A REVIEW
of
SHIP STEEL RESEARCH
and
RECOMMENDATIONS FOR FUTURE STUDIES

by

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Prepared for

NATIONAL RESEARCH COUNCIL'S
COMMITTEE ON SHIP STEEL

Advisory to

SHIP STRUCTURE COMMITTEE

Division of Engineering and Industrial Research
National Academy of Sciences - National Research Council
Washington, D. C.

SERIAL NO. **SSC-70**
BuShips Project NS-011-078

February 15, 1954

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:

SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

February 15, 1954

Dear Sir:

In the course of pursuing its function as one of the National Research Council's activities advisory to the Ship Structure Committee, the Committee on Ship Steel recommended the preparation of the report enclosed herewith, entitled "A Review of Ship Steel Research and Recommendations for Future Studies" by Dr. C. S. Barrett, University of Chicago, and Mr. W. E. Mahin, now with the Vanadium Corporation of America. This report was prepared specifically to assist the Committee on Ship Steel in formulating recommendations for the Ship Structure Committee's "Materials" research program.

The report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee, in the hope that the information contained therein may be of assistance.

Any questions, comments, criticism or other matters pertaining to the report should be addressed to the Secretary, Ship Structure Committee.

Very truly yours,

K. K. Cowart

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Rear Admiral, U. S. Coast Guard
Chairman, Ship Structure Committee

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National Research Council's
Committee on Ship Steel

Advisory to

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under

Department of the Navy
Bureau of Ships Contract NObs-50148
BuShips Project NS-011-078

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A REVIEW OF SHIP STEEL RESEARCH AND RECOMMENDATIONS FOR FUTURE STUDIES

EDITOR'S NOTE: This report has been prepared at the request of the Committee on Ship Steel to review the research work completed on "Ship Steel" during the past decade, and particularly that conducted during the last five years. The report has been organized primarily to assist the Committee in evaluating the work and to aid in formulating new research proposals to be recommended for support by the Ship Structure Committee. It has therefore been drafted primarily for metallurgists who have a comprehensive background in the brittle fracture of mild steel.

INTRODUCTION

The Committee on Ship Steel of the National Academy of Sciences-National Research Council requested the writers to make an evaluation of the progress to date of the research on the metallurgical aspects of brittle fracture in ship steel and to report the conclusions of this in a manner that would aid the Committee in making the best possible recommendations for future research studies in this field. The preparation of the review became desirable because the present general program has been under way for several years, some projects having been in continuous operation for as much as five years.

In accordance with this request an attempt has been made to "consider all phases of the ship steel problem," and to include as many of the divergent views of different investigators as possible in the time available, and to suggest what investigations now appear desirable, especially those that should be recommended for future support by the Ship Structure Committee, to which the Committee on Ship Steel is advisory. No assumption was made that the suggested research must exclude studies in statistical, economic, or operational fields, or investigations that could best be undertaken by private industry.

Obviously, the scope thus outlined is so wide that many fields of lesser interest to the Committee can only receive brief comment. No detailed plans for any specific project are offered; these should be developed by individual investigators and advisory committees. Since a number of extensive literature summaries are now available (see page 5) and more are in preparation, the present report includes only brief mention of those papers and reports of particular concern to matters being discussed.

OUTLINE OF THE PROBLEM

The main problem is to find means of reducing the probability of catastrophic failure of welded steel ships through economical improvement of notch toughness. A review of the known facts indicates that research and development have provided many of the necessary answers. This research and the further research that is needed may be classified into three broad areas, namely:

A. Applied research leading to knowledge of the relationship between brittle fracture and specific variables involving the materials, design, and fabrication techniques employed.

B. Statistical, economics, and process research aiding in deciding (1) what degree of improvement in the steel beyond that supplied during World War II is necessary, and what further improvement, if any, beyond that currently supplied, is desirable, (2) which existing practices or materials may be most economically applied, and (3) what new, more economical means might be developed for accomplishing improvements such as reduction of grain size. The above factors must be considered in the light of wartime, as well as peacetime, conditions.

C. Fundamental research leading to a better understanding of the brittle fracture problem.

Under the first class above are the studies of the controllable factors which relate to the brittle fracture problem. In general much practical information is available. Of particular importance are the facts that (1) V-notch Charpy tests for notch brittleness have been found to correlate adequately with a tendency for ship failure, and (2) a number of controllable variables relating to steel composition and treatment have been explored, and it is known that certain changes in the control points for these should result in a reduction in failure probability.

The second class of research appears to be of the greatest immediate importance since the objective of such research would be to evaluate the cost, and therefore the economic feasibility, of presently available alternative solutions to the main problem.

The third class of research is considered by the writers to be of the greatest long-range importance, since there remains a serious void in the understanding of brittle fracture. While much empirical knowledge exists, brittle failure needs to be explained more adequately than has yet been possible, in terms of physical fundamentals. Until such a full explanation is available, it is doubtful whether the most economical or direct treatment of the main problem will be available.

A. APPLIED RESEARCH

A review of the pertinent literature indicates that much progress has been made during the past ten years towards a better understanding of what can be done about brittle fracture in ship steels. As this is being continually summarized*, the present report has been limited chiefly to a discussion of areas where further research is needed. Some of the research in this field runs inevitably into fundamental questions as well.

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*See, for instance:

Final Report of a Board of Investigation to Inquire into the Design and Methods of Construction of Welded Steel Merchant Vessels, Washington, D. C.: Government Printing Office, 15 July 1946.

Ship Structure Committee, First, Second, and Third Technical Progress Reports, dated March 1, 1948; July 1, 1950; and August 1, 1953, respectively.

Ship Structure Committee, "Research Summary," fifth edition, January 1, 1953.

Siegle, L., and Brick, R. M. "Mechanical Properties of Metals at Low Temperatures--A Survey," Trans. ASM, vol. 40, pp. 813--869, 1948.

