

Lawrence Berkeley National Laboratory

Recent Work

Title

METASTABLE AUSTENITIC STEELS WITH ULTRA-HIGH STRENGTH AND TOUGHNESS

Permalink

<https://escholarship.org/uc/item/9jt7z9tj>

Author

Gerberich, W.W.

Publication Date

1968-11-01

UCRL-18609

ey-2

RECEIVED
LAWRENCE
RADIATION LABORATORY

APR 3 1969

LIBRARY AND
DOCUMENTS SECTION METASTABLE AUSTENITIC STEELS WITH
ULTRA-HIGH STRENGTH AND TOUGHNESS

W. W. Gerberich

November 1968

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545*

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

UCRL-18609

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to Society of
Automotive Engineers

UCRL-18609
Preprint

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California
AEC Contract No. W-7405-eng-48

METASTABLE AUSTENITIC STEELS WITH
ULTRA-HIGH STRENGTH AND TOUGHNESS

W. W. Gerberich

November 1968

METASTABLE AUSTENITIC STEELS WITH
ULTRA-HIGH STRENGTH AND TOUGHNESS

W. W. Gerberich

Inorganic Materials Research Division, Lawrence Radiation Laboratory,
Department of Mineral Technology, College of Engineering,
University of California, Berkeley, California

ABSTRACT

A combination of chemical balancing and thermal-mechanical processing has led to a new class of high strength steels. These steels utilize the strain-induced austenite to martensite transformation to produce unusually good combinations of strength, elongation, toughness and corrosion resistance. The principle behind enhanced elongation is discussed in terms of the increased work-hardening rate provided by the hard martensitic phase. The mechanism responsible for enhanced toughness is discussed in terms of the plastic energy absorption occurring during the transformation. It is further shown that elongation is three times greater, toughness may be two times greater in thin or thick sections, and corrosion resistance is an order of magnitude greater than the comparable properties of conventional, high-strength martensitic steels.

INTRODUCTION

A recent development of a new class of steels has generated considerable interest because of the possibility of simultaneously increasing strength, elongation, and resistance to crack propagation.^{1,2} These steels have been called TRIP steels after Transformation Induced Flasticity and are essentially warm-worked austenitic steels that transform to martensite with subsequent straining at service temperatures. Although the thermal-mechanical treatment necessary to obtain these 200,000 to 300,000 psi strength steels requires 70 to 80% prior deformation, the benefits to elongation and toughness are considerable. For example, how many 200,000 psi yield strength steels have a uniform elongation of 50%?

As warm-forming techniques gain acceptance throughout the auto industry, adoption of more complex thermal-mechanical treatments might be expected. However, before any material can be utilized in mass production, it must be shown that, besides providing increased performance, it is also cost competitive. For this reason these more expensive steels (~ 18-28% alloy additions) are not likely to find wide-spread usage in the automotive field. Nevertheless, with new generations of bodies and engines (e.g. a turbine engine), the need for materials with unusual properties is likely to increase. It is the purpose of this paper to inform you of the present technology in TRIP steel in the eventuality that the need for such a material might arise.

MATERIAL AND PROCESSING

Hundreds of alloy compositions have been evaluated at the Inorganic Materials Research Division of the Lawrence Radiation Laboratory. Although nearly all of these exhibit the strain induced transformation, some of the best mechanical properties have been observed in the following compositions:

- A 9Cr-8Ni-4Mo-2Si-2Mn-0.28C (Good Room Temperature Properties)
- B 13Cr-9Ni-3Mo-2Si-2Mn-0.20C (Good Low Temperature Properties)
- C 13Cr-8Ni-3Mo-2Si-1Mn-0.24C (Good Corrosion Resistance)

There has been some question as to whether all the molybdenum contained in these alloys is necessary. In fact, one alloy has been evaluated without any molybdenum and has been found to have uniaxial behavior nearly identical to other TRIP steels. Also, the silicon can be reduced considerably without detrimental effects.

