

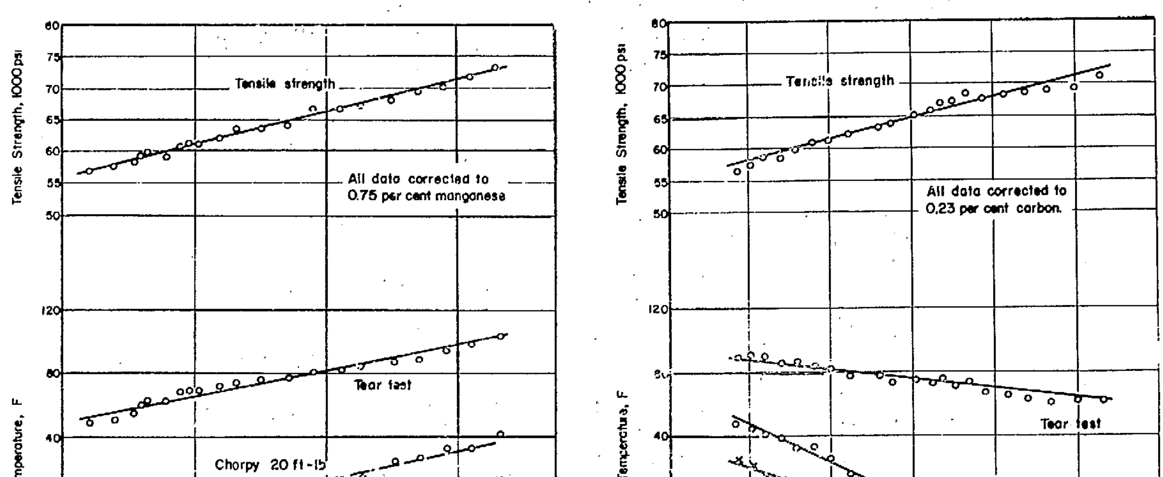


Figure 6 - Influence of carbon (left) and manganese (right) on properties of hot-rolled semi-killed steels made and processed in the laboratory. (Ref. 6)

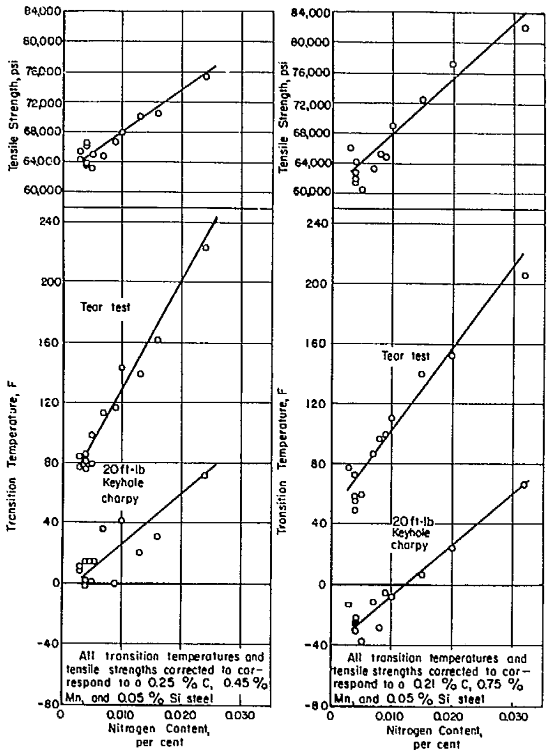


Figure 7 - Influence of nitrogen on tensile strength and notched-bar properties of semi-killed steels. (Ref. 6)