Brick, R. M., Low, J. R., Jr., and Lorig, C. H. "Behavior of Metals at Low Temperatures," published by the American Society for Metals, 1953.

Harris, L. A., Hoeltje, W. C., Jr., Sinnamon, G. K. "Ferrous Arc Welding," Part I entitled "Correlation of the Literature on Weldability," University of Illinois, July 19, 1951.

Armstrong, T. N., Kahn, N. A., and Thielsch, Helmut. "Transition from Ductile to Brittle Behavior in Pressure Vessel Steels," THE WELDING JOURNAL, August 1953, pp. 371-s--380-s.

Parker, E. R. "Brittle Behavior of Engineering Structures," Monograph in preparation for the Ship Structure Committee under the guidance of the Committee on Ship Steel.

1. The relative importance of plate material, effect of welding, and effect of pre- or post-heating.

It is felt by some investigators that since a majority of failures in ships have started at or near defective welds or at points of stress concentration where weld metal is present, the greatest opportunity for improvement lies in the weld. It must be admitted that better welding materials and practices will lower the probability of crack initiation and are therefore clearly of great importance, but there remains the unavoidable fact that arc strikes, various accidents in service, minor tack welds, and repair welds also frequently have served to initiate cracks. Thus improvement of the primary welding can never be a complete cure for brittle failure. There have been many brittle failures, too, of riveted structures.* It is also significant that a crack almost never follows the weld or the heat-affected zone for more than a short distance, as it would if the vicinity of the weld were a line of weakness in a ship, but instead runs out into the plate.

Consequently, it appears that the primary problem concerns the properties of the plates themselves. If these are of "crack-stopping" quality at service temperatures, they should limit damage to minor amounts regardless of the defect in welding or design that initiated a crack. By improvement of the notch

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*Shank, M. E. "Brittle Failure in Carbon Plate Steel Structures other than Ships," Ship Structure Committee Report Serial No. SSC-65 (to be published).

toughness of ship plate there would seem to be the possibility of complete elimination of serious brittle failures. It may be that a given amount of research can lead to greater improvements in welding than in ship plate manufacture, but it appears to the writers that the greatest ultimate gain in ship performance can come through research on plate.

2. Metallurgical variables in plate steels.

a. Grain size and related variables.--A relationship between grain size and transition temperature* has been fairly well established. However, the writers, having looked into this relationship rather critically, have found several points of interest that seem to warrant further investigation.

First of all, there is a lack of agreement in the type of grain size investigated. For example, the National Bureau of Standards work covers only fracture grain size number, while Battelle counted the ferrite grains per unit of area (note error produced by variable area of pearlite). Although in most ship steels, ferrite grain size may be related to the fracture grain size number, no such general rule should be assumed.

Secondly, the writers believe that it remains to be established that grain size as measured by any technique is a primary controlling variable. Based upon the evidence available, a case can be made for austenitizing temperature (either finishing temperature or normalizing temperature), cooling rate,

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*Hereafter referred to as TT.

and deoxidation practice as more fundamental variables, with grain size being dependent on these.

The basis for the above belief rests on the following observations: Several investigations have provided examples in which the ferrite grain size effect seems to be overshadowed by chemical composition, deoxidation practice, or rate of cooling. For example, a type B steel with a larger ferrite grain size than a type A steel may have a lower TT. Or, steels with the same ferrite grain size may differ greatly in TT, as for example Kahn and Imbembo's* heat 31, Figures 10 and 11, in which two ingots from the same heat, one treated with aluminum and the other semi-killed, show tear test TT's of -20°F and +70°F, respectively, with essentially the same ferritic grain size. Again, ferrite grain size does not appear to be the controlling variable in the data of Figures 16 and 17 of the Second Progress Report on SR-110 (SSC-53) of Battelle, whereas there is a clear relationship of TT with finishing temperature. Still other examples are found in recent unpublished results of cooling rate studies carried on at Battelle, in which a number of instances are found where both austenitizing temperature and cooling rate seem to be the major controlling variables rather than ferritic grain size. In one of these instances the Charpy keyhole 12 ft.-lb. TT was raised from 7°F up to 75°F as

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*Welding Research Supplement, 1950, Vol. XV, p. 93-s.

the rate of cooling from 1600°F to room temperature was changed from that of an air blast to that of furnace cooling. The importance of cooling rates in semi-killed 1020 steel has also been emphasized by Low, who has observed that when cooling rates below 1275°F were reduced from the rate approximating that for 1/2-inch plates in the mill to that for 3/4-inch plates, the TT was raised about the amount of the difference between 1/2- and 3/4-inch plates rolled from the same heat. (Welding Journal, Research Supplement, 1952).

The writers believe that a more critical review of data previously obtained on grain size and related variables is needed. But more important, further carefully planned and critical experiments need to be conducted on the effects of austenite grain size, ferrite grain size, grain coarsening temperature, austenitizing temperature, cooling rate (both from the austenitizing temperature and from temperatures below A_1) and deoxidation practice. Included also should be studies of the effect of degree of reduction during rolling and the possible role of subcritical heat treatments; and also further investigation of the reason for plates of different thicknesses having different TT's.

These variables are closely interrelated, and affect the properties of the finished plate only by controlling its inner structure. Therefore <u>structure</u> (macro, micro, sub-micro, and atomic) must be considered to be the primary factor and the real subject of the research program. The object of the program should be to isolate the effects of the variables on this metallurgical structure and to understand why they affect the structure as they do and why given structures have the notch toughness they do. Thus the program should be regarded as a program on <u>fundamentals</u>, and the results sought should be those that develop general principles that would apply to all manufacturing conditions, not just to the set of conditions under which the results were obtained.

