SSC-94

MECHANICAL PROPERTIES OF HIGH PURITY Fe-C ALLOYS AT LOW TEMPERATURES

by

R. M. Brick

SHIP STRUCTURE COMMITTEE

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ADDRESS CORRESPONDENCE TO:
SECRETARY
SHIP STRUCTURE COMMITTEE
U. S. COAST GUARD HEADQUARTERS
WASHINGTON 25, D. C.

March 31, 1959

Dear Sir:

The University of Pennsylvania has completed an investigation sponsored by the Ship Structure Committee in conjunction with its research program on the improvement of hull structures of ships. Herewith is a copy of SSC-94, Final Report on "Mechanical Properties of High Purity Iron-Carbon Alloys at Low Temperatures," by R. M. Brick.

This project was conducted with the advisory guidance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council.

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

This report is being distributed to those individuals and agencies associated with and interested in the work of the Ship Structure Committee.

Yours sincerely,

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

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Serial No. SSC-94

Final Report
of
Project SR-109
to the

SHIP STRUCTURE COMMITTEE

on

MECHANICAL PROPERTIES OF HIGH PURITY Fe-C ALLOYS AT LOW TEMPERATURES

by

R. M. Brick

University of Pennsylvania
Philadelphia, Pennsylvania

under

Department of the Navy
Bureau of Ships Contract NObs-50062
BuShips Index No. NS-011-078

transmitted through

Committee on Ship Steel
Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

under

Department of the Navy
Bureau of Ships Contract NObs-72046
BuShips Index No. NS-731-036

Washington, D. C.
National Academy of Sciences-National Research Council
March 31, 1959

ABSTRACT

The mechanical properties of high-purity iron-carbon alloys, 0.003 to 0.49% carbon, at low temperatures were investigated. Results obtained indicate that the binary ferrites do not differ qualitatively from commercial ferritic steels in low-temperature behavior, assuming that in both cases oxygen contents are sufficiently low for fractures to be transcrystalline rather than intercrystalline.

The study indicates that the exponent of strain hardening appears to be more significant in defining low-temperature brittleness than the slope of the uncorrected stress-strain curve. An hypothesis is also extended that while carbides initiate cracks, they also interfere with crack propagation and thus reduce the abrupt change from ductile to brittle behavior upon a decrease of temperature.

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INTRODUCTION

The investigation of the fundamental mechanical properties of binary ferrites at low temperatures was inspired by a series of brittle failures of steel under service conditions involving, among other factors, notches and low temperatures. It was thought that a knowledge of the true stress-strain curves of pure alloys would serve to clarify the data collected by assorted practical tests on commercial steels, and in particular to indicate the specific effect of different alloying elements and impurities. This report re-examines and summarizes the results of this study on binary iron alloys, the details of which have been reported in three prior progress reports.[1--3]

Part I of this report is concerned with data resulting from true stress-true strain tensile tests for alloys with from 0.02 to 0.49% C in high purity iron; Part II deals with ductility and with strain hardening as affected by temperature, ferrite grain size and carbide morphology in the range 0.02 to 0.12% C content in the same pure irons; and Part III examines alloys with carbon contents ranging from 0.003 to 0.03% in order to 1) determine the effects of substructure or veining in the ferrite and 2) determine the under-saturated, saturated or precipitated Fe_3C in the ferrite. These structural states are evaluated in terms of yield strengths and fracture strengths as determinants of Charpy V-notch transition temperatures.

