EFFECTS OF AUSTENITIC GRAIN SIZE AND OTHER FACTORS ON THE BRITTLE FAILURE OF MILD STEEL

By

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ABSTRACT

The manifestation of brittle fracture in mild steel fabricated structures has been known for sometime but came into the lime-light following the failure during the last war, of all-welded American-built ships very often into two halves. In this short paper the importance of the subject has been stressed in relation to Indian conditions. Various factors which contribute to brittle fracture of mild steel have been reviewed and those which reduce the propensity towards brittle failure, like the austenitic grain size of steel and manganese/carbon ratio, have been discussed at some length. The effects of stress raisers and constraint provided by the surrounding metal in developing triaxial, volumetric tensional stresses leading to brittle failure of mild steel have been outlined.

INTRODUCTION

Mild steel is often regarded as a fool-proof material, inasmuch as it is ductile and does not normally lend itself to brittle fracture. Under some service conditions however, it has broken in such a brittle manner as to almost resemble plate glass. There are three distinct ways in which a metal might fracture during service or testing. It might break in the normal manner by deformation though the crystals giving the so-called fibrous fracture, also known as ductile, tough or shear fracture. It may break along the crystal boundaries; this form of fracture is very often associated with some form of chemical attack. It may also break by cleavage through the grains but with no plastic deformation, depicting what is known as brittle or cleavage fracture. A metal failure may either depict only one mode of fracture or a combination of the above three.

It is now well-known that at very low temperatures many of the properties of mild steel differ greatly from those at room temperatures. At temperatures approaching that of liquid air its ultimate tensile strength and yield stress are much higher and the reduction of area or elongation considerably lower than corresponding values at room temperatures; whilst the notched-bar impact value is practically zero at that sub-zero temperature. Sub-zero temperatures are frequently met with in refrigeration engineering. Besides the effect of sub-normal temperatures, a further factor to cause brittle fracture in mild steel structures, is the effect of 'locked up' or 'residual stresses' in relation to notch effects. Examples of such residual stresses will generally be found in welded structures such as all-welded ships, welded plate girder bridges etc. In the latter, examples of brittle fractures were met with in Germany and in the former, brittle failure on a mass scale during the last war, of all-welded American ships affords an outstanding example.

India is embarking upon big industrial installations involving ship-building, welded bridge structures, refrigeration industry etc. Researches will have to be undertaken towards an assessment of low temperature properties and strain-age embrittlement characteristics etc., of Indian-made mild steels in relation to their transition temperature ranges and brittle failure. Indian mild steels include those made by the Duplex process involving Bessemerizing and open-hearth refining or by a straight Siemens-Martin open hearth process. There are expected to be significant differences between these types, as the nitrogen contents of Bessemerized steels introduce strain-ageing and intensify their propensity to cleavage-embrittlement. The presence of carbon and nitrogen in the iron lattice causes distortion and a predisposition to cleavage along the cleavage planes. A systematic, long term study of the subject should be instrumental in preventing possibilities of catastrophic failure of engineering and ship building structures encountered elsewhere, which have been attributable to the brittle fracture of mild steels.

The problem should be of great interest not only to ship-builders, bridge-builders, power and boiler plant engineer but also to oil industry using mild steel plates for storage tanks and to manufacturers of mild-steel gas cylinders, chains etc. Out of 4700 ships built by welding methods in U.S.A. during the last war, 20% suffered structural failures, half of which were serious. More than 40 of the ships broke completely into two, resulting in large loss of life. Admiral Cowart estimated the damage cost by this metallurgical problem at 50 million dollars[1].

Metallurgical factors determining low temperature properties of mild steels in relation to brittle fracture:

(*a*) Chemical composition of steel in respect of carbon, manganese, silicon and aluminium and effects of impurities like nitrogen, oxygen, etc.

(*b*) Mode of deoxidation of steel.

(*c*) Inherent austenitic grain size of steel.

(*d*) Actual ferrite-pearlite grain size at room temperatures.

(*e*) Effects of thermal-treatments and resulting structures in respect of size and distribution of carbide, inter-lammellar spacing of pearlite, non-metallic inclusions etc.

(*f*) Incidence of cold work and ageing, determining the degree of strain-age embrittlement.

(*g*) Residual stresses involving constraint in the fabricated structures, welded components etc. and effects of surface conditions, notches and stress-raisers, etc. in promoting brittle failure.

Before each of these factors is briefly examined, a reference to transition temperature range of metals seems necessary.