Since the program is best regarded as fundamental in spite of its immediate practical interest, it is included and further discussed in Section C-3, page 29.

b. <u>Chemical composition</u>.--With certain noteworthy exceptions outlined below, there appears to be little need for additional research into the effect of chemical composition upon TT. Work at the Naval Research Laboratory, the National ~~Bureau of~~ Standards, and Battelle has established moderately well the correlations between TT and the content of the various elements ordinarily found in ship steels and low alloy steels. Remaining therefore is the need for fundamental research on the mechanisms by which the elements influence TT. This is referred to in Section C-2, page 28.

c. <u>Texture studies</u>.--From early work on armor plate and from the TT's of certain laminated samples that were tested in the ship steel program, it seems obvious that desirable TT's can be reached by producing laminated or fissured plates either of homogeneous steel or steel differing in composition in different layers. Clearly, such plates would have disadvantages, particularly in the matter of fabrication, and it appears that because of the effectiveness of other remedies such plates could probably not meet the competition of improved conventional plates. Furthermore, there is some evidence that the low temperature end of the TT curve may not be improved. However, since the difficulties are not insuperable, at least in theory, the subject should probably not be completely dropped.

It is not apparent that an economical way of introducing a suitably laminated plate could be found with current steel mill practices. Therefore, it does not seem appropriate to spend appreciable funds in such a study. Nevertheless, a very few plates made up by laboratory methods and subjected to full-thickness tests, say Navy tear tests or drop-weight tests, would be desirable. To keep the cost at a minimum, this should be done as part of a going project and not as a separate project and expenditure could well be strictly limited. It is noted that the Committee on Ship Structural Design presented proposals for work of this type to the Ship Structure Subcommittee on February 25, 1953.

3. Properties of the weld and heat affected zone.

While full consideration of this subject undoubtedly will be placed with the Fabrication advisory groups of the Ship

Structure Committee, nevertheless the subject is closely related to problems associated with the metallurgy of the plate material. Accordingly some comments on this field are included below.

There seems to be general agreement that welding usually produces a heat affected zone of increased TT, as compared with the original plate material. (McGeady and Stout, Baldwin (Project SR-99), Nippes and Savage). Also pre-heating at 400°F or post-heating at 1100--1200°F substantially removes the effect of welding upon the heat-affected zone.

On the basis of the above facts, one would expect catastrophic failure of ships to follow heat-affected zones of welds running normal to the most severe applied stresses, unless pre- or post-heating practice had been followed. However, as mentioned earlier, such failures rarely follow these zones even in the cases when they start there. Also, Dr. Shank's report (SSC-65, to be published) on structures other than ships reveals a lack of coincidence of failure longitudinally through welds and heat-affected zones. Obviously, the above facts seem to contradict each other and an explanation is needed. An hypothesis that occurred to the authors and resembles a suggestion made independently by A. A. Wells (<u>Welding Research</u>, April 1953), is that either the stress pattern produced by welding or hairline cracks normal to the weld bead, or both, discourage a crack from progressing parallel to the weld in the weld metal and heat-affected zone and deflect it outwards nearly at right angles to the weld. Either the tension zone at and near the weld or the compression zone a little farther from the weld discourages a crack parallel to the weld and close to it. The tension zone encourages the crack to proceed at right angles to the weld, while the compression zone tends to stop it.

In the above hypothesis could be found an explanation for Pellini's observation that welds may act as crack stoppers and the observation mentioned to us by Williams that a crack may cross and recross a weld, progressing parallel to the weld at a distance of 3 to 6 inches, beyond the heat-affected zone. The compression zone adjacent to the weld would tend to have that effect.

Whether the above hypothesis holds or some other explanation may exist, the mechanism of brittle failure at and near welds needs to be thoroughly understood. Until such an understanding is reached, one could hardly feel sure that low temperature stress relief is invariably desirable, or that some change in welding process or plate material might not result in an epidemic of weld failures.

4. New test methods.

Various notch-sensitivity tests appear adequate for normal testing, and with exceptions noted below, further research on testing does not seem warranted. Further studies of eccentrically loaded notch-tensile tests as possible acceptance tests, for example, seem unnecessary.

The exceptions, however, are important. More should be learned about the stresses necessary to initiate and propagate a rapidly spreading crack. One of the best approaches to this appears to be the modified Robertson test using a sample at constant temperature, a crack that has maximum sharpness and that is unblunted by any relaxation resulting from the crack remaining stationary at room temperature, and a specimen long enough to avoid shock-wave reflections from the ends of the specimen. It is important to know whether this test discloses any serious deficiency introduced by a reduction of carbon in ship steel.

The second test development that should be encouraged, as has been mentioned, is the drop-weight test, in which a hard surfacing weld deposit is made to start a crack which then is made to run into or through a flame-cut, full-thickness sample of plate. Can this be the basis for a "go, no-go" test that is simple, cheap, rapid, and sufficiently reliable to find wide application? At present Pellini feels that an accuracy in the neighborhood of $\pm 10^{\circ}$F is obtained for TT determined by this test on different samples of a given plate. The reliability of this estimate is difficult to assess at present and some statistical studies are needed to define the scatter more accurately.

The drop-weight test confronts the full-thickness specimen with a running crack, which certainly is extremely sharp, and with stored energy sufficient to cause rapid propagation of a brittle crack. Both of these characteristics are appropriate;

on the other hand, it may be a disadvantage that strain waves are being reflected from various surfaces during the spreading of the crack, possibly thereby introducing some variability. Recent experiments in which size and shape are altered suggest that this variability is minor, but further proof of this would be desirable.

Although Pellini's explosion-bulge test may be interpreted so as to match service conditions even more closely than this drop-weight test, as he points out, there is almost no chance of its widespread use because of its cumbersomeness; its usefulness appears to be limited to the research laboratory. Additional fundamental studies relating to testing are mentioned in Section C-4, page 31.