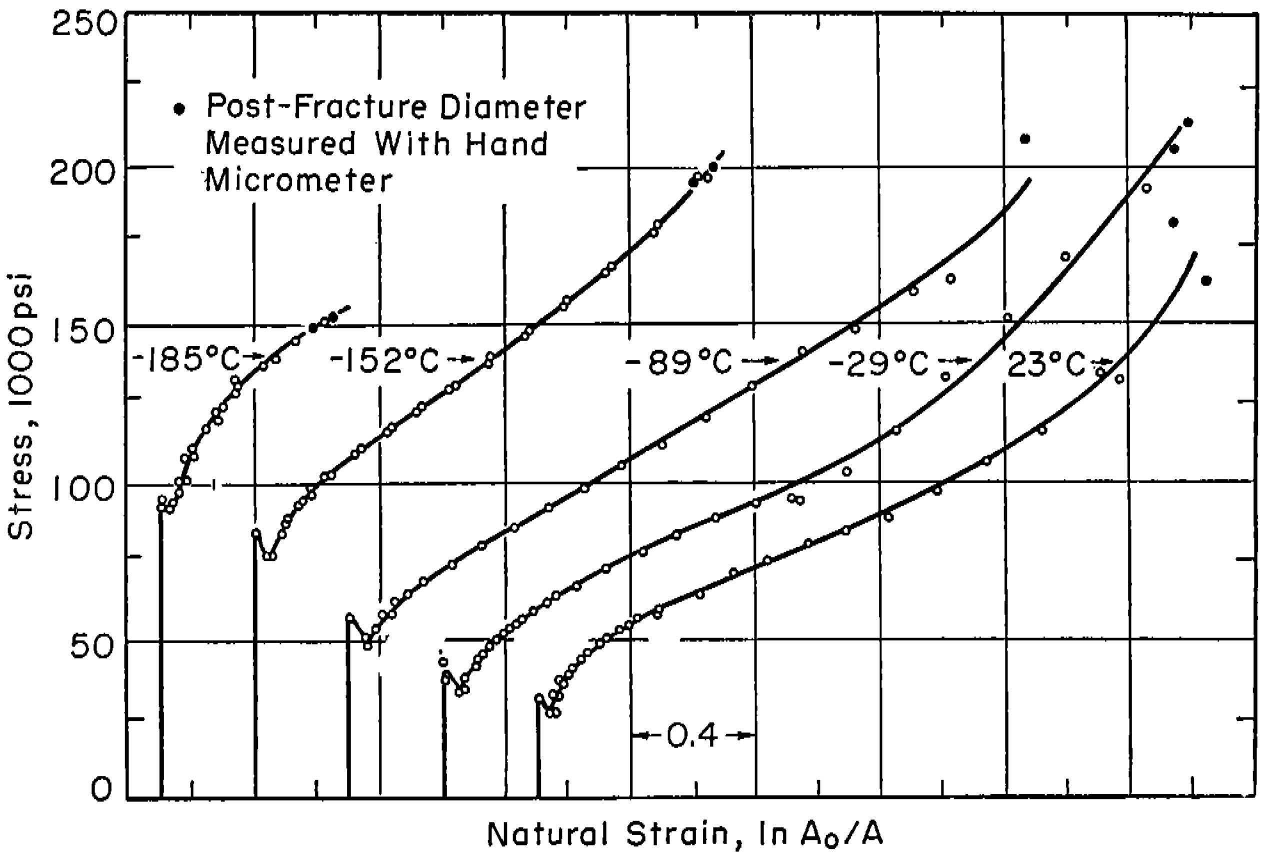

Fig. 1. Natural Stress-Strain Curves for Iron-Carbon Alloy Containing 0.02% Carbon.

Part I - True Stress-True Strain Tests

The true stress-true strain tests were made on high-purity iron containing from 0.02 to 0.49% carbon. The testing material was prepared by one of two methods: 1) carbon deoxidation in the liquid state followed by vacuum melting, or 2) hydrogen deoxidation in the solid state followed by vacuum remelting. Metallic impurities and sulphur in these alloys were generally below 0.003% each, while oxygen and nitrogen were present in quantities of less than 0.001%. The alloys were forged and rolled to 7/16 in. rounds and heat treated to give structures of the same ferrite grain size (about ASTM No. 4) and the same pearlite spacing as a normalized steel.

Tensile test bars were then made and tested at five temperatures, generally at about 23 C, -29 C, -90 C, -150 C and -185 C. Axial loading was attained by use of chain-loading members. A special diameter gage was constructed to give autographic recording of load vs. instantaneous diameter from the time of yielding to fracture. This enabled calculation and plotting of true stress vs. strain, as shown in Fig. 1. From graphs of this nature, charts were constructed showing the variation of particular properties derivable from the σ vs. ϵ graphs with temperature (Fig. 2) and with carbon content (Fig. 3), and the following conclusions were reached:

1. Yield strengths and flow stresses increase continuously with decrease of temperature (Fig. 2) and increase of carbon (Fig. 3).