The thermal-mechanical processing cycle consists of forging at 2000°F, cross-rolling at 1800°F, austenitizing at 2200°F for 2-1/2 hours and quenching in an ice-brine solution. These annealed plates, which were wholly austenitic, were then warm-worked 75-80% at 840°F to provide an austenite which had a yield strength above 200,000 psi. Other processing temperatures can be utilized in the range of 400-1000°F as long as the temperature is maintained above M_D , the temperature below which strain-induced martensite occurs. From this material and processing, the following mechanical property behavior was observed.

TENSILE BEHAVIOR

For most ultra-high strength steels, the sequence of events in a tensile test is as follows: first, an elastic stage occurs; second, this is followed by a plastic stage commencing at the proportional limit; the steel work-hardens to maximum load where necking occurs; shortly afterwards failure results. In contrast to this, the behavior of TRIP steel is more like mild steel except that it occurs at very high stress levels. Shortly after the elastic limit,^{*} there is a yield point phenomenon coincident with a Luder's band forming in the gage section. In this Luder's band, the austenite has at least partially transformed to martensite and the resulting surface tilts from the transformation are easily seen in Figure 1. As the Luder's band traverses the gage length, work hardening is occurring locally in the yield band but not outside that region, the overall result being that the load remains constant. However, as the Luder's band reaches the end of the gage section and now starts to retrace the specimen, the work-hardening rate increases rapidly as interaction of the yield front with the hard martensitic phase is now occurring. This process continues until the whole gage section is nearly all martensitic at which point the maximum load is reached and failure ensues. An engineering stress-strain curve reflecting these features is shown in Figure 2.

The reason the material does not neck prematurely is because the

* Depending upon the stability of the austenite, the elastic limit might not even be exceeded at very low test temperatures where the martensite may be stress induced.

local work hardening rate is enhanced by the hard strain-induced martensite. In terms of true stress (σ_T) and true strain (ϵ), the local work-hardening rate, $\partial\sigma_T/\partial\epsilon$, must be greater or equal to the applied stress, σ_T , to prevent tensile instability. One can appreciate that at very high stresses, i.e. greater than 200,000 psi, that the work hardening rate must be large to prevent necking. For this reason, almost all high strength steels, e.g. SAE 4340 and 18Ni maraging steels, which have low work-hardening rates, neck shortly after yielding. With the TRIP steels, the measured work-hardening rate becomes very large after the Luder's band has traversed the gage length once and strain-hardening exponents ranging from 0.4 to 0.8 are typical. These are very high considering that the exponent is normally less than 0.1 for high strength steels while the theoretical upper limit is unity for elastic behavior.

This work-hardening phenomenon results in very large uniform elongations for these high strength metastable austenitic steels. As seen in Figure 3, the elongation attained in these steels is two to three times as great as those obtained in the best specialty steels. Thus, it is seen that the work-hardening mechanism resulting from the transformation provides good combinations of strength and elongation. A somewhat different mechanism associated with the transformation provides good fracture toughness.

RESISTANCE TO CRACK PROPAGATION

In the plastic zone that develops at the tip of a crack in TRIP steel, the strain-induced transformation occurs. The shear strain accompanying the austenite \rightarrow martensite transformation is sufficiently

large in steel to act as an energy dissipation mechanism. It has been shown² that the degree of energy dissipation from this mechanism may be greater than other plastic deformation processes. The resulting plastic zone as shown in Figure 4 is seen to be well outlined by the surface tilts resulting from the transformation. This zone was obtained in a 6-inch wide sheet sample with a 2-inch center-crack by loading to an applied stress of 100,000 psi. These conditions represented a stress intensity factor, K, of 190,000 psi-in^{1/2} as taken from

$$K = \sigma \left[\pi a \sec \left(\frac{\pi a}{W} \right) \right]^{1/2} \quad (1)$$

where σ is the applied stress, a is the half-crack length and W is the plate width. This stress intensity level is reasonably high for a steel with 201,000 psi yield and 240,000 psi ultimate-strengths. For similar thin sheets ranging from 0.070 to 0.10 inches thick, plane stress critical stress intensity factors, K_c , were evaluated using equation (1). This measure of resistance to crack propagation is shown in Figure 5 as a function of yield strength and is compared to the values³ obtained for typical high strength quench and tempered steels. The TRIP steels are clearly superior at yield strengths above 220,000 psi.