It is characteristic of body-centered cubic ferrous materials to show brittle behaviour at some low temperature, the different alloys differing from each other only in respect of temperature range where the ductility vanishes, as depicted in Fig. I. In many steels, the brittle transition temperature is very roughly around room temperature in the Charpy or Izod test, well below room temperature in tension and still lower in torsion. It should be understood that the brittle transition temperature does not depend only upon the composition of the metal or alloy—it is not a material constant in itself like the melting point or critical temperatures. The state of stresses residing in the structure will determine the brittle transition temperature in service or testing, besides the overall effects of chemical constituents.

Taking into account the chief variant, *i.e.* the temperature, it is observed that, with carbon steels, the transition temperature range from ductile to brittle fracture in the Charpy test lies within +25 deg. C. to —60 deg. C. In this connection the striking paper by Herty and McBride[2] can be summarised in a nutshell that with a decrease in the temperature, a sudden decrease in the notched-bar impact value of ferritic steels takes place on passing through what is termed the transition temperature range.

In notched-bar impact testing the metal will fail in a characteristic way depending upon its composition and the testing temperature. With falling temperatures, the energy absorbed before fracture is reduced and the nature of the fracture changes from the fibrous, ductile and shear type to the brittle, crystalline and cleavage pattern at the transition temperature. Notch ductility of a material is its capacity for deformation in the presence of stress-raisers. For a steel to have high notch ductility at low temperatures is expected to reduce the risk of 'brittle' fractures in service. In a ductile material, impact fracture at room temperatures may start

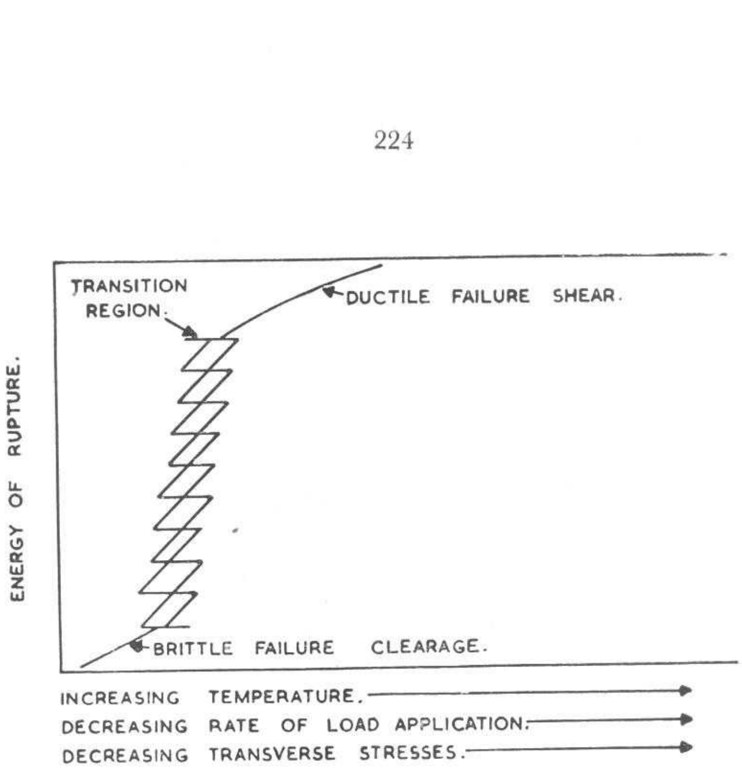

FIG. I. TYPICAL CURVE SHOWING THE INFLUENCE OF TEMPERATURE ON THE NOTCHED BAR RESISTANCE OF FERRITIC STEELS. (AFTER C. ZENER AND J. H. HOLLOMON AM. SOC. OF METALS 1944, 33, 143).

through cleavage but ultimately change into a shear type. Under certain conditions however, the metal fails entirely through cleavage with no evidence of accompanying plastic deformation, giving the typical crystalline appearance of a 'brittle' fracture. With decrease in temperatures ferritic steels become less adaptable to relieve stress concentration through plastic deformation which, however, does not necessarily imply a decrease in the intrinsic room temperature ductility of the metal. The localisation of deformation at low temperatures reduces the energy absorbed before fracture. Barr[3] pointed out that the manganese content of 0.30—0.35% in American ship plates involved in brittle fracture was comparatively lower than the customary manganese content of 0.45—0.55% employed in British practice. It had been shown by him that low manganese contents of steels lower the room temperature Izod-impact values of normalised or 'as-rolled' mild steels. Rinebolt and Harrist[4] made a sytsematic study of the effects of some elements on the transition temperature and showed that small additions of boron and chromium do not affect the transition temperature; carbon and silicon uniformly raise it respectively by 5.5°F and 1.25°F per 0.01%. Manganese on the other hand lowers the transition temperature by 1.0°F per 0.01% upto 1.5%, whilst titanium and vanadium at first raise and then lower it.

Barr[3] further noticed that Mn/C ratio influenced the transition temperature as shown in Table I and depicted in Fig. 2.