B. ECONOMICS AND STATISTICAL RESEARCH

As pointed out under A, there are available a number of practical approaches to the main problem of reducing the probability of catastrophic failure of ships through reduction of notch brittleness of steel or through more effective utilization of superior steels. Let us review these again, pointing out in each case what dangers or difficulties might be involved if the change were made:

Method of Reducing Brittleness	Remarks
1. Reduce Carbon and Increase Manganese to Maintain Strength.	Will add to cost of steel and consume critical Mn in wartime.
2. Use Fully Killed Steel	Will add to cost of steel and monopolize critical availability of hot top capacity in steel mills in wartime.
3. Use Lower Finishing Temperature.	Slows down production of rolling mills. Increases mill maintenance cost.
4. Normalize after Rolling.	Insufficient normalizing capacity for war emergency. Adds to cost. Chiefly effective in fully killed steel.
5. Reduce Tensile Strength by Lowering Carbon Content.	Requires research to establish whether better ships would result from such a change.
6. Use Highly Notch Tough Steel in Critical Areas.	Increases cost somewhat. Needs further evaluation--only limited service experience to date.

Counterbalancing the added cost and manufacturing difficulties mentioned above are the loss of lives and loss of shipping capacity resulting from ships lost or dry-docked for repairs as a direct result of brittle failure. So, there is ample reason for considering the use of a more expensive steel.

Also, from a national viewpoint, it would appear justified to encourage whatever steel plant expansions or alterations might be necessary in order for the industry to produce ample supplies of notch-tough steel plates during a war emergency situation. (There may well be a growing need for such facilities anyway in connection with peacetime requirements, such as large welded tanks, welded pipelines, etc.).

Further studies, then, are needed on the economics and operational type of problems included in the above table. The results of these investigations should make it obvious to those concerned as to which one or more of the available approaches would be most acceptable to the nation, especially in wartime, from the standpoint of economics and critical materials.

Also there is the problem of determining how far it is necessary to go in reducing the average and maximum values of TT in ship steels.

And finally, there are the questions of test method, sampling procedure, and variability of product that should receive further study prior to the specification of laboratory tests for controlling notch brittleness in ship plate steels.

To be more specific on the above points, the following questions seem to require answers.

1. What test method would be most suitable for mill inspection of notch toughness in plate steels?

The Advisory Committee for Project SR-116, Monograph on "Brittle Behavior of Engineering Structures," is surveying the extent to which steels are rated in the same order of brittleness by many testing procedures, including the Charpy V-notch; Charpy keyhole 72", 3/4" thick, centrally notched plates; and the Navy tear test. Although the TT's determined by these various methods on the same steel will not be the same, they presumably could be related to each other with reasonable accuracy, at least within a given class of steel, given ample statistical data. Possible exceptions are in steels containing nitrogen, where the wide plate tests and the Navy slow tear test appear to have the ability to discriminate more critically between various levels of nitrogen than an impact test does.

It is necessary to move progressively towards a position that will permit TT specification. This cannot be done if effort is continually directed towards new tests. While new tests having desirable characteristics are to be encouraged from the long-range research standpoint, they must not be permitted to interfere with progress in application of current tests. No advantage possessed by a new test is likely within several years to overbalance the advantage of the confidence that has laboriously been acquired for the V-notch Charpy test.

It is noted that the British Admiralty Ship Welding Committee has settled upon the V-notch Charpy as an adequate test (though they also state that their decision is not intended to discourage further research).

When a sufficient volume of data on a new test has been accumulated, published, discussed, and confirmed, it may appear that it may ultimately have a chance of displacing the currently favored tests for reasons of greater reliability, closer correlation with service failures, or lower costs.

Of particular interest from a research point of view would be a continuation of Pellini's work on the drop-weight test.

2. <u>What average and maximum values of TT are needed for each range of plate thickness</u>?

M. L. Williams' data indicate that no crack starter plates have been found in failed ships with TT below 60°F for 15 ft.-lb. V-notch Charpy. Williams' data covered ships of various designs, including substantially all of the serious failures encountered in American shipping in recent years. Some of the ships had been modified since originally constructed to reduce stress concentration. A wide range in temperature and other service conditions was involved.

One might deduce from Williams' data that setting a limit on TT equivalent to 60°F maximum for the V-notch Charpy 15 ft.-lb. test would result in a substantially complete elimination of catastrophic failure of ships. However there is the possibility that the cost of such a specification would be excessive and that a less significant improvement would be adequate.

As a starting point for complete evaluation of the extent of improvement in TT needed, it would seem that a more extensive statistical survey should be made of the TT of unfailed plates in ships in service. The literature seems to offer all too little data on steels previously made. Williams' data, for example, are limited largely to plates removed from seriously failed ships and his samples have mostly been taken from the vicinities of the cracks. As Williams and Dr. W. J. Youden pointed out to one of the writers, it is unfortunate that a better sampling of the total plates in both the failed ships and the unfailed ships has not been made. A similar point was made by W. J. Harris and Finn Jonassen at the 45th meeting of the Ship Structure Subcommittee in January 1953.

There is a possibility that a relatively small shifting of the statistical curve for TT might result in an appreciable improvement in ship durability. Such a change might reduce the proportion of crack-starting plates appreciably and shift a certain proportion of plates from the crack-propagating variety to the crack-stopping classification. Since catastrophic failure can occur only in the absence of crack-stopping plates, the small shift mentioned above might greatly reduce such serious failures although not at all eliminating the probability of some cracks in a ship.

At any event, the statistical approach to this problem is of great importance and should be pursued actively, aided by the collection of needed additional data.

3. <u>What statistical spread may be anticipated in notch toughness of heats of steel plates and what number and location of test specimens are needed in order to represent adequately the steel and the heat?</u>

Before any attempt should be made to specify any form of notch-bar testing procedure, exploratory tests should be carried out on a series of actual production heats. It is understood that data on currently produced steels being accumulated by Kahn are on samples obtained from shipyards. At this stage identification as to location in the heat is not available and the direction of rolling may not be known in all cases.