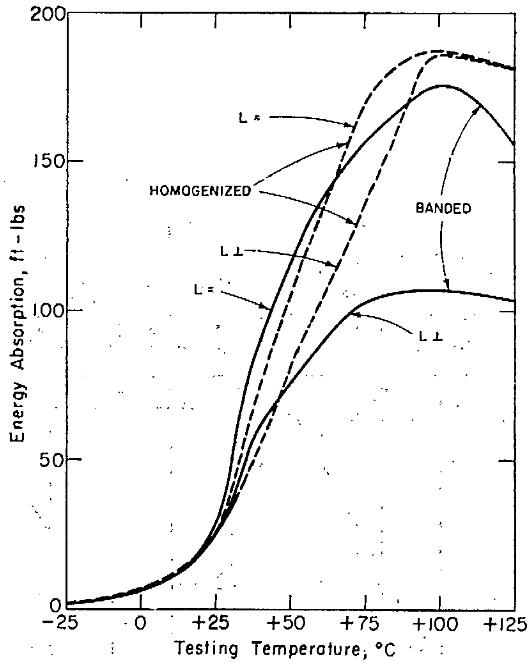


Figure 8 - Effect of banding on Charpy-Vee impact energy and the removal of this by homogenization. (Ref. 8)

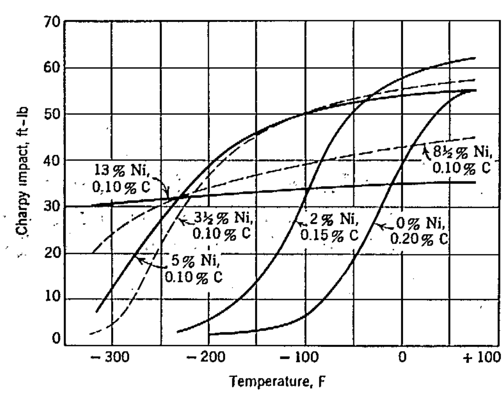
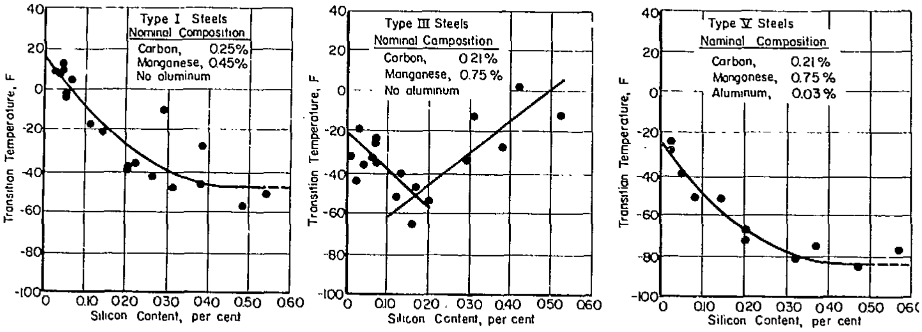
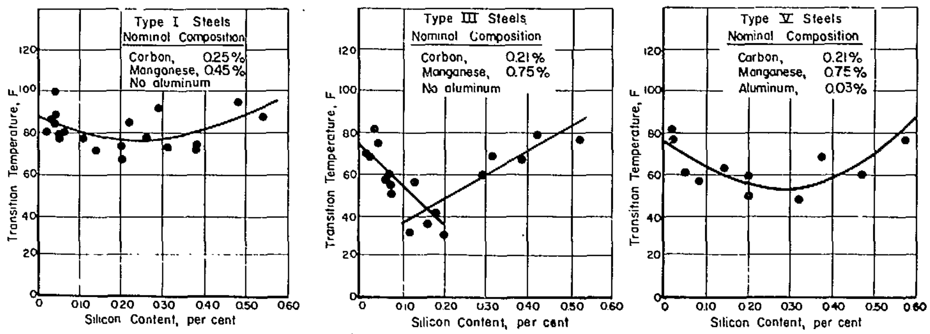


Figure 9 - Effect of nickel content on keyhole Charpy impact energy in normalized low carbon steels. (Ref. 3)



(a) Keyhole Charpy (12 ft-lb)



(b) Tear test (P = 0.5)

Figure 10 - Effect of silicon on the transition temperatures of three steels. (Ref. 6)