For some years,⁴ it has been recognized that toughness in thin sections is not equateable to toughness in thick sections. That is, just as there is a ductile-brittle transition due to environmental temperature, there is also a toughness transition due to thickness changes. In all high-strength materials, the toughness drops with increasing thickness. This is because plastic deformation is limited in the interior of a thick sample and the plastic energy dissipation per unit

volume decreases in thicker samples. This transition from a plane stress to a plane strain situation normally involves a 50 to 80% decrease in toughness.

Examples of this thickness transition for two typical high strength steels are given in Figure 6. For the medium carbon low-alloy steel and the precipitation-hardening stainless steel, the toughness drops from about $200 \text{ ksi-in}^{1/2}$ to about $80 \text{ ksi-in}^{1/2}$ which is a 60% decrease in critical stress intensity. In contrast to this, the TRIP steel, which actually has a slightly higher yield strength, only decreases about 30%. Moreover, the $170 \text{ ksi-in}^{1/2}$ toughness level in one-inch thick sections is about double that of the conventional steels. Significantly, crack propagation in the TRIP steel, even in one-inch thick sections, was not catastrophic but involved slow tearing.

The reason for this relatively high toughness and slow crack propagation may be partially attributed to the strain-induced transformation. Formation of the martensite about the crack-tip is shown in Figure 7 which is a vertical section taken from the slow crack growth region. It is seen that the martensite comes out along the macroscopic maximum shear planes through the thickness and that the strain-induced martensite terminates at the elastic-plastic boundary. It may also be shown that the martensite emerges preferentially along maximum shear planes in uniaxial tensile samples.² These results may be interpreted to show that the martensite is coming out to minimize the strain energy of the system and, in so doing, higher toughness levels may be attained.

Resistance to crack propagation has also been evaluated under fatigue conditions for one alloy. Here, a pre-cracked sample was cycled under zero

to maximum stress conditions with the range of stress intensity, ΔK , being calculated at the start and end of a crack growth interval. The average ΔK value was determined over N cycles and the observed crack growth rate, da/dN , was also measured for that interval. It had been previously shown⁵ that there was a fourth power relationship between these two parameters given by

$$da/dN = m(\Delta K)^4 \quad (2)$$

where m is a material constant.

This relation is also shown to be valid for TRIP steel in Figure 8. It is seen that as stress intensity increases the crack growth rate rapidly increases. For comparison, it is shown that the fatigue crack growth rate is about three times faster in conventional high-strength steels. However, the data are too limited to say that TRIP steels, in general, offer better resistance to fatigue crack growth than other materials.

ENVIRONMENTAL SITUATIONS

Although only limited studies have been performed, there are good indications that TRIP steels may be quite resistant to corrosion and hydrogen embrittlement. Considering corrosion behavior, eleven different TRIP steels which were totally austenitic and six which had been partially transformed to austenite-martensite mixtures were evaluated using a potentiostatic technique.⁶ Potential/current density curves were obtained in a 10% by weight solution of sulphuric acid. Current densities in the passive range were then compared as a function of alloy content. Assuming the reaction



is the major contributing dissolution reaction, a current density of $1 \mu\text{amp}/\text{cm}^2$ compares to about 0.5 mils per year of corrosion.

Results showed that chromium content was of importance but, surprisingly, that manganese content was even more critical. That is, if the manganese content was greater than 2%, the corrosion rate increased rapidly. There did seem to be an upper bound for this behavior in that manganese contents above 4% did not seem to increase the corrosion rate further. The other large alloy factor was carbon, which, with increasing amounts, increased the corrosion rate. An alloy parameter which grouped the experimental data about a single curve is given by

$$\text{Alloy Parameter} = 10\text{Cr} - 3(2 < \text{Mn} < 4) - 10\text{C} \quad (4)$$