Through cooperation with the steel industry, it should be possible to obtain the necessary test samples or test data by paying a so-called testing extra on the commercial heats of plates being produced currently and by the steel mills properly selecting and identifying the samples. Perhaps a project sponsored by AISI should be initiated, or some other mechanism of assembling data used. Some suggestions as to procedure might be derived from the statistical study of gun steels that has been conducted at Carnegie Institute of Technology.

Prompt initiation of a program is important if the many data are to be collected that are believed necessary in similar projects now operating abroad, and especially if the United States is soon to enter a period in which few ships are built.

4. Determine whether some reduction in tensile strength by reduction in carbon content would be advantageous.

This has been suggested by a number of persons and from many standpoints is very attractive. It is therefore important to evaluate all the consequences of this possible solution and to determine whether poor performance in ships would in any way be anticipated. Studies should also include investigation of the fracture strength of the material. (See discussion of tests on page 14.

5. From the standpoint of obtaining maximum reduction of TT, which would be the more feasible and/or economical in each range of thickness: a) reducing finishing temperature, or b) normalizing after rolling?

Such a study would combine economics and statistical research investigations with the obtaining of metallurgical data. On one hand, there should be consideration of the steel industry's problem of capacity operation of rolling mills, especially during emergencies, meaning that extra requirements on rolling practice might not be feasible or economical. On the other hand, perhaps there should be two or three normalizing plants of sufficient capacity to serve the main centers of production of steel plates during periods of emergency as well as in peacetime.

6. Can a controlled rolling practice be developed that would provide grain refinement equivalent to normalizing but at less cost?

This question should be given detailed consideration. The thought here is that if some change in steel mill practice is to be considered, perhaps a considerably altered rolling and finishing practice could be developed that would be more economical and better than adding normalizing to present rolling techniques.

In general it would seem appropriate from a national point of view to explore to the utmost the utilization of controlled rolling to obtain the necessary reduction in TT preferably to the use of either normalizing treatments or manganese additions.

7. Could an ingot practice be developed that would reduce the cropping losses and other costs experienced with hot-topped ingots?

The thought here is whether the requirements for a fully killed carbon steel could be met with a relatively less costly ingot practice than that currently used for this class of steel.

8. Would it be feasible for the steel industry in wartime to maintain the manganese levels currently being used?

It is known that the steel industry has been giving serious consideration to avoiding manganese shortages in a future war. This problem should be evaluated in the light of possible changes in the manganese picture.

C. FUNDAMENTAL RESEARCH

Of unquestioned value to understanding the problems of fracture are the many studies on the fundamental science of plastic flow in all metals conducted in many cases without direct relation to the present problem.

While basic research of this type will undoubtedly eventually contribute to our understanding of brittle fracture in steel, the long-term nature and the possible limited extent of the contributions of individual studies do not justify extensive support of many investigations of this type by the Ship Structure Committee, in the face of probable reductions in the "materials" research budget. However, in view of the great importance of this type of study to the ultimate understanding of the TT phenomenon, continued support of this work by Government agencies, such as ONR, OAR, NSF, more directly concerned with fundamental research is desirable. It seems likely that the only fundamental research in the field of materials which can be supported in the future by the Ship Structure Committee is that which is quite directly related to the ship steel problem.

1. Mechanical properties of High Purity Alloys.

For the purpose of eliminating as many variables as possible and thereby clearly showing the effect of the remaining ones, several laboratories have been experimenting with high purity alloys. Results in this attack have come slowly in all laboratories, for the work is difficult; but the accomplishments are sufficient to indicate that continuation of this approach will result in further worthwhile contributions. This is indicated, for example, by results on oxygen mentioned below.

a. Embrittlement by oxygen.--The detrimental effect of oxygen is now known to be associated with lack of ductility in grain boundaries. In vacuum cast alloys the embrittling constituent follows delta grain boundaries; after working and recrystallization, it follows ferrite boundaries and serves to initiate intergranular cracks that may subsequently become transcrystalline.

Deoxidation of high purity melts with Al or Ti reduces embrittlement, but Brick's results show that the addition of 0.020% Al to very low oxygen alloys does not alter the ductility, which indicates that it is deoxidation, not alloying effects, that is involved. Removal of the grain boundary-embrittling oxygen effect has been accomplished in several laboratories by adding about 0.006 to 0.01%C or by reducing oxygen to 0.003% (Brick (Project SR-109), Rees, and Hopkins; Gibbons; Low; Hall). The mechanism by which a solid state reaction between carbon and oxygen at subcritical carburizing temperatures removes embrittlement is not known, but Gibbons finds that decarburizing again lowers ductility.

b. Intergranular vs transgranular fracture.--There is a growing recognition by those active in the field that there may be, in effect, two TT's, one for grain boundaries and the other for transcrystalline fracture. Low has noted cracks that were able to run along boundaries but that ended soon after they left a boundary and attempted to progress transgranularly. Rees and Hopkins have remarked about the partially intergranular nature of fracture in a 0.22%C, 0.4%Mn commercial steel and that TT's are likely to be higher when cracks are partially intergranular. Brick finds a correlation of carbide envelopes at grain boundaries with loss of ductility and also finds the absence of carbides (in quenched samples) results in a very steeply dropping TT curve. Rinebolt and Harris also find a steep transition in 0.01%C alloys, as does the National Physical Laboratory in high purity iron and iron alloys.

It has been suggested to the writers by Gensamer that the Penn State samples could well be inspected with regard to the intergranular vs transgranular fracture characteristic. New insight into the results might be reached.

Is it possible that intergranular crack initiation is responsible for the gradual nature of the TT curve and largely responsible for cases of abnormally high TT's? Is nitrogen active in altering the properties of grain boundaries in a way similar to oxygen? Is the most fundamental question the matter of distribution of these interstitial elements between grain boundaries and grain interiors?