In the normalised condition, the increase in the Mn/C ratio from 1.4 to 11.9 lowered the transition temperature by 50 deg. C. Annealing had a similar effect on transition temperatures.

In Fig. 2, it has also been shown that the impact toughness increases with the increase in Mn/C ratio. The effect of manganese is not only to improve the notch toughness values at ordinary temperatures but also to preserve them at low temperatures. An increasing carbon content raises the transition range and may lower the impact values at all temperatures for steels in the normalised and annealed conditions, while manganese exercises an opposite effect. It is desirable therefore, to meet the tensile requirements by additional manganese contents. The beneficial

Table I:—Effect of Manganese on Transition Temperature

Cast No.	C. %	Mn. %	Mn/C ratio	Heat treatment deg. C.	Grain Size Jernkontoret	*Transition Temp. deg. C.
1229	·19	·27	1·4	N. 860	8·5	0
	,,	,,	,,	N. 900	10·0	20
	,,	,,	,,	A. 860	10·5	80
	,,	,,	,,	A. 900	11·0	90
1230	·17	·68	4·0	N. 860	8·5	—20
	,,	,,	,,	N. 900	9·0	—20
	,,	,,	,,	A. 860	9·5	30
	,,	,,	,,	A. 900	10·5	50
1278	·115	·89	7·8	N. 900	8·5	—35
	,,	,,	,,	A. 900	10·0	40
1232	·10	1·19	11·9	N. 880	8·5	—60
	,,	,,	,,	N. 900	9·0	—50
	,,	,,	,,	N. 950	9·5	—45
	,,	,,	,,	A. 880	10·0	10
	,,	,,	,,	A. 900	10·5	25
	,,	,,	,,	A. 950	11·0	60

N—Normalised (1 hour soak. Air cooled)

A—Annealed (1 hour soak. Furnace cooled)

*—Transition Temperature=Temperature for 50% Cleavage Fracture.

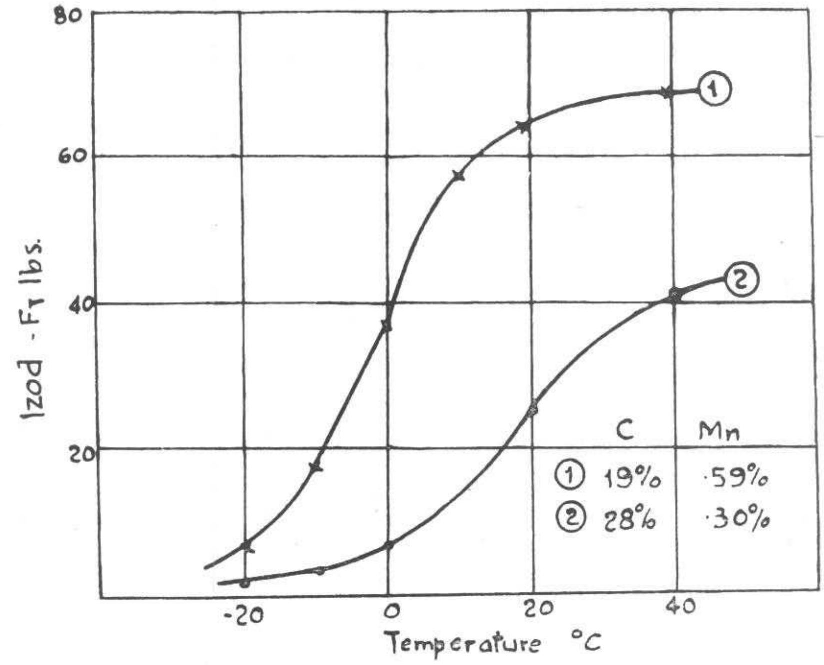

Fig 2 - Effect of manganese/carbon ratio on temperature impact curve

AFTER W. BARR. METALLURGIA, VOL 38 NO 224.

action of Mn/C ratio has further been illustrated by results obtained by Barr[3] for steels conforming to B.S. specification No. 15 and by Bradley[5] as shown in Table II and III respectively.

Table II:—Improvement in Transition Temperature by increasing Manganese contents

Steel	C%	Si%	S%	P%	Mn%	Mn/C ratio	Condition	Tensile require-ments, tons/sq"	Tran-sition Temp. 50% clea-vage	Impact Value ft-lb at O deg. C	Impact Value ft-lb at 20 deg. C
A	·19	·065	·02	·017	·55	2·9	As Rolled	26-33	40	20	35
E	·15	·07	·03	.015	·99	6·6	,,	26-33	10	50	70

Table III:—Mn/C ratio, Grain Size and Transition Temperature.