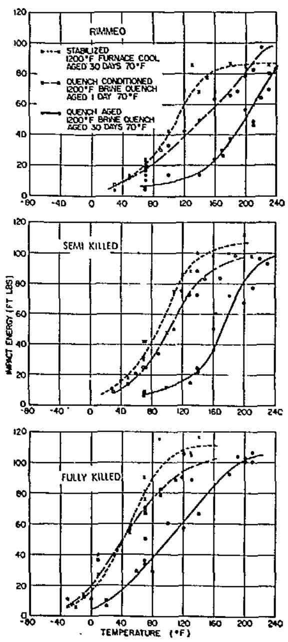


Figure 11 - Effect of aging on the energy-temperature relationship in impact. (Ref. 7)

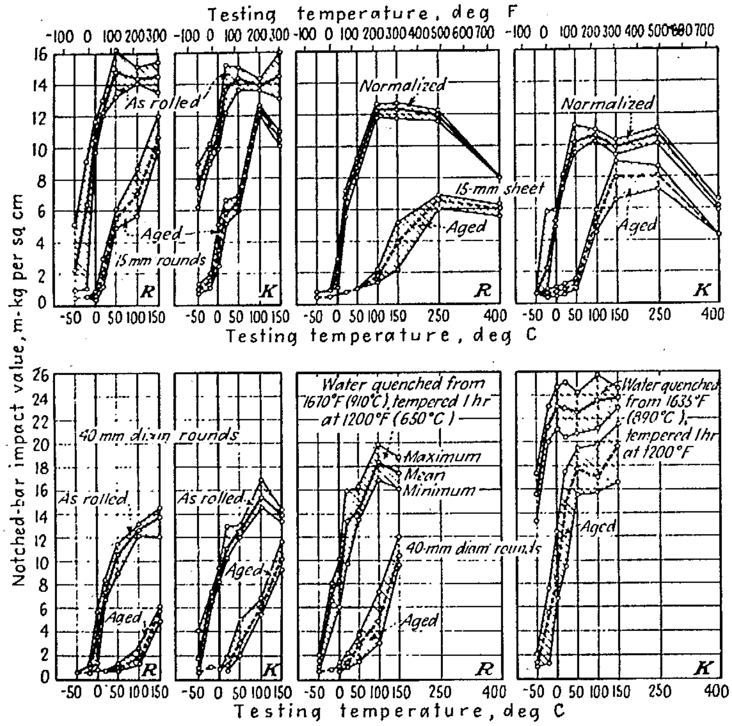


Figure 12 - Notched-bar impact values versus testing temperatures of rimmed (R) and aluminum-killed (K) basic Bessemer steels. (Ref. 7)

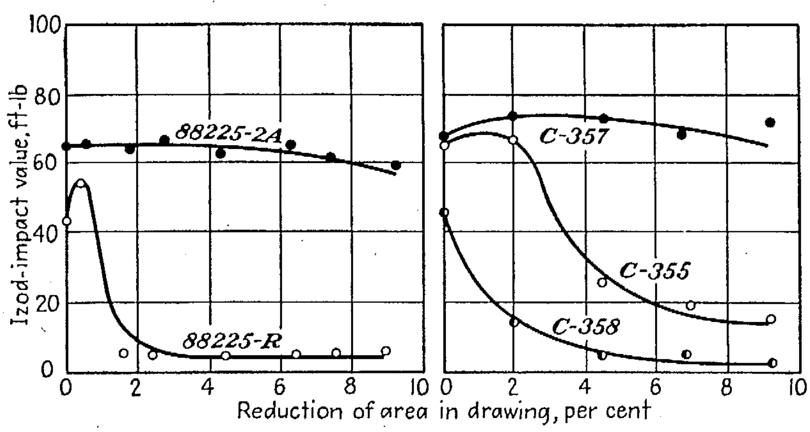


Figure 13 - Typical strain-embrittlement curves. 88225-2A and C-357 show a very low order of strain sensitivity; 88225-R and C-358 show a high order of strain sensitivity; C-355 is intermediate. (Ref. 3)