Is the rate of flow in the boundaries a criterion of brittleness because of triaxial stress concentrations built up at grain junctions through boundary flow? Or is it the cohesive strength across a boundary that is most definitive--and is this altered chiefly by the presence of invisible oxides, carbides, or nitrides? (The elements that raise TT are strong carbide formers and also nitride and oxide formers.) Or is it the rate of redistribution of stresses at the ends of slip lines (perhaps the rate of "climb" of dislocations)?

c. Internal friction vs oxygen and hydrogen.--Gibbons at the University of Chicago found a shift of 300°F in the internal friction peak of high purity polycrystalline iron when the oxygen content was changed from 0.003% to 0.021%. In some manner as yet undetermined the oxygen altered the rate of relaxation of shear stress at the boundaries, and since it also embrittled the boundaries at low temperatures, the two properties appear associated. It is indicated by these studies that the grain boundary peak in internal friction tests is a useful tool for further studies of the properties of ferrite boundaries.

Gensamer has stated that internal friction is making a contribution in his current ONR program on high purity vacuum-degassed ferrites: a peak has been found in the neighborhood of 100°K which is ascribed to hydrogen in some form (believed not as protons) and that quench aging due to this may occur in the 100°K range at rates comparable to the rates of quench aging from carbon and nitrogen in the 300°K range. It may even be possible that the chief effect on the shape of stress-strain curves at low temperatures is due to the action of hydrogen interfering with the movement of dislocations. Extremely small amounts of hydrogen would be sufficient, just as small amounts of interstitial C and N interact with dislocations at higher temperatures to produce the yield point and strain aging.

It has been shown by Fast's internal friction studies that the precipitation of nitrogen from Fe-N alloys is greatly retarded by the presence of manganese. This suggests that interactions between various substitutional elements with the interstitial elements may alter their mobility and thereby their tendency to reduce ductility by segregation at grain boundaries or at dislocations. (This is commented on also under the discussion of delayed yielding.)

2. Chemical composition.

As emphasized above (Sections 1(a), 1(b), 1(c)), there is promise of rapid advancement in understanding through continued research of fundamental nature on such subjects as oxygen and hydrogen content and distribution, on the interaction of interstitial elements with each other and with other elements, and on the properties of grain boundaries and sub-boundaries as influenced by composition.

An understanding is needed of the mechanism by which Mn and Ni lower TT and C, N, and P raise it, and of the role of the deoxidizing elements, Si, Al, Ti, Zr, and V. For example, it would be well to know the basis for the anomalous behavior of Ti and V as reported by Harris and Rinebolt, in first raising

TT and then, with further added amounts, lowering it nearly back to the original value.

The question of distribution of the deoxidizing elements between carbides, nitrides, and oxides at various oxygen and nitrogen levels should be of interest. Also, more should be known as to whether P, N, H, and O are in solid solution or in combined form at the grain boundaries either of ferrite or of the former austenite structure. (It is noted that grain boundaries in Cu-Sb alloys become embrittled at low temperatures when as little as 0.14% Sb is present; this is ascribed by McLean to segregation without precipitation. (J. Inst. Metals, 1952).

A practical reason for extending studies of the interrelations of the elements, C, Mn, Si, Al, N, P, H, and O would be with the hope that a key could be found for reducing TT adequately without increasing Mn.

3. Metallurgical structure

It was emphasized in Section A, p. 7 that a better understanding was needed of the effect on TT of the variables of rolling and deoxidation practice. To be effective, a program in this field must consist of well-planned fundamental research rather than mere data collecting. In this way the results could be of value throughout the industry rather than being limited in validity to the particular mills on which the test materials were produced.

The emphasis of the program might well be on the metallurgical structure of the steel, since the effect of the processing variables must reside somehow in the structure (macro, micro, submicro, atomic). If the relation of the structure of the steel to notch toughness were well understood, and if the significant features of the structure could be seen and measured, then by proper choice of variables to yield a desired structure, plate with desired properties can be produced. The difficulties are unquestionably great; for example, only with carefully planned and executed experiments is it possible to isolate the effects of the spacing of the carbide lamellae in pearlite without confusion caused by variation in ferrite grain size, rate of cooling, or other significant variables. Unexpected variations in results have plagued nearly every investigator in the field. But there is much reason to believe that the chief factors and relationships can be isolated by suitable research, that the relation of metallurgical structure to notch toughness can be determined, and finally, that the mechanism of crack initiation and propagation in the steel can be much better understood.

The writers suggest that this program be coordinated under a single competent investigator, or at least under a single advisory committee. The work need not be confined to a single laboratory but could well be split among two or more, still retaining unified leadership of the work. For example, one organization might undertake the preparation of materials and samples; another the planning, the testing and the analysis of results. The work must be coordinated, too, with further fundamental work on chemical composition, for the two fields are intimately related.

4. <u>Mechanics of crack initiation and propagation</u>.

Committees on Ship Structural Design and on Fabrication are more properly concerned with this field than the Ship Steel Committee. The development and test of theories of critical crack length is important. A reliable theory and sets of measurements on proportionality constants in the theory are needed for proper understanding of test data, and should lead to a basis for quantitative estimation of the danger associated with a crack or a weld defect. It might lead to a better understanding of the effect of microstructure and of grain boundaries on fracture properties.

Progress in the field is slow but continuous. Recently E. O. Hall at Cambridge has been extending Orowan's modification of the Griffith theory by using Mott's ideas on the kinetic energy of the moving plate after passage of the rapidly running crack, Von Karman and Duwez's results on the rate of propagation of plastic waves, and Yoffe's work on the moving elastic wave running ahead of the crack.

It seems clear that at high crack velocities the plastic flow is restricted to a narrow band because of the finite rate of propagation of the plastic wave and the plastic work is thereby restricted to a small fraction of the value for low velocity cracks. The velocity of the plastic wave may therefore be a controlling variable in brittle fracture. If so, it would seem that the shape of the stress-strain curve at high strain rates should be a fundamental criterion of brittle behavior.