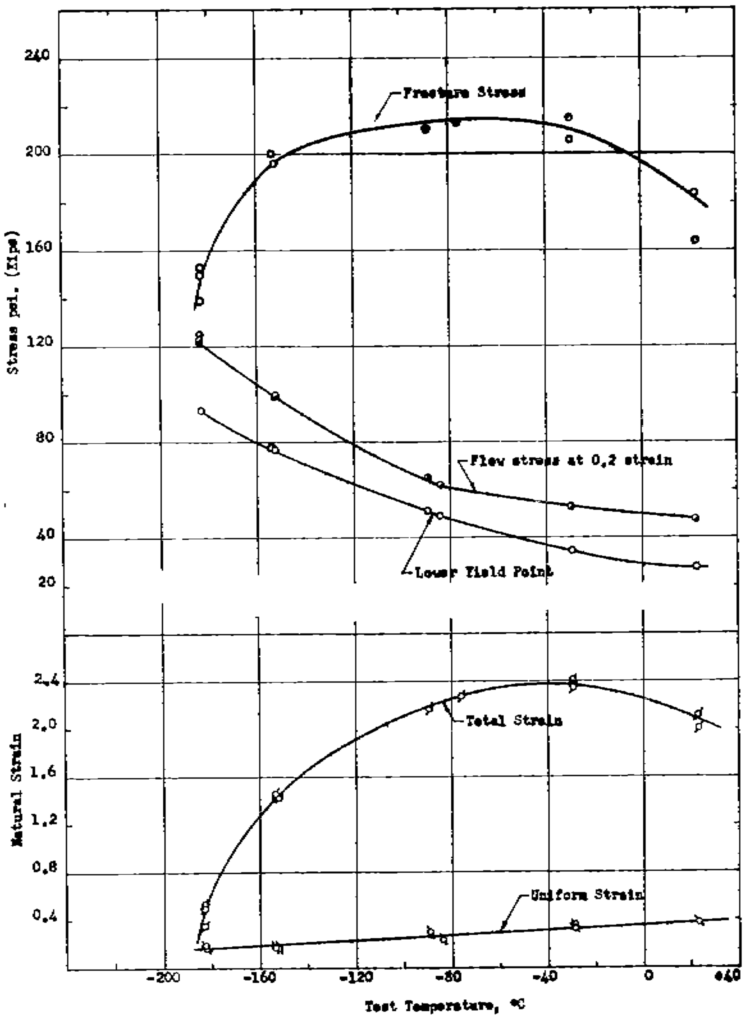

Fig. 2. Variation of Tensile Properties with Temperature Alloy 72V, 0.020% carbon, Series III.