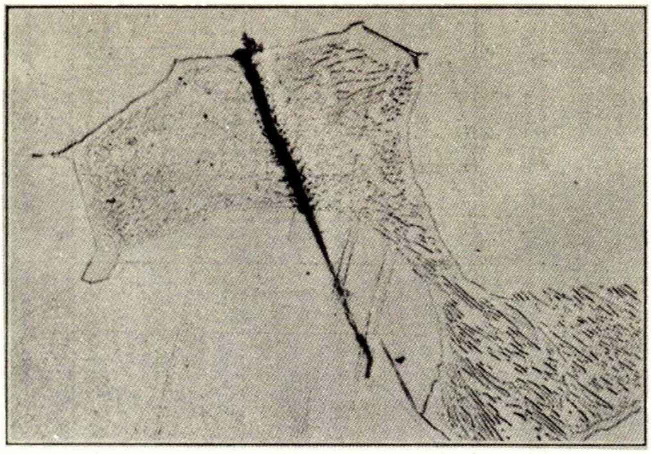


Figure 14 - Crack extending from carbide through an area of pearlite into ferrite grain in an iron-0.05 per cent carbon alloy. X1500. (Ref. 4a)

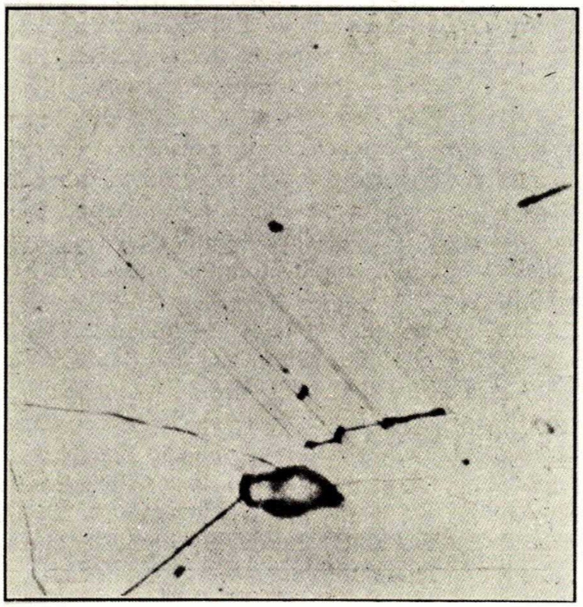


Figure 15 - Initiation of cleavage fracture in mechanical twins in low-carbon rimmed steel. Etchant, 5% nital; X1500. (Ref. 12)

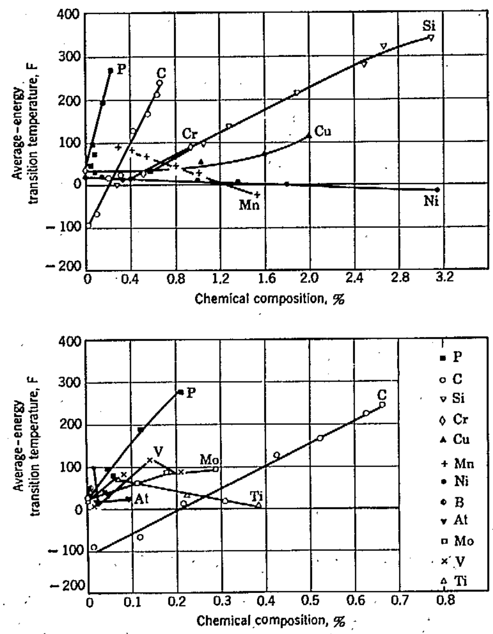


Figure 16 - Effect of chemical composition on average-energy transition temperature. (Ref. 3)

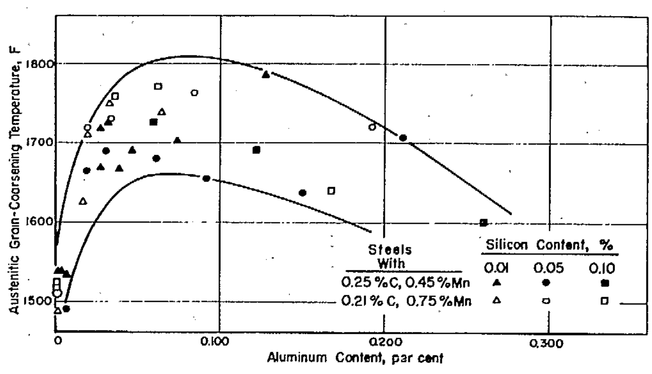


Figure 17 - Influence of acid-soluble aluminum on austenitic grain-coarsening temperature. (Ref. 6)