According to this line of reasoning there should be a correlation between the presence of a yield point in a polycrystalline metal and the tendency for it to accept a rapidly running brittle crack. However, the fact is that prior straining of steel (which should remove the yield point) does not eliminate the transition temperature. It appears likely that strain aging is taking place to a sufficient extent between the time of working and the time of testing so as to hide this effect in all tests to date and that a quicker test should be tried. (Some effects of quench aging have been detected an hour after quenching).

Propagation of the plastic wave may also be influenced by the delayed yielding phenomenon*, for if yielding is delayed for a time after the arrival of the stress wave ahead of the crack, less time is available for the spreading of the plastic wave and therefore the flowed region is limited. The criticism has been made that time delays are observed only when carefully polished and axially loaded specimens are used, and therefore are not to be expected at a growing crack. But in the interior of a specimen at a place subjected to a local stress concentration

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*Clark, D. S. "The Behavior of Metals under Dynamic Loading," ASM Campb. Memorial Lect, 1953.

the conditions would appear to us to be appropriate for delay times to occur. The fact that the studies of Wood and Clark have disclosed an upper limiting stress above which no time delay can be observed does not remove the possibility that this phenomenon could operate at lower stress levels, upon the first arrival of the stress wave and thus concentrate the flowed region.

The group at California Institute of Technology should be encouraged to continue investigating delayed yield, both at the fundamental level, and also on steels of known TT or fracture strength. Their studies of microstrains during the delay period suggest that there is a possibility through such work of getting fundamental information on the anchoring of dislocations by interstitial elements and the effect of alloying elements on this process.

Related to the plastic wave propagation, too, is the linear proportionality between the strain rate and the logarithm of the absolute temperature of a point on the transition temperature curve, i.e., the strain rate sensitivity of the steels. Data on this subject should eventually be fitted into the theoretical formulas.

The amount of plastic work during fracture must also be influenced by localized flow and tearing at grain boundaries, at the junction of misaligned crack origins, and at any occasional grains that fail in a ductile manner. These must be considered in theories.

The theory of the size effect in brittle fracture is likewise important but does not lie directly in the metallurgical field. Orowan has suggested that the critical size of a crack that will propagate spontaneously in a brittle manner is not the largest of the pre-existing microcracks assumed in the Weibull theory, but is a crack that results from shear fracture at the base of a notch. He is continuing his interest in this type of problem.

Irwin and his co-workers stress the importance of the strain energy release which accompanies an increment of the cracked area, and the relation of this to the rate of doing work by spreading the crack by this amount. Instability occurs when the available energy exceeds the work necessary, and a fast propagating crack then results. In the long run it might be anticipated that mathematical formulation of these ideas would lead to engineering principles governing the safety factor in structures. Irwin is to be encouraged in his efforts to write a monograph on the subject.

A. A. Wells' important article in Welding Research of April 1953 (which we received as this report was being typed) organizes available data and advances the theory that "When static external loads are applied to notched mild steel specimens having no residual stress or strain systems and showing usual ductility in the tensile test at temperatures within or just below the notch-brittle transition range (as determined by a static full-plate thickness test), brittle fracture from the root of a notch will not normally take place until general yield has occurred, and the general yield zone embraces the root of the notch allowing the notch to open. General yield is defined as that state in which no path exists wholly through elastic material between at least one pair of opposite external loading points. In the axially-loaded notched tensile specimen, general yield occurs when the net average stress across the notched zone reaches the yield point of the material for very thin plates, and two-and-a-half times this value when the plate thickness and depths of the notches are large compared with the notched width."

Thus Wells concludes that the strains at the root of a notch must be suitably intensified by general plastic flow before a brittle fracture will be initiated. The observed breaking stress is therefore understandably always equal to or greater than the yield stress. For crack propagation, Wells concludes that the elastic strain energy of the surroundings must supply a certain measurable minimum surface energy of the order of 4.5 ft.-lb. per square inch of crack surface for mild steel at room temperature.

Wells concludes that local residual stresses of the order of yield-point magnitude aid the external stresses in extending transverse micro-cracks that form in a weld in cooling. Since a tensile residual stress field has been shown to span no more than a distance of 6 in. in a 1-in. thick plate, the critical point in the history of crack propagation out from a butt weld comes at the time it is about 6 in. long. Brittle fracture will continue if the service stresses are high enough at this point to supply the required surface energy.

Wells calculates that, for an internal crack to propagate in a stress field of about 45,000 psi, the crack must be about 3/4 in. long; for 20,000 psi, it must be about 6 in. long; for 11,000 psi, about a foot long. He suggests that better methods of evaluating the minimum surface energy are required for further progress. A portion of the effect of plate thickness that is not dependent on metallurgical changes can be attributed to this surface energy requirement. But certain instances of surface energies greater than the minimum value are not accounted for by the theory. (Perhaps these were in plates of superior notch toughness).

5. Metallography of fractures.

Research on the metallography of fractures can be expected to be effective only under the active leadership of one of the few authorities in this country who is well acquainted with the brittle fracture problem as a metallurgist and as an expert on crack initiation and propagation. An approach that is entirely metallographic cannot be effective, even though it be highly skillful. This is especially true if the metallography is with the electron microscope.

To be effective there must be not only very good metallography at high and low magnification, but also theories proposed that need to be tested. Then there should be carefully controlled tests of those theories made by various methods in addition to the metallographic, and the generation of new theories by observations during the tests. As mentioned elsewhere, discrimination between intergranular and transgranular fracture is important.

If there are features in the microstructures that are not understood, they need to be explored individually by a series of studies properly designed to disclose artifacts and to differentiate one possible origin of the features from another. The groups in the country meeting these requirements are not numerous. Dr. Irwin's group at the Naval Research Laboratory is continuing in this field with some of its effort, and is to be encouraged.