Steel	Chemical analysis		Mn/C ratio	A.S.T. M. Grain Size No.	Mechanical Properties			Transition Temp. deg. C.
	C%	Mn%			T.S. Tons/ Sq."	Elong. %	Redn. of area %	
P	0·25	0·58	2·3	5 — 7	33·4	26	62	—20 to —25
Q	0·23	0·56	2·4	2 — 3	33·4	31	61	—20 to —10
R	0·22	1·62	7·4	2 — 4	40·8	28	69	—20 to —30
S	0·20	1·61	8·0	6 — 8	38·3	30	61	—20 to —40

Steels marked R and Q had been deoxidised only with silicon while steels P and S had finally been deoxidized with aluminium to confer on them a fine inherent grain size, the effects of which will be shortly discussed. From the effects of carbon and manganese it is apparent that the transition temperature will be lower in steels having high Mn/C ratio since both lowering carbon and increasing manganese contents reduce the transition temperature. The results obtained by Rinebolt and Harris[4] concerning the effects of Mn/C ratio on the transition temperature show that increasing the Mn/C ratio from 1 to 3 lowers the transition temperature from about 150 deg. F. to —20 deg. F, supporting the recommendations of Barr and Tipper[6] that to avoid brittle fractures in mild steels conforming to B.S. Specification No. 15, the Mn/C ratio should not be less than 3.

Differences in small amounts of nitrogen have been noticed to affect the performance of mild steels. Nitrogen exists in steel as a nitride Fe_4N dissolved in ferrite. Its solubility like that of most elements in solution increases considerably with temperature. When the steel is cooled rapidly from high temperatures, the nitrides do not as rapidly separate out and are held in enforced solution. Given time to age at room or higher temperatures, the nitrides are thrown out of solution, gradually forcing aside iron atoms and creating centres of intense local strain and hardening. There are certain preferred locations for the nitrogen atoms so precipitated out, which lie chiefly on the cleavage planes of the iron crystal. By creating such centres of intense strain on the cleavage planes, nitrogen causes the steel to strain-age and intensify the cleavage embrittlement of iron. Thomas Bessemerized steels which are high in nitrogen fall in the above category. Recent trends in the Bessemer steel process especially on the Continent and the U.K. have been directed to such modifications as would reduce the nitrogen content of the blown steel immunizing them as far as possible from the latter's deleterious effects on notch-ductility.

Concerning oxygen in steel, the subject can be discussed along with the mode of its deoxidation and resulting austenitic grain size—factors that are closely inter-related to each other.

The deoxidation process practised in a steel plant has long been known to exercise a decisive influence on the impact notch toughness of steel. This subject has been fully discussed by Nijhawan [7,8,9] and Nijhawan and Chatterjea[10]. To determine the effects of aluminium additions to steels in relation to their transition temperature, Barr and Honeyman[11] added 0.06% Al to one half of each cast in two casts with different Mn/C ratios. Their results are contained in Table IV. Figure 3 illustrates the beneficial action of grain-refinement on the impact toughness of the special carbon-manganese steel, grain controlled and normalized, in relation to plain mild steel. Fig. 4 shows the transition temperature range (tough to brittle fracture) of ordinary and killed mild steels.

Sinclair and Dolan[12] noticed that an increase in the austenitic grain size of steels shifted their transition zone to higher temperatures and gave lower values of energy absorption over all ranges of temperature. From the results presented in Table III, it will be noticed that grain-refinement in the case of aluminium killed steels P and S has improved their transition tempera-

Table IV:—Effect of Grain-refinement on Transition Temperature of Steels Normalised from 900 deg. C. (After Barr and Honeyman).

Reference	Chemical Analysis		Mn/C ratio	A.S.T.M. Grain Size	Mechanical Properties				Transition, Temp. deg. C.
	C%	Mn%			Y.P. Tons /sq. inch	M.S. Tons /sq. inch	Elong. %	Redn. of area %	
A No Al	0.175	0.43	2.5	2-5 (Coarse)	18.8	28.6	40	64	0
B Al-treated	0.185	0.46	2.5	very fine	21.6	29.6	42	67	—25
A No Al	0.11	1.23	11.2	3-5 (Coarse)	20.2	30.2	43	73	—35
B Al-treated	0.12	1.27	10.6	very fine	23.4	30.6	44	76	—70