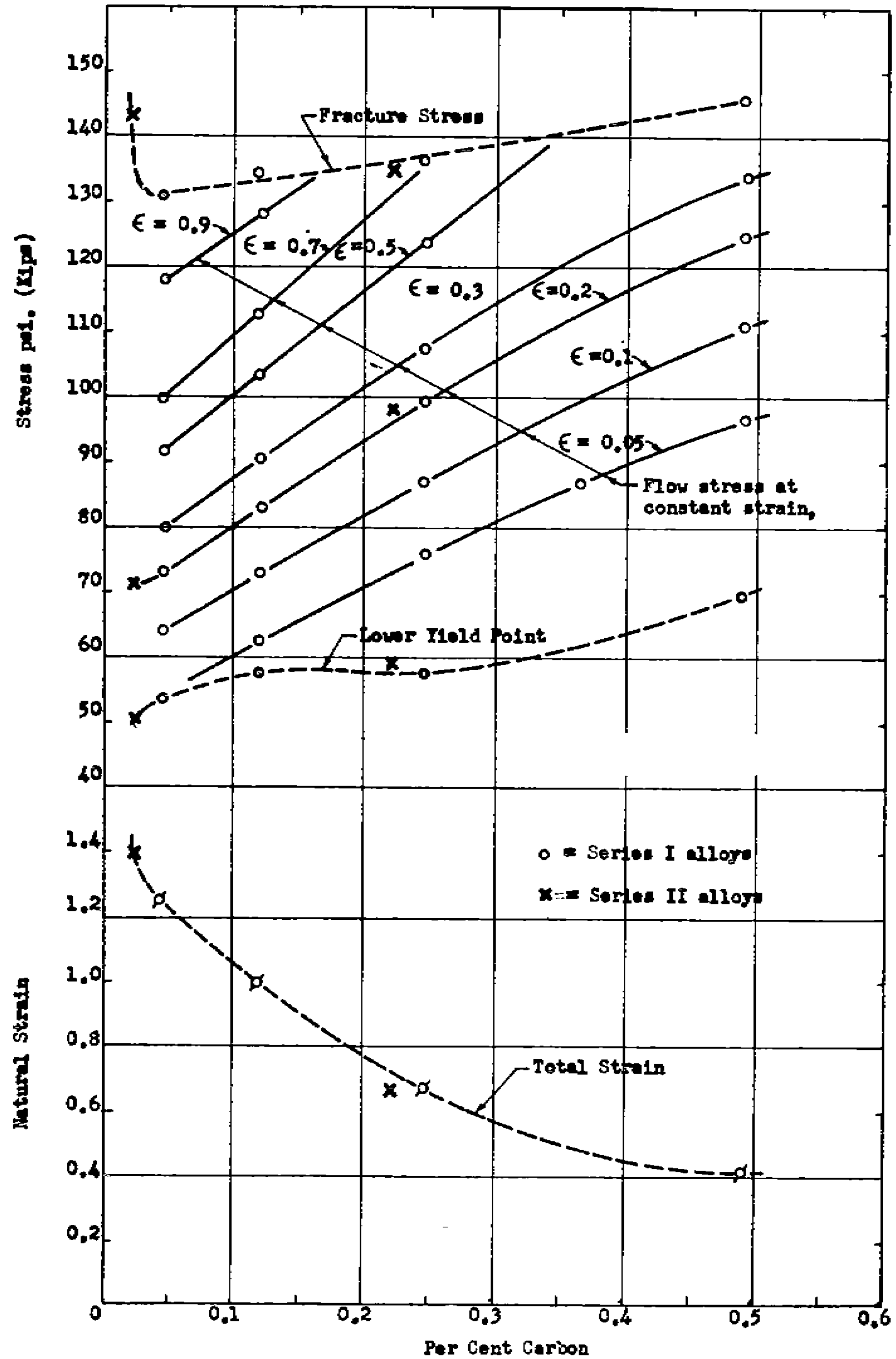

Fig. 3. Variation of Tensile Properties at -95 C with Carbon Content

2. Fracture stresses also increase with decrease of temperature until, at around -150 C, loss of ductility becomes pronounced and with less strain hardening the fracture stress drops to a considerably lower value at -185 C. The fracture stress increases with increase of carbon, but it does so less rapidly than the yield strength.
3. Ductility, as indicated by the total strain to fracture, remains relatively constant upon cooling to -100 C and then drops rapidly with further cooling until it approaches zero at -185 C. Ductility at any temperature decreases with increase in carbon content.
4. The tensile transition temperature, based on half the maximum energy-to-fracture of these axially loaded, unnotched tensile specimens, was in the range of -160 to -170 C for all alloys tested. Although carbon content has little effect in terms of this parameter, the total energy to fracture decreases sharply with increase of carbon content at temperatures above -160 C.
5. The addition of 0.02% Al to an 0.02% C high-purity and oxygen-free alloy did not measurably affect the low-temperature tensile properties.

The above conclusions show that high-purity iron-carbon alloys do not differ qualitatively from commercial ferritic steels in low temperature behavior,

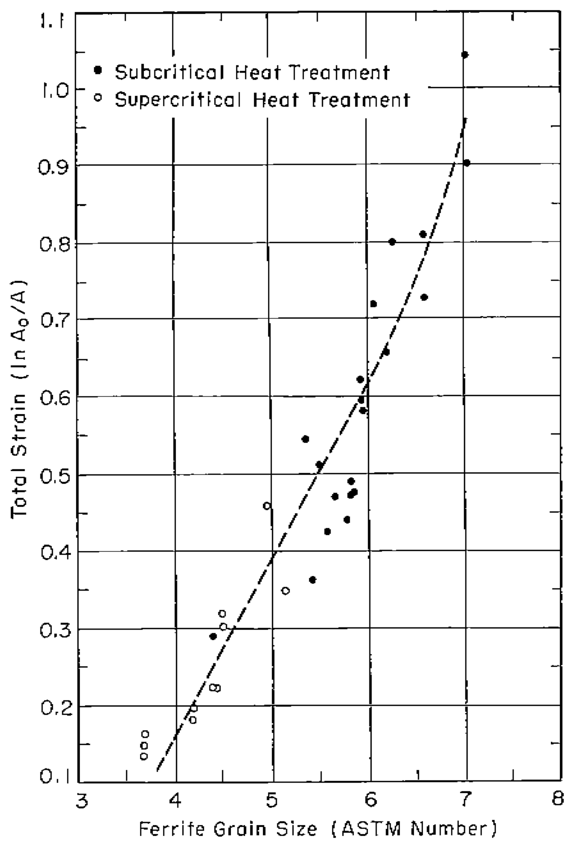

Fig. 4. Effect of Ferrite Grain Size on Total Strain at Liquid Air Temperature. (0.02% carbon alloy.) (-185 C)