Current informed opinion is in moderate agreement that twinning does not control the TT of ship steels, and that further metallographic research on this is not necessary. Twins can form in low speed tensile tests in the early stages of plastic deformation, and yet the specimen may continue to deform in a ductile fashion thereafter (although strain hardening is likely to be more rapid when twinning is excessive). Twinning tends to be suppressed by prior plastic deformation, but the TT is generally raised. Rees and Hopkins found twinning in impact tests of their high purity samples conducted above the TT.

On the other hand, Gibbons, in high purity iron, observed instances in which twinning in the neighborhood of an embrittled boundary seemed to be responsible for initiating fracture.

6. <u>Fundamental research on single crystals</u>.

In attempting to evaluate single crystal work from the standpoint of its contribution to the understanding and solution of the ship steel problem, it is difficult to avoid the conclusion that single crystal work has reached the point of diminishing returns for the particular objectives of the Ship Structure Committee. Single crystal research would seem more appropriately continued under sponsorship that has broader scientific scope.

The mechanisms of flow have been established in broad outline and the temperature-dependent, strain-dependent, and stress-dependent trends are known; to this extent single crystal work, including the studies under cognizance of the Committee on Ship Steel, has contributed greatly to our understanding. But to seek further precision data on the absolute value of the critical stresses or critical orientation for slip, twinning and cleavage in the hope that they can be applied in some way to ship steel would require an experimental reproducibility that can scarcely be expected and would imply a rather unreal degree of similarity between single crystals and polycrystalline aggregates as regards the micromechanism of flow and fracture, and the degree of perfection of the crystal structure.

Twinning, for example, is notoriously sensitive to grain size and structural imperfections, as are also slip line spacings and the displacements at individual slip lines. (The work at Carnegie Institute of Technology has recently shown that prestraining single crystals of iron raises the brittle fracture stress if the fracture propagates through a strain hardened region but lowers it if the fracture occurs in a region of little or no slip; and prestraining lowers the fracture stress of ductile specimens.) Fracture may initiate at boundaries or in areas of stress concentrations neighboring on boundaries, in ways not duplicated in single crystals. Segregation at boundaries (as a solid solution or as a precipitate) cannot well be investigated with single crystals.

7. Quench aging and strain aging.

Brittleness in the heat-affected zone is intimately associated with quench aging, and it is an important factor in raising the TT of this zone; conversely, over-aging appears responsible for much of the improvement of properties obtained by postheating and possibly also by low temperature stress relief. Low has found an increase in TT of 70°F in three years' aging of a quenched 1020 semikilled steel. Pellini found marked effects with various structural steels. The possible relation of aging to the TT of thick plate is clearly of interest.

Strain aging can raise TT even more than aging after quenching. This subject has been investigated under the sponsorship of the Pressure Vessel Research Committee. Strains of 1% have been found to increase Charpy TT by 60°F in an A-70 rimmed steel, although the TT in a normalized A-201 steel was not raised at all in tests at Lehigh University. The effects are complicated by anisotropy and the varying response to strains of different magnitude.

Better understanding of these aging factors is desirable. Consideration might be given to the possibility that danger from strain aging could be minimized by low temperature heat-treatment which overages the strained plates. The general solution advocated elsewhere in this report would seem to offer adequate protection against the dangers of strain aging in local areas, namely, to have plates of good notch toughness throughout the structure.

RECOMMENDATIONS FOR FUTURE RESEARCH

Evaluation of the progress to date in the ship steel research program and consideration of possible research programs for the future have led the writers to suggest the following applied research, statistical analysis, and fundamental research as most appropriate for consideration by the Committee on Ship Steel. These are listed in what the authors feel is the relative order of importance, i.e., number 1 is considered to be the most important, etc.

1. Evaluation of the consequences of increasing notch toughness by lowering tensile strength through lowering carbon content at constant manganese. This should include investigation of the fracture strength of the material and of the influence of the reduced carbon on grain size. (It should be remembered that reduced tensile strength may require increased plate thicknesses--the lower carbon material must be evaluated on this basis also.)

2. Expansion of the studies of steel from failed ships at the National Bureau of Standards. This should include further examination of material from plates already tested (ferrite grain size measurement, for instance,) and further statistical studies of the improved performance which might be expected to result from given shifts in the distribution curve of transition temperature of ship

steels. Efforts to obtain more samples from unfailed plates should be maintained.

3. Initiation of a testing program at the mills to determine notch toughness of currently produced ship steels. This would permit the testing of many precisely identified samples in a relatively short time and would allow comparison of results on a heat, mill and industry basis, thus assisting in determining the numbers and locations of test specimens that are needed to adequately assess ship plate quality.

4. Continuation of the long range program at the New York Naval Shipyard of testing random samples of ABS steels currently supplied to shipyards. This will permit evaluation of currently supplied steels on an industry-wide basis. This work should be correlated with that proposed as #3 above and both projects should be related to steel from fractured ships (#2 above).

5. Initiation of fundamental research on the influence of metallurgical structure on transition temperature. This would include study of effects of ferrite grain size, of austenite grain size, and of size, shape and distribution of carbides on the transition temperature, and study of the mechanisms by which interstitial and substitutional elements (particularly the deoxidizers) alter notch

brittleness, the way they interact, and the way they are distributed.

6. Initiation of research to study how processing variables, such as re-heat temperature, amount of reduction, amount of cross rolling, finishing temperature, rate of cooling, etc., influence transition temperature. This investigation should be integrated with the studies of metallurgical structure (#5 above).

It is recommended that further research be supported by appropriate agencies: on the scatter and the significance of the NRL drop-weight test; on the reason for cracks not following the heat affected zone of welds; on the feasibility of controlling finishing temperatures and cooling rates, developing cheaper killed steel practices and increasing normalizing capacity; and on numerous areas of fundamental research that bear importantly but less directly on notch toughness.