VEE NOTCH CHARPY IMPACT TESTS

1" THICK PLATE

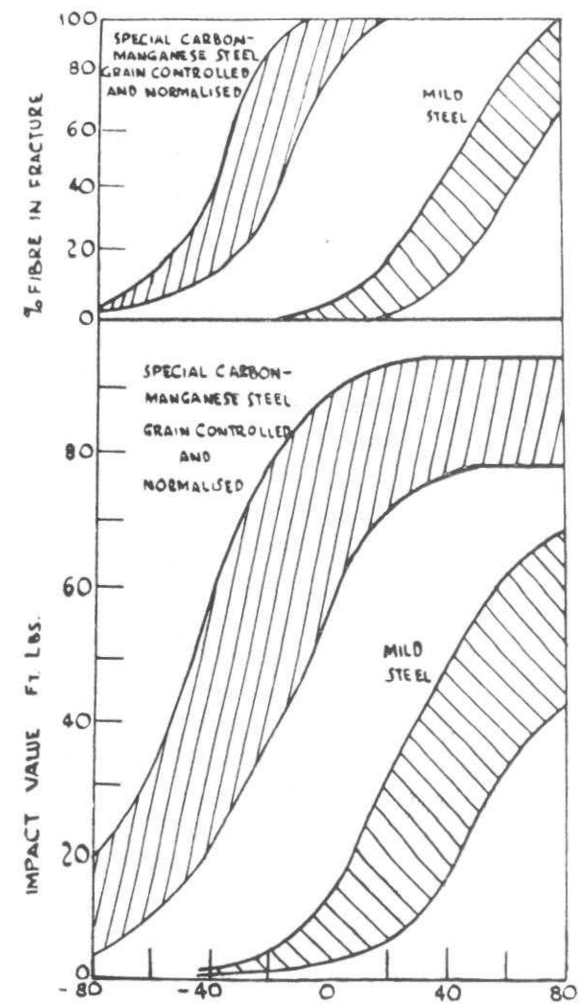

FIG. 3.

AFTER W. BARR. WEST OF SCOTLAND. IRON AND STEEL INSTITUTE. PRESIDENTIAL ADDRESS 1950.

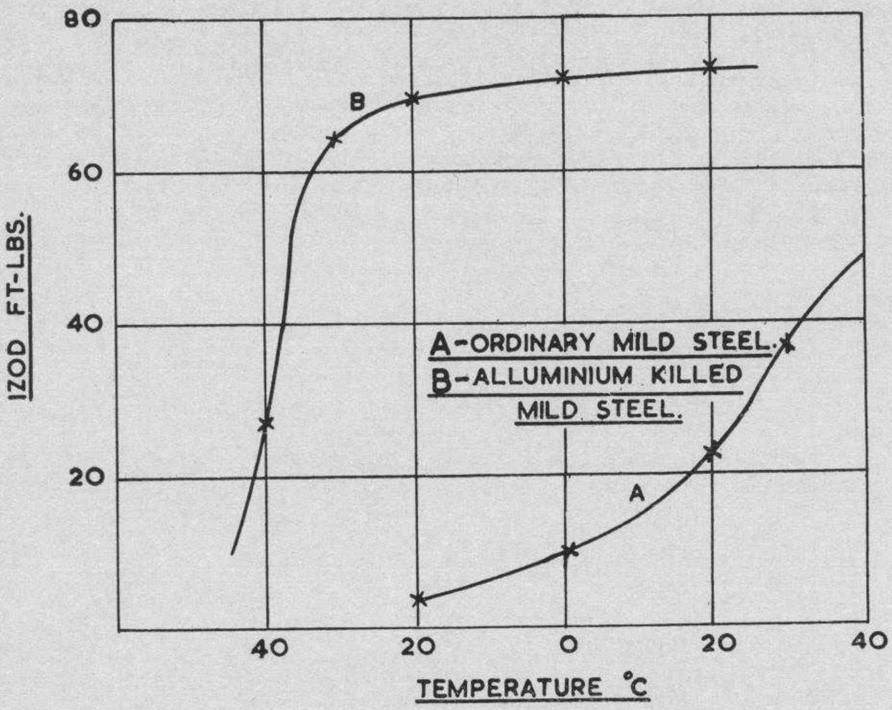

FIG. 4. IMPACT VALUE ON TESTING TEMPERATURES.

BARR AND HONEYMAN INSTITUTION OF ENGINEERS AND SHIP BUILDERS 1948—p. 72.

tures. It has also been shown that the grain refined steel P, containing less manganese, has almost the same transition temperature range as the coarse-grained higher manganese steel R. The same conclusions can be arrived at from a study of results embodied in Table IV. Grossmann[13] observed that with the same pearlite inter-lamellar spacing, varying the structure from large to small grains decreased the transition temperature and for a given grain size, the finer pearlite spacing showed a lower transition temperature than the coarser pearlite lamellar formation.