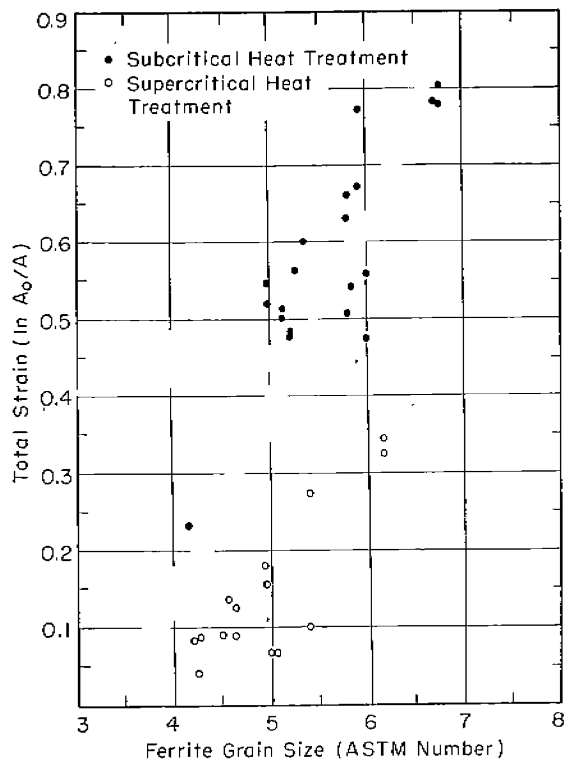

Fig. 5. Effect of Ferrite Grain Size on Total Strain at Liquid Air Temperature (0.04% carbon alloy.) (-185 C)

assuming that, in both cases, oxygen contents are sufficiently low for fractures to be transcrystalline rather than intercrystalline.

Part II - Ductility, Strain Hardening and Carbide Morphology Effects

During the second phase of work on this project, attention was directed to determining if there was a difference between alloys prepared from carbon-deoxidized stock and those prepared from hydrogen-deoxidized stock. No difference was found between these in either composition or properties. An earlier indication of an apparent difference was attributable to pronounced changes in properties occurring in compositions approaching the solubility limit of carbon in ferrite at 723 C (0.02% C).

Work was also directed at determining with greater certainty the effect of ferrite grain size and carbide morphology on properties of alloys having compositions in the range of 0.02% C to 0.12% C. True stress-strain data were again obtained and analyzed, and the following conclusions were reached:

1. Ferrite grain size is the sole factor determining the ductility or total strain of high-purity iron containing 0.02% C when it is tested under uniaxial tension at liquid air temperature. Total strain at -185 C of this alloy increases strongly with decrease in ferrite grain size (Fig. 4).
2. In the case of higher carbon content, 0.03 to 0.12% C, the ductility at -185 C is determined by ferrite grain size and by carbide

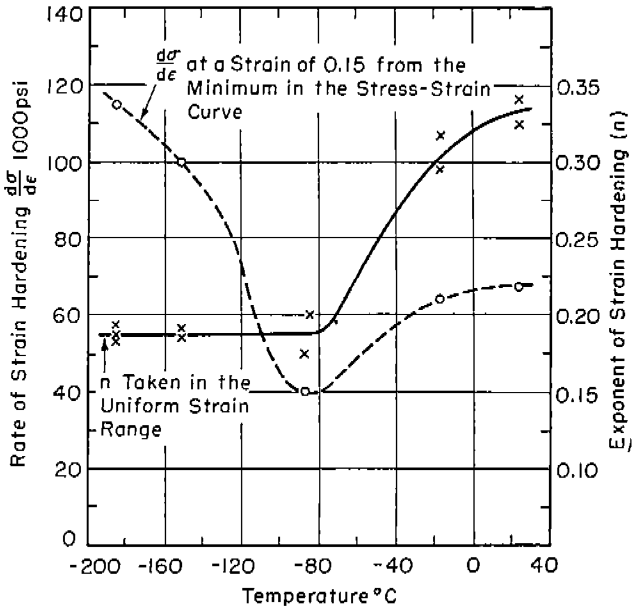

Fig. 6. Effect of Temperature on Strain Hardening.(0.02% carbon alloy heat treated subcritically.)