where the alloy contents are in weight percent. Of course, there is a basic difference between corrosion behavior of martensitic and austenitic steels and so two separate groups of data are presented. For each specimen, the alloy parameter was calculated and plotted in Figure 9 as a function of current density. It is obvious that with an increase in the alloy parameter that there is a decrease in current density or corrosion rate. As expected, the austenite-martensite mixtures follow a similar trend with slightly higher corrosion rates. For comparison, type 316 stainless steel corrodes at a rate between 2 and 20 mils per year in a 10% sulfuric acid solution.⁷ Thus, the better TRIP steels, which appear to corrode at a rate near 5 mils per year, are commensurate with austenitic stainless steels and better than ferritic stainless which may be a factor of 3 to 10 less resistant.

Limited evaluations of hydrogen embrittlement behavior have been made using pre-cracked samples. Single-edge-notch specimens from alloy A

were cathodically charged for 50 minutes at 125 ma/in^2 in a standard hydrogenation solution of 4% sulfuric acid with a phosphorous-carbon disulfide poison. A standard test on a 0.4 carbon martensitic steel showed this to be a very effective hydrogenation procedure with failure resulting in 34 minutes at a stress intensity level of $42 \text{ ksi-in}^{1/2}$. A sample of the TRIP steel was taken to $130 \text{ ksi-in}^{1/2}$ and no crack growth was observed in 480 minutes. This stress intensity level was high enough to produce a fairly large plastic zone in this 220 ksi yield strength steel and so a large amount of strain-induced martensite formed at the crack tip. Since there was no cracking, it was felt that either the hydrogen did not diffuse into the austenite or that little diffusion of hydrogen occurred across austenite-martensite boundaries.

As an additional experiment, a specimen was purposely loaded to $130 \text{ ksi-in}^{1/2}$ to produce a plastic zone about 0.1 inches in length containing strain-induced martensite. This specimen was then hydrogenated so that hydrogen could be put into already existing martensite at the crack tip. This was then loaded to $115 \text{ ksi-in}^{1/2}$ and held for 420 minutes. Although there was some cracking observed in the first 60 minutes, there was none observed in the last 360 minutes. A metallographic section of the mid-thickness is shown in Figure 10. with the tip of the original crack shown as the blunt opening at the far left. The total amount of crack extension was on the order of 0.01 inches, this cracking undoubtedly occurring in the hydrogen-bearing martensite. Significantly, however, the diffusion of hydrogen to martensite formed after charging was not sufficient to extend the crack further. Thus, it appears that hydrogen picked up during heat treatment, pickling or fabrication processes would not be a

serious problem in TRIP steels.

CONCLUDING REMARKS

It has been shown that metastable austenitic steels exhibiting a strain-induced austenite \rightarrow martensite transformation at room temperature have unusually good properties. Depending upon alloy content, either good combinations of strength and toughness, or low temperature properties or resistance to corrosion and hydrogen embrittlement may be attained. Whether all of these desirable characteristics can be achieved with a single alloy composition is yet to be shown. Nevertheless, sufficient interest has been generated in these steels so that they are presently being considered for the following applications: high-strength fasteners, surgical instruments, armor plate, cutlery, and containment vessels for aircraft turbine engines. Whether or not similar applications are to be found in the automotive or allied markets depends on future metallurgical and engineering developments.

ACKNOWLEDGEMENTS

The author appreciates the comments and review of this paper by Professor Victor F. Zackay of the Department of Mineral Technology, University of California, Berkeley. This work was sponsored by the Atomic Energy Commission through the Inorganic Materials Research Division of the Lawrence Radiation Laboratory, Berkeley, California.