Considerable more research work is required to determine the direct effect of oxygen in steel on impact transition temperature ranges. Rees, Hopkins and Tipler[14] have studied the effects of oxygen, carbon and manganese in steels on their transition temperature ranges as determined by notched-bar impact, tensile elongation and bend tests at sub-zero and room temperatures. They have clearly demonstrated the pronounced effects of increasing oxygen contents of steels in raising the transition temperature ranges in terms of notch-bar impact tests. The oxygen contents of steels can be effectively controlled by judicious additions of aluminium producing inherent grain-refined steels. With regards to manganese, Rees, Hopkins and Tipler confirmed its effects in lowering the impact transition ranges. Additions of 0.01% carbon to high purity iron had little effect on the tensile and impact transition properties of normalised materials. Larger additions of carbon raised the impact transition temperature ranges appreciably. According to these authors, the transition from tough to brittle fracture in impact to be usually very sharp in iron and iron-manganese alloys that fail entirely by cleavage in the brittle condition but less sharp where fracture was partly along grain-boundaries.

Heat-treatment and metallographic structures in relation to low temperature embrittlement :

The heat-treatment and micro-structures have marked influence on the notch-toughness of steels. One well-known form of embrittlement discussed by Gorrissen[15] is caused by the occurrence of cementite films around the ferrite grains as observed in dead soft steels slowly cooled through the critical range. This may be a source of potential trouble in ship plates made from rimming steel where the plate surfaces correspond to a very low carbon rim. Micro-constituents, whether ductile or brittle, in continuous net-work formation may be harmful to transition properties. Treatments designed to break up such continuities will produce improvements in toughness, ductility and notch-sensitivity of steels at low temperatures. Microscopic examination of brittle fractured materials has shown the crack formation to be trans-crystalline and has revealed the presence of Neumann bands (mechanical twins) which occur in mild steel under sudden shock and are initiated by slight plastic deformation. The presence of these bands indicated that the fractures occured without much plastic deformation. Shock twins have been observed near the fracture in specimens broken at low temperatures. The cleavage in ferrite grains initiates the brittle fracture.

The following structural variations affect the mechanical properties of mild steels possessing a pearlitic structure :

1. Inter-lamellar spacing of pearlite
2. Amount of free ferrite
3. Composition of pearlite
4. Non-metallic inclusions.

Metallographic structures corresponding to different rates of cooling the condition of carbides and thus affect the transition temperature. A reference to Table I illustrates the changes in the transition temperature in steels having different Mn/C ratios after normalising and annealing treatments which will show that for steels having the same Mn/C ratio, annealing treatment raises the transition temperature ranges. Normalising and specially water quenching and tempering increase the resistance to cleavage fracture. The presence of free ferrite in quenched and drawn mild steel is associated with abnormal brittleness and the elimination of free-ferrite phase improves the steel's low temperature performance. The influence of ferrite grain size and cooling rates on transition temperatures has also been studied by Klier, Wagner and Gensamer[16] and is in line with the observations of other workers. The lowering of transition temperature ranges after normalising in relation to as-rolled condition may not be effective in all cases because the latter may have a finer grain size and an initial favourable stress distribution—factors, which lower the embrittling temperature. In the as-rolled condition thick plates are usually finished at higher temperatures due to lesser number of passes through the rolls. Their austenitic grains are therefore, relatively coarse and are transformed into corresponding coarse ferrite-pearlite structures. Besides, the thick plates would cool more slowly through the critical range causing still coarser grain formation. Fig. 5, after Barr clearly shows that for plates rolled to different thickness from the same cast, a marked variation in their transition temperature results from the finishing temperatures employed.

Different rates of cooling from the austenitizing temperature will affect the amount of carbide precipitated from the ferrite. After passing through the critical range, the ferrite still contains carbon, nitrogen etc. in solution and the rate of cooling from 600 deg. C. to room temperature will determine the final analyses of the ferrite. This would account for different transition temperatures of steels possessing identical micro-structures.

Sub-microscopic segregation, non-metallic inclusions and precipitated phases, if present, in lamellar form and parallel to the rolling surface may influence the transition temperatures of the material. The steel should show freedom from non-metallic inclusions which act as potential stress-raisers depending upon their incidence *vis-a-vis* the distribution of applied stresses.

RELATION BETWEEN IMPACT VALUE FINISHING TEMPERATURE AND PLATE THICKNESS.