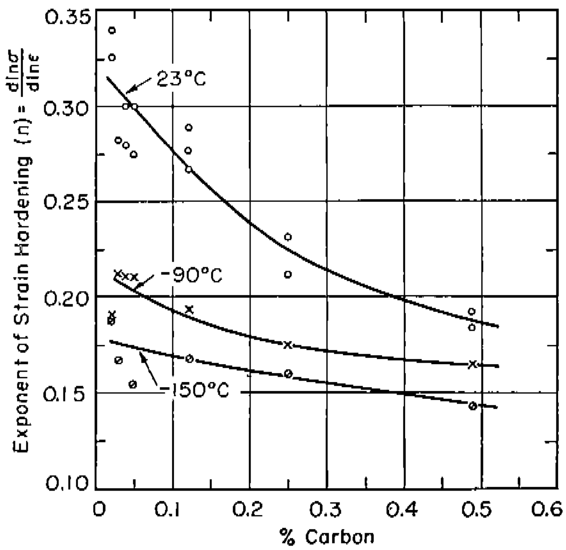

Fig. 7. The Effect of Carbon on the Exponent of Strain Hardening. All heat treatments are super-critical except for the 0.02% carbon alloy.

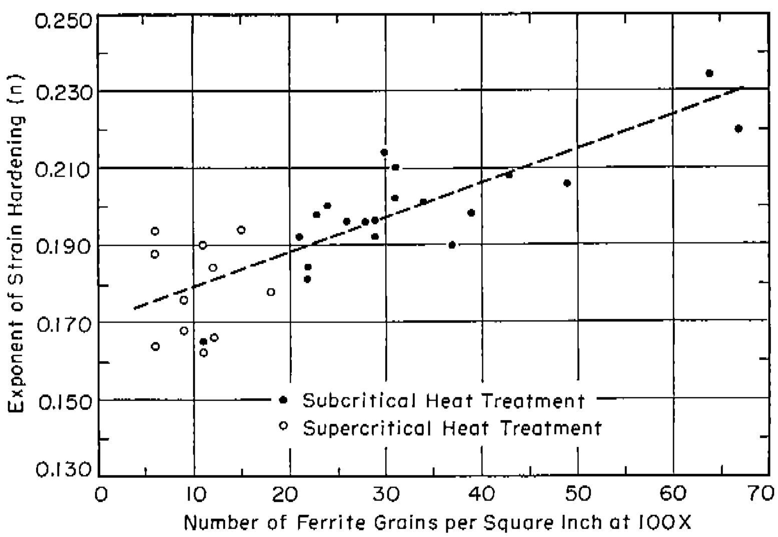

Fig. 8. Effect of Ferrite Grain Size on the Strain Hardening Exponent of an 0.02% Carbon Alloy Tested at Liquid Air Temperature.

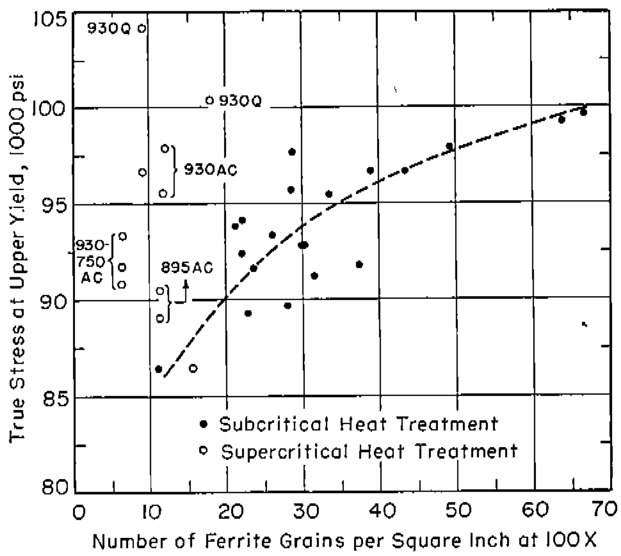

Fig. 9. Effect of Ferrite Grain Size on the Upper Yield Point at Liquid Air Temperature. (0.02% carbon alloy.)

morphology. The supercritical treatments that cause carbides or pearlite at ferrite grain boundaries materially reduce ductility. The subcritical annealing of the cold-worked structures that produces aligned spheroidized carbides considerably reduces this detrimental effect, especially on ductility in the direction of aligned carbides (Fig. 5). The curve for the 0.02% carbon alloy shown in Fig. 4 has been redrawn in Fig. 5 to indicate the reduction in ductility of supercritical heat-treated 0.04% carbon alloy specimens because the values lie well below the curve.