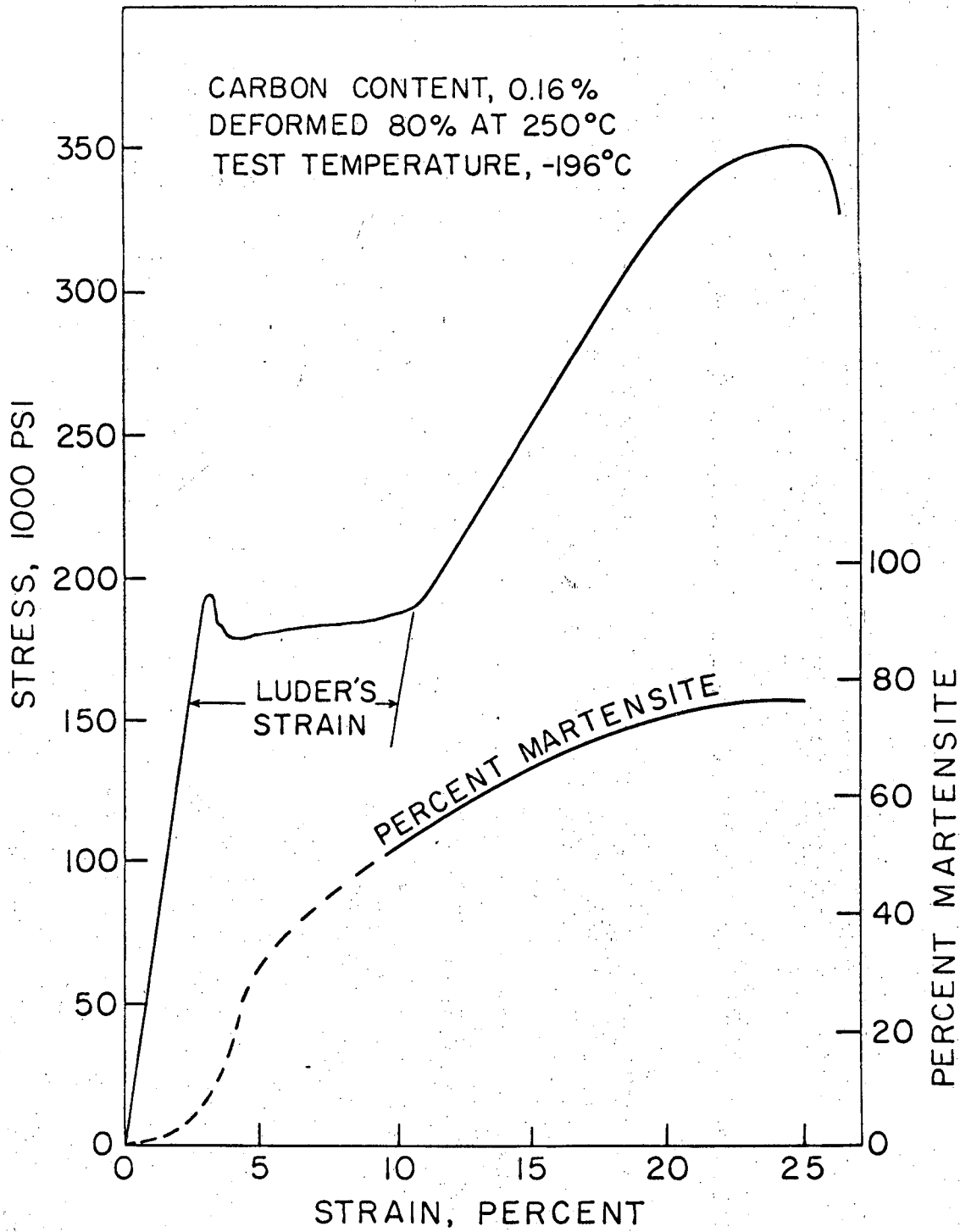
REFERENCES

1. V. F. Zackay, E. R. Parker, D. Fahr, and R. Busch, "The Enhancement of Ductility in High-Strength Steels," ASM Trans. Quart. 60, 2, 252 (1967).
2. W. W. Gerberich, P. L. Hemmings, V. F. Zackay and E. R. Parker, "Interactions Between Crack Growth and Strain-Induced Transformation," to be presented at Second International Conference on Fracture, Brighton, England, April 1969; UCRL-18467, September 1968.
3. W. W. Gerberich, "Current Trends in Testing Methods, Design, and Materials for Fracture Toughness," Metals Eng. Quart., ASM, 4, 4, 23 (1964).
4. G. R. Irwin, "Relation of Crack Toughness Measurements to Practical Applications," Welding J. Res. Supp. November, p. 5198, (1962).
5. P. C. Paris, "The Fracture Mechanics Approach to Fatigue," Proc. 1963 Sagamore Conf., Syracuse University Press, 1964.
6. J. Challande, "Corrosion Resistance of Metastable Austenitic Steels," M.S. Thesis, University of California, Berkeley, UCRL-18475, September 1968.
7. G. A. Nelson, "Corrosion Data Survey," Metals Handbook, American Society for Metals, Vol. 1, p. 569, 1961.