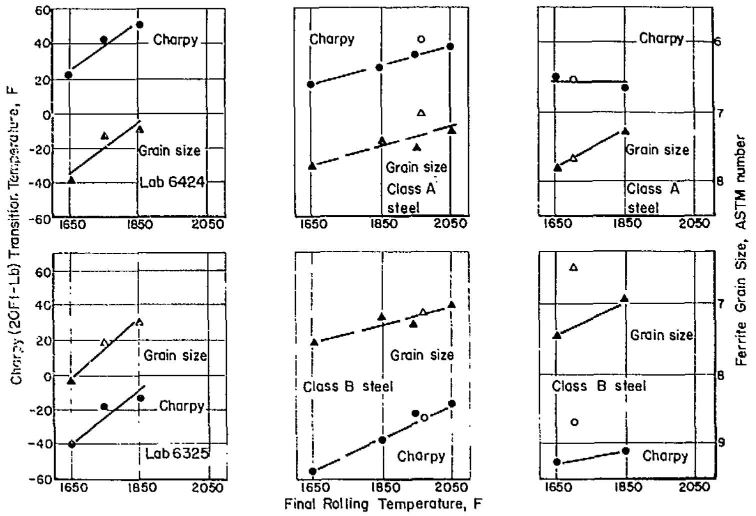


Figure 18 - Influence of finishing temperature on two laboratory steels (left) and four open-hearth steels. (Ref. 6)

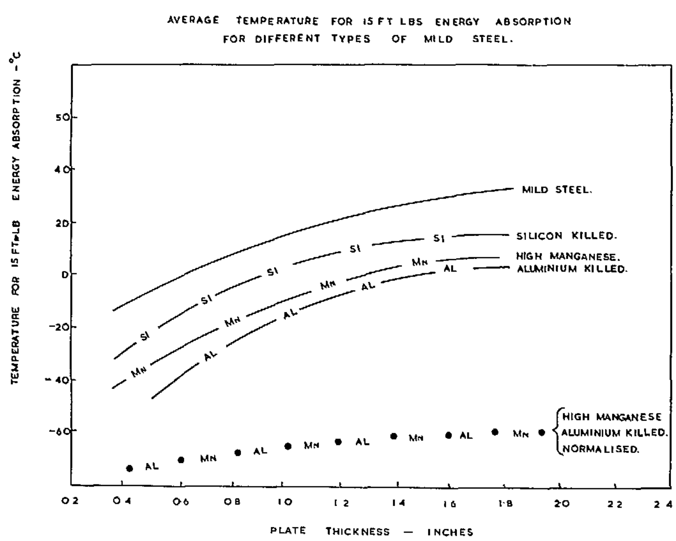


Figure 19 - Comparison of mean level of notch ductility for various qualities of mild steel plate rolled in mill B. (Ref. 4b)