3. The exponent of strain hardening, n, decreases with a decrease in temperature (Fig. 6), with increase in ferrite grain size (Fig. 7) and with increase in carbon content (Fig. 8).

4. The initial presence of a substructure (veining) in ferrite (resulting from the austenite-to-ferrite transformation) or a decrease in grain size increases materially the yield strength at liquid air temperatures (Fig. 9).

The above conclusions represent generally new, and in the case of item three, unanticipated information. Item three is important because the exponent of strain hardening appears to be more significant in defining low temperature brittleness than the slope of the uncorrected stress-strain curve or $d\sigma/d\epsilon$. It can be shown that the exponent of strain hardening is numerically equal to the strain at maximum load or the total uniform strain; it is also inversely related to the strain

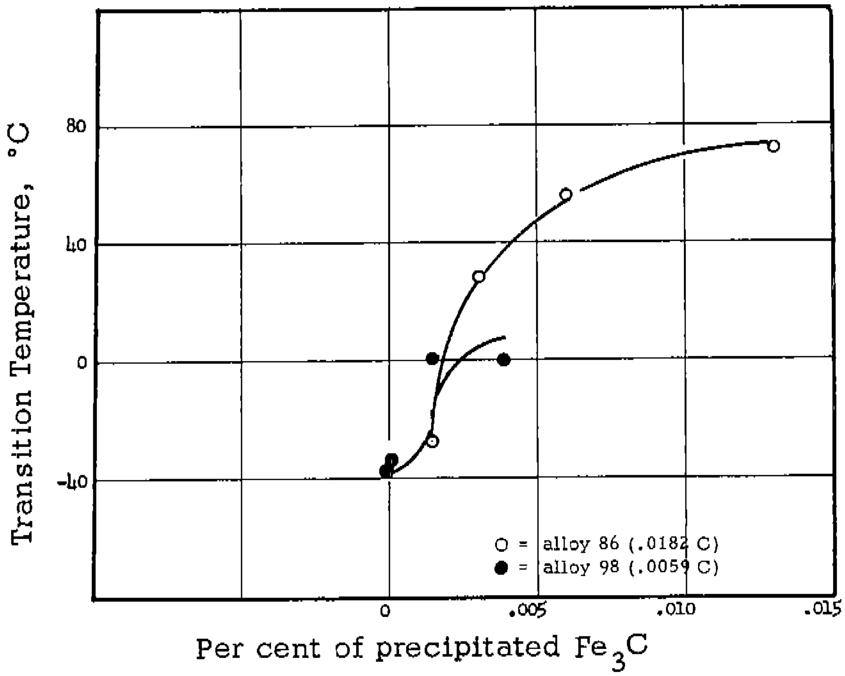

Fig. 10. Increase in Charpy V-Notch Transition Temperature with Increase in Amount of Precipitated Fe_3C.