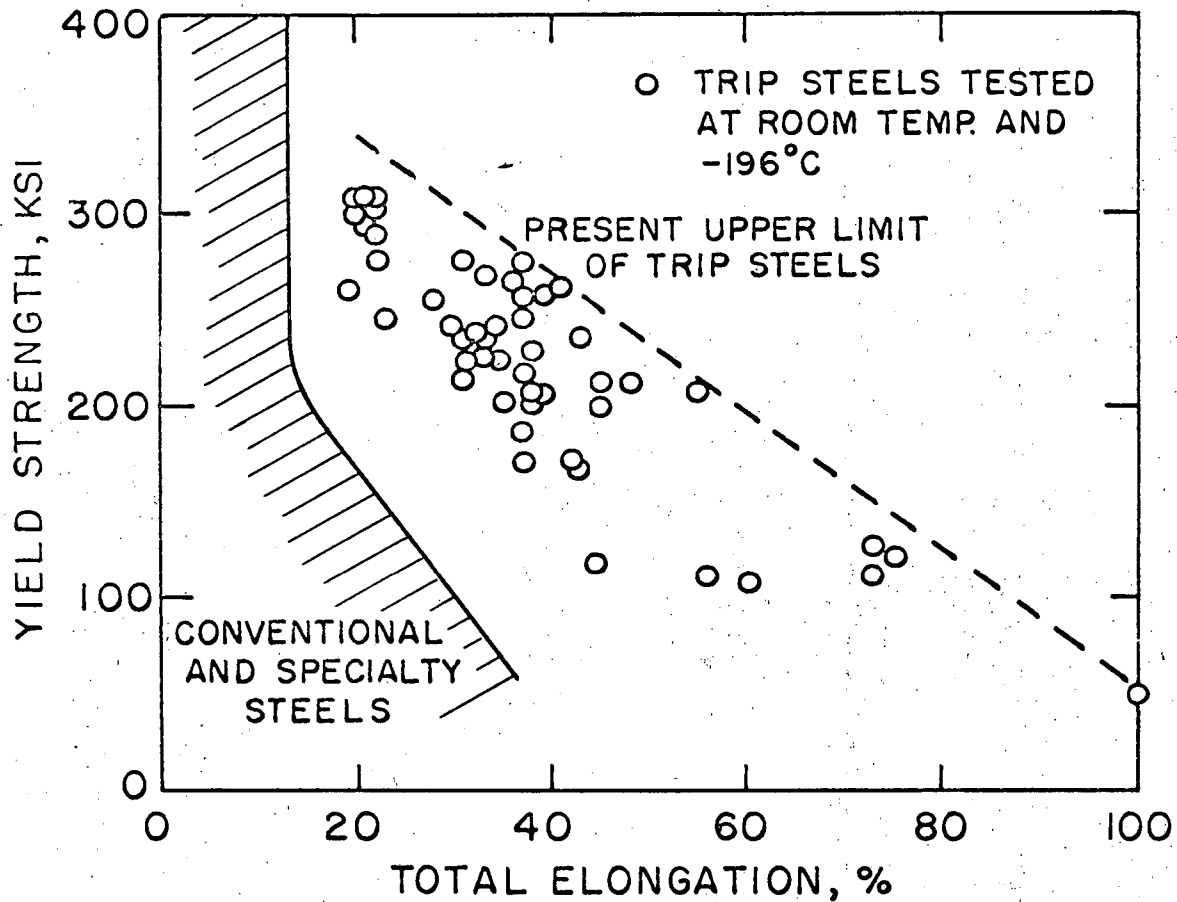
XBB 6811-6879

Fig. 1 Luder's band in tensile sample of metastable austenite.



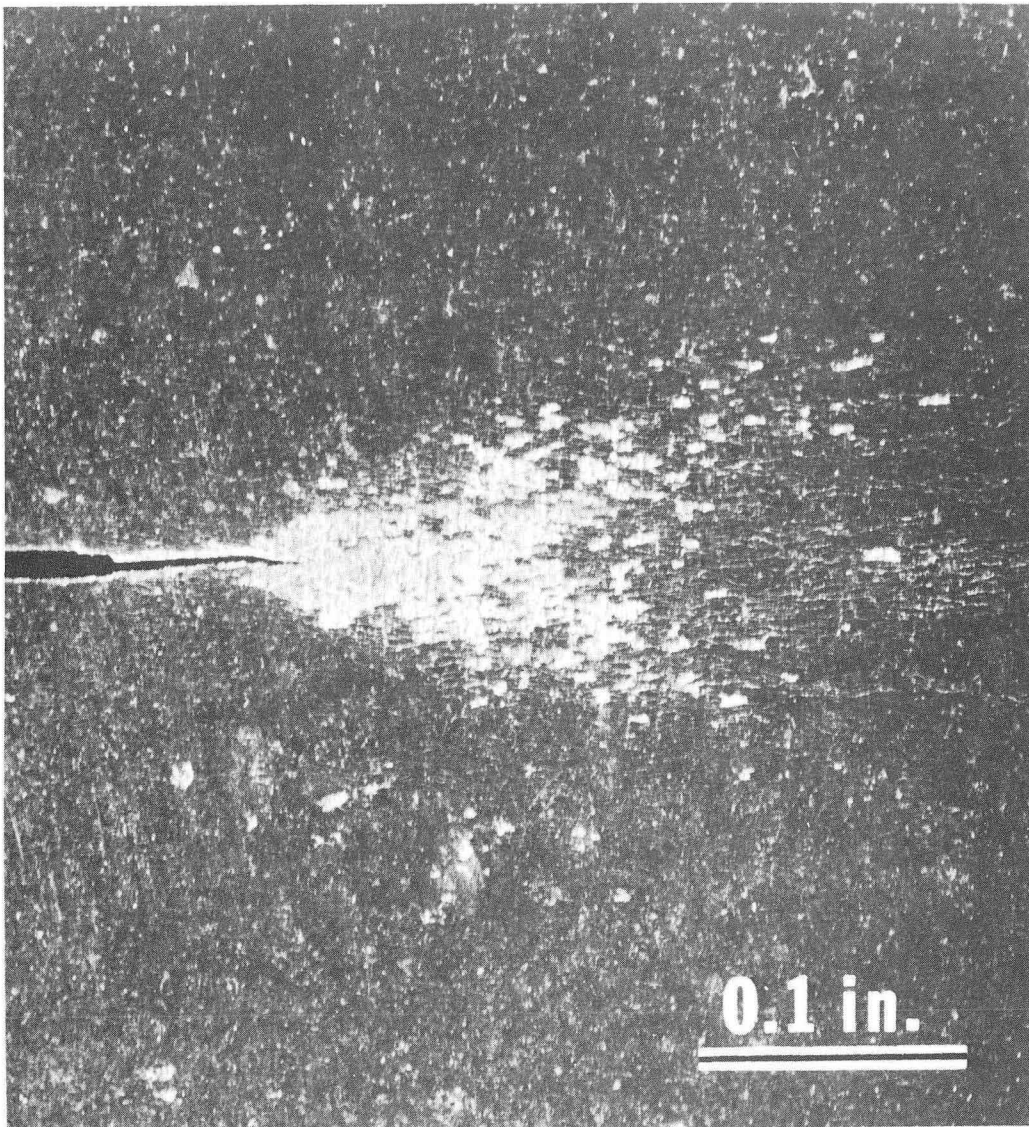
XBL 684-404

Fig. 2 Stress-strain curve of TRIP steel tested in liquid nitrogen