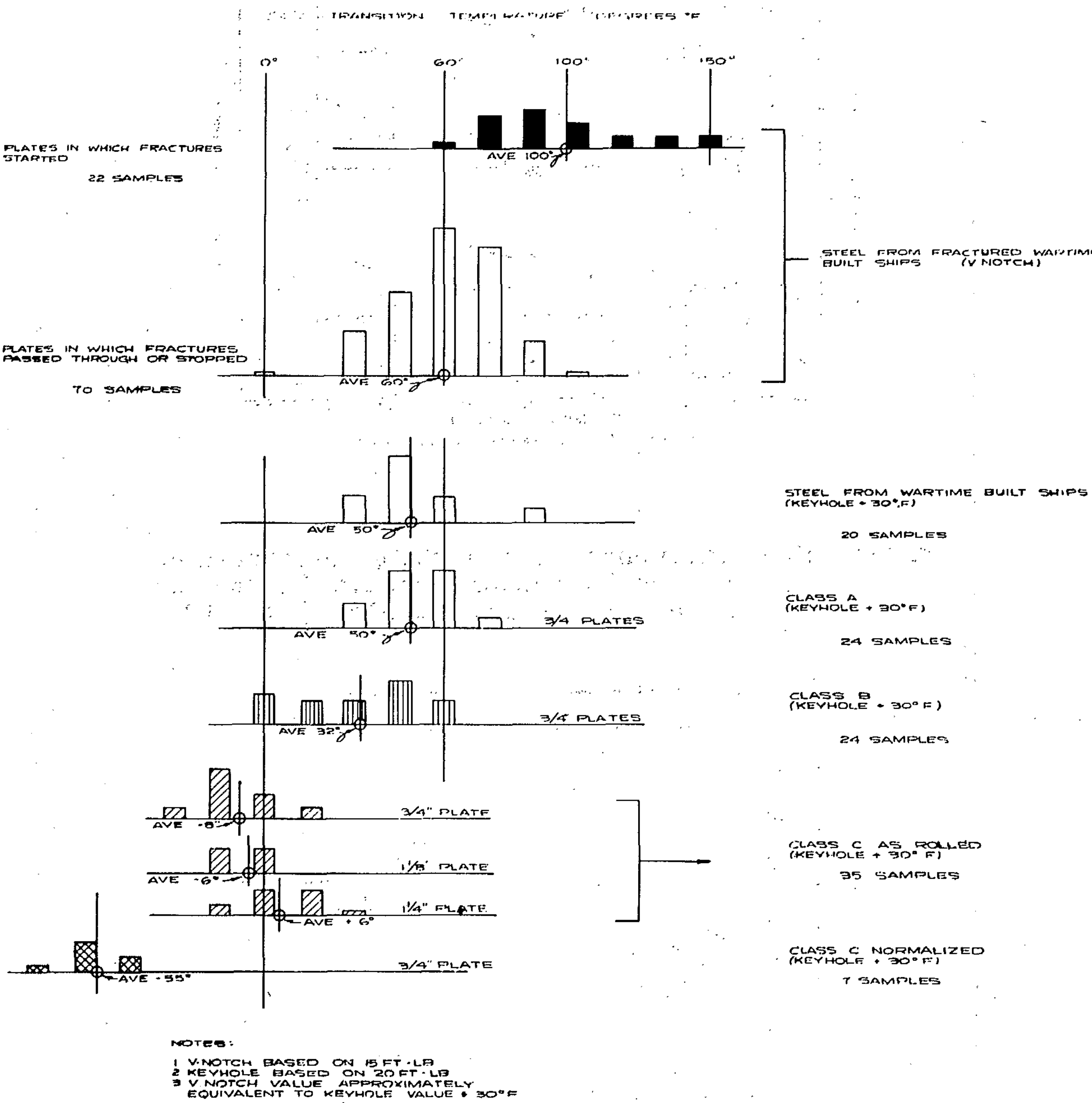
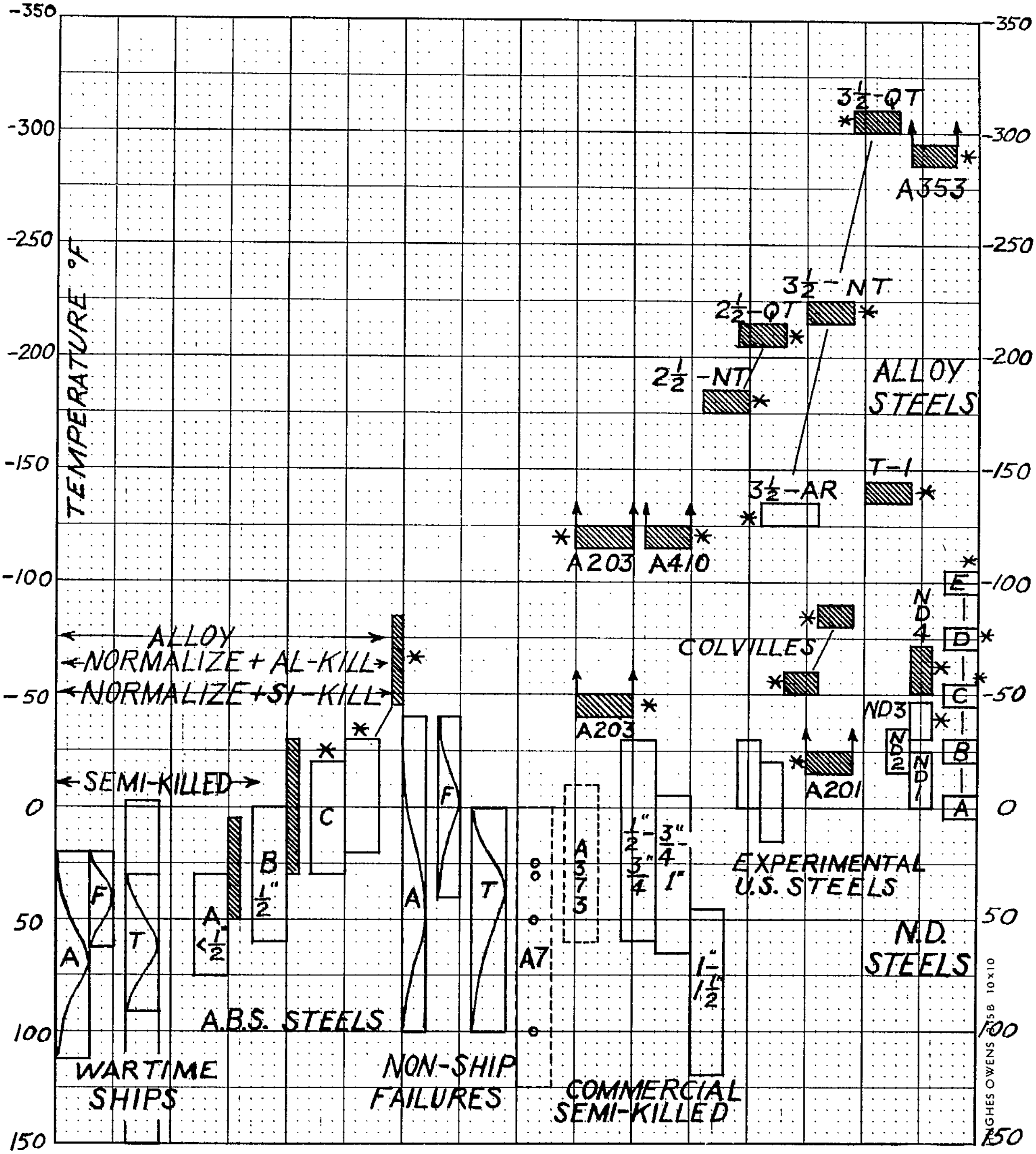