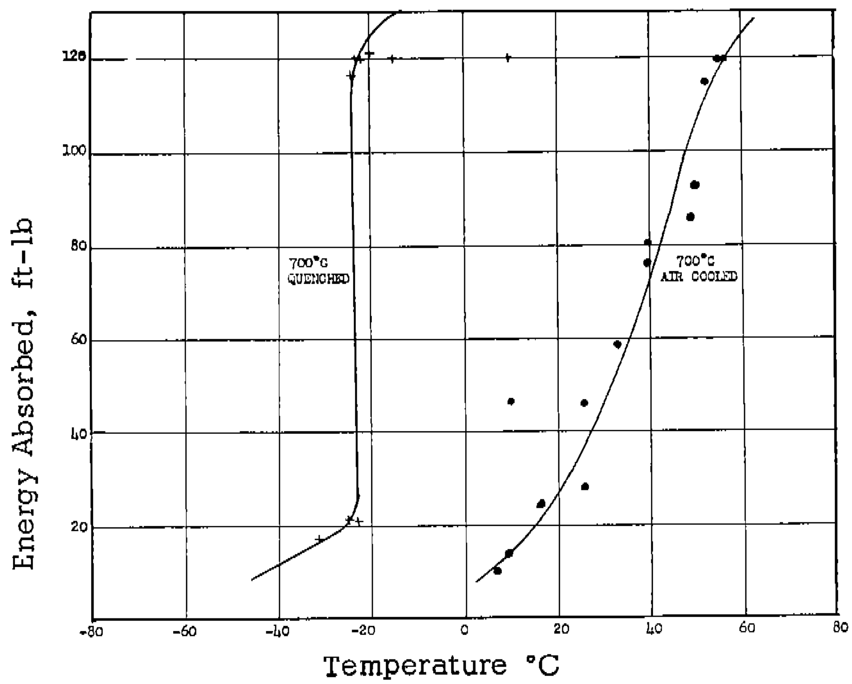

Fig. 11. Standard Charpy V-Notch Impact Tests of Alloy with 0.018% C Showing Effect of Precipitated Carbides.

gradient. Thus a decrease in the exponent of strain hardening means less uniform strain and earlier necking, with an associated earlier development of triaxiality of stress. It also means a higher strain gradient or localization of deformation and, consequently, less absorption of energy.

Part III - Yield Strengths, Ductility and Transition Temperatures

The results of the second part of this investigation as just reported led to a more detailed study of ferrite structural effects. This included some work on Charpy V-notch transition temperatures. It then became essential to relate the tensile property data and microstructural observations to notched bar transition temperature data. Early work showed the anticipated increase in Charpy V-notch transition temperature accompanying increase in carbon content. In addition, the shape of the absorbed energy-temperature curve changed from a sloping line to what was practically vertical for carbon contents of 0.02% and less. The most marked differences in transition temperature with changes in microstructure were found in alloys of 0.03% C and less. Work was then confined to alloys with from 0.003 to 0.03% C, and a study was made of different ferrite structures, ranging from the under-saturated, through the saturated, to the precipitated Fe_3C state. The following speculative reasoning is advanced to explain the structural effect observations in terms of relative yield strengths and crack strengths.

1. Fe_3C precipitated from ferrite at temperatures in the range 400--700 C and caused a sharp rise in transition temperature (Fig. 10), which is a continuous function of the amount of precipitated

carbide. Since this precipitation of Fe_3C results in a <u>decrease</u> in hardness and therefore of yield strength (which theoretically should decrease the transition temperature), the observed increase in transition temperature can be attributed solely to the structural effect of Fe_3C crystals. This structural effect causes the initiation of cracks and thereby decreases the ductility.

2. The presence of precipitated carbides in low-carbon alloys tends to change the shape of the energy-temperature curve from a vertical line to a sloping line (Fig. 11). It is hypothesized that while carbides initiate cracks, they also interfere with crack propagation and thus reduce the abrupt change from ductile to brittle behavior upon a decrease of temperature.

3. Alloys with 0.03% C have higher transition temperatures when in the supercritically recrystallized state than comparative subcritically recrystallized alloys, even when both were subsequently quenched from 723 C to eliminate precipitated carbides. The increase in transition temperature in this case is due to the grain boundary carbides resulting from the residual γ to α transformation.

4. When alloys containing under 0.015% C are quenched from 723 C and are thus in an undersaturated state with respect to carbon, the transition temperature is at a minimum for subcritically recrystallized alloys

containing no substructure. For supercritically recrystallized alloys with a substructure or veining, a distinct rise in transition temperature above the minimum is found upon quenching from the saturated state, i.e. from the solvus temperature for the carbon content of the iron (Fig. 10). Associated with the rise in transition temperature and independent of strain rate is a rise in yield point that is observable from 23 C to -185 C. The undersaturated state with veining shows less ductility in terms of total strain.

These observations would not seem to be peculiar to high purity ferrites if they are compared with Ake Josefsson's[4] equivalent data with respect to the effects of carbide precipitation on commercial grades of steel with very low carbon content.

Future work should be planned to determine whether the transition temperature of ship plate grades of steel will, under similar conditions, show the same effects as the transition temperature in the very low-carbon alloys.

ACKNOWLEDGMENT

The authors thank the American Society for Metals for permission to reproduce Fig. 1, 4--9 in this report which originally appeared in vol. 46 of the ASM Transactions.

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4. Josefsson, Ake, "Impact Transition Temperatures of Some Pearlite-Free Mild Steels as Affected by Heat Treatments in the Alpha Range," Transactions, AIME, vol. 200, pp. 906-913 (1954).

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