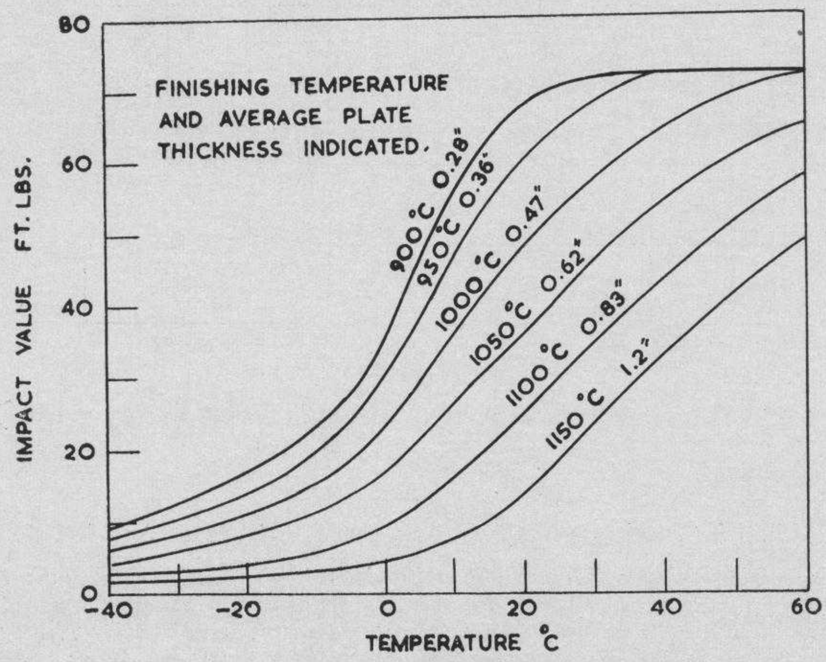

FIG:—5

AFTER W. BARR. WEST OF SCOTLAND. IRON AND STEEL INSTITUTE. PRESIDENTIAL ADDRESS. 1950.

Cold working and Strain-ageing:

Structural yards will have to devise methods of material fabrication designed to minimise conditions which give rise to strain-ageing influences. Strain-ageing in steel has been attributed to the separation of carbides, oxides or nitrides held in super-saturated solution in ferrite. Plastic deformations followed by ageing, result in recovery of elastic properties of the metal, the formation of a new yield point which may be as high as the original ultimate breaking stress and a serious loss in general ductility. Besides, strain-ageing adversely affects the low temperature properties of steels substantially raising their transition temperature ranges particularly in the case of non-grain-refined steels containing little or no aluminium in solution. Aluminium killed steels possessing fine austenitic grain sizes are much less susceptible to adverse influences of strain-ageing as depicted by curves in Fig. 6 after Barr.

Slater[17] has shown that aluminium-killed steels inspite of their high nitrogen contents are much less susceptible to strain-ageing characteristics which gives them relatively greater immunity to brittle failure.

Strain-ageing is likely to develop either as a result of plastic strains introduced into the plates due to partial cold worked conditions during rolling or as a result of plastic strains set up in subsequent welding and fabricating operations. Strain-ageing influences manifest themselves in engineering shops engaged in mild steel fabrication in severe cold winter particularly where cold flanging or bending is performed.

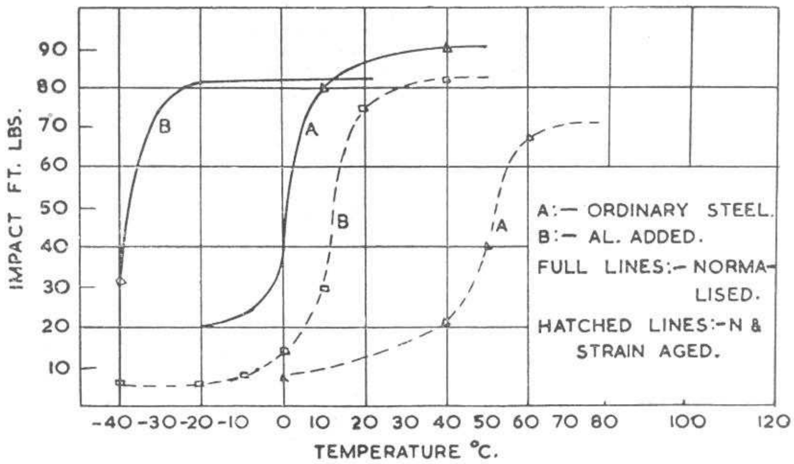

FIG. 6. EFFECT OF STRAIN AGEING ON TRANSITION RANGE (AFTER W. BARR[3]).

Effects of residual internal stresses, welding, stress-raisers etc. on brittle failure:

A mass of evidence shows that welding process itself has little effect on an un-notched tensile specimen in terms of yield point, ultimate strength, reduction in area and percentage of elongation. These observations lulled the welding engineers into a sense of false security which was to later bring disaster through mass failure of welded structures such as of ship plates. High local or locked up stresses are produced in the process of welding arising out of plastic deformation which occurs in the weld and in a zone of the plate-material parallel to the weld. Such stresses would always be present unless stress relieved, a procedure impracticable in case of welded structures like ships, bridges, etc. Residual stresses are bound to develop in metals by non-uniform deformation causing elastic distortion. These internal stresses can be quite high. They are often tri-axial so that their intensities across different axes can be very severe. The effects of residual internal stresses assume great importance in the presence of notches and stress-raisers usually present in welded structures. These effects can multiply to dangerous proportions due to 'constraint' effect of the surrounding mass of metal in the vicinity of welded joints. By notches are meant a variety of structural discontinuities or imperfections resulting in stress-concentration. In riveted structures little residual stresses reside since a re-distribution and dissipation of originally applied service stresses take place at the rivet-joints which act as stress-arrestors or barriers besides affording opportunities for a certain amount of slippage and elongation to occur, thereby localizing the damage and relagating the stress raising influences of notches etc. into relative ineffective back-ground. In the case of welded structures however, there is no such stress-relief which would thereby behave as less ductile materials. It therefore, becomes necessary to have welded structures well designed and constructed through the elimination of any type of notch effect. Surface imperfections such as scratches, machine tool marks, stamped-in-numbers and other flaws may provide areas of potential stress-concentration. At a notch root, stress concentration can not only cause stresses beyond the elastic limit of the material but also induce its plastic yielding. Such plastic deformation whilst affording localized stress-relief, is engulfed by the constraint of the surrounding un-deformed mass of metal, which gives rise to severe triaxial stress conditions eventually leading to brittle failure of the metal. In large steel structures the incidence of stresses is far from being uniform. In the moving hull of a ship, stresses vary rapidly in intensity and distribution. A peak stress suddenly developed may attain a value above the plastic limits but the constraint effect of the surrounding rigid material well below this peak stress, neutralises the intensity of such local peak stresses thus creating a condition of enforced elasticity. Chances of finding such constraint examples are greater in larger structures than in smaller ones. Such an enforced elastic state develops tri-axial or volumetric tensional stresses, like the rapid outward displacement of all the atoms in a sphere, which can on repeated applications, cause a brittle failure. With a Poisson's ratio of 0 285 the intensity of transverse side stresses required to maintain a compact cross section need only be 40 percent of longitudinal stresses for a fatal brittle fracture to result. In a ship's hatch way corners, peak stresses can cause havoc especially in welded ships unless corrective measures are introduced such as suitable thickening of the metal at the corners, proper radiussing etc. Identical failures through 'constraint' effect in relatively much smaller welded structures of armoured-carriers made of bullet-proof armour-plate of hardened Ni-Cr-Mo steel have been recorded by Nijhawan[18] and Bucknall[19] et al. In either case the brittle failure took place during storage without any evidence of prior plastic deformation. This shows that the same phenomenon could be observed in the harder alloy steels in much smaller welded structures.

SUMMARY

To summarize, it may be stated that brittle failure of mild steel structures is dependent upon the prevalent residual internal stresses in relation to the surrounding constraint, service temperatures, the magnitude of service loads and stresses, the chemical composition of the steel in respect of Mn/C ratio and residual aluminium content, the austenitic and room temperature grain-size of the material etc.

The damaging influence of these factors in causing brittle failure of mild steels can very considerably be reduced where an initial proper selection of the material is made and with the application of suitable corrective measures, the latter should give satisfactory performance. In brief, such measures may include a selection of steel with a carbon content of less than 0·15%, Mn/Carbon ratio of more than 4, thorough deoxidation of the steel with aluminium ensuring a residual aluminium content of 0·02—0·04% causing it to inherit a fine austenitic grain size, devising mechanical and thermal treatments to ensure a corresponding fine room temperature ferrite-pearlite grain size, avoiding the incidence as far as possible, of cold work during fabrication and introducing remedial measures designed to eliminate notches and other stress-raisers and relieve residual internal stresses in the fabricated structures as far as possible.

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DISCUSSION

Mr. C.E. Phillips :

Mr. Phillips appreciating the paper stated that considerable work on this problem was underway although fundamental studies on different aspects of britlle behaviour of mild steel needed great emphasis. Many questions arose in one's mind such as, if the effects of Mn/C ratio were squarely established; was sufficient attention being paid to the size effect as related to the problem ? The original experiments of Prof. Haigh conducted 30 years back showed that some material fractured in a ductile manner in small sizes whilst big sizes failed in a brittle manner.

Dr. B.R. Nijhawan :

Appreciating the significant remarks of Mr. Phillips he agreed that much more fundamental work was necessary on different aspects of the problem. Apart from Mn/C ratio, most minute additions of cerium to the steel had lately been known to confer considerable resistance to brittle failure in the latter. The failure of welded 'Liberty' ships during the last war had triggered off immense research on both sides of the Atlantic and definite conclusions were still in formative stages. The National Bureau of Standards, U.S.A. had just concluded a Symposium on this subject and their findings would be worthy of study. The position to-day, appeared rather misty and conflicting in more than one way.