Figure 20 - Comparison of Charpy transition temperatures of wartime and present ABS steels. (Ref. 11)



*Indicates killed steels. Shading indicates heat-treated steels.

Figure 21 - Charpy-Vee impact energy (15 ft-lb) transition temperatures (°F) for various steels.

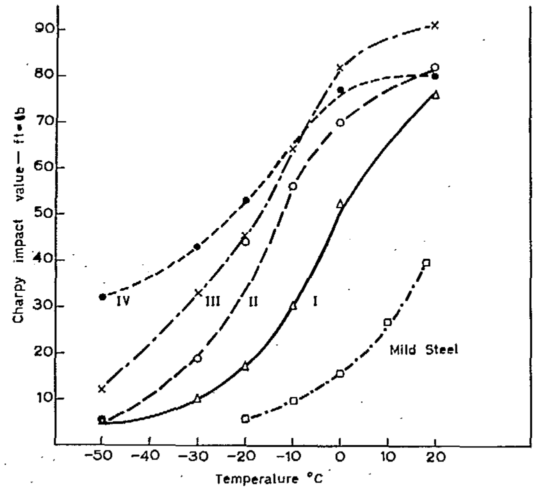


Figure 22 - Typical transition curves for ND1, ND2, ND3 and ND4 steels approximately 1 in. thick (Charpy-Vee). (Ref. 14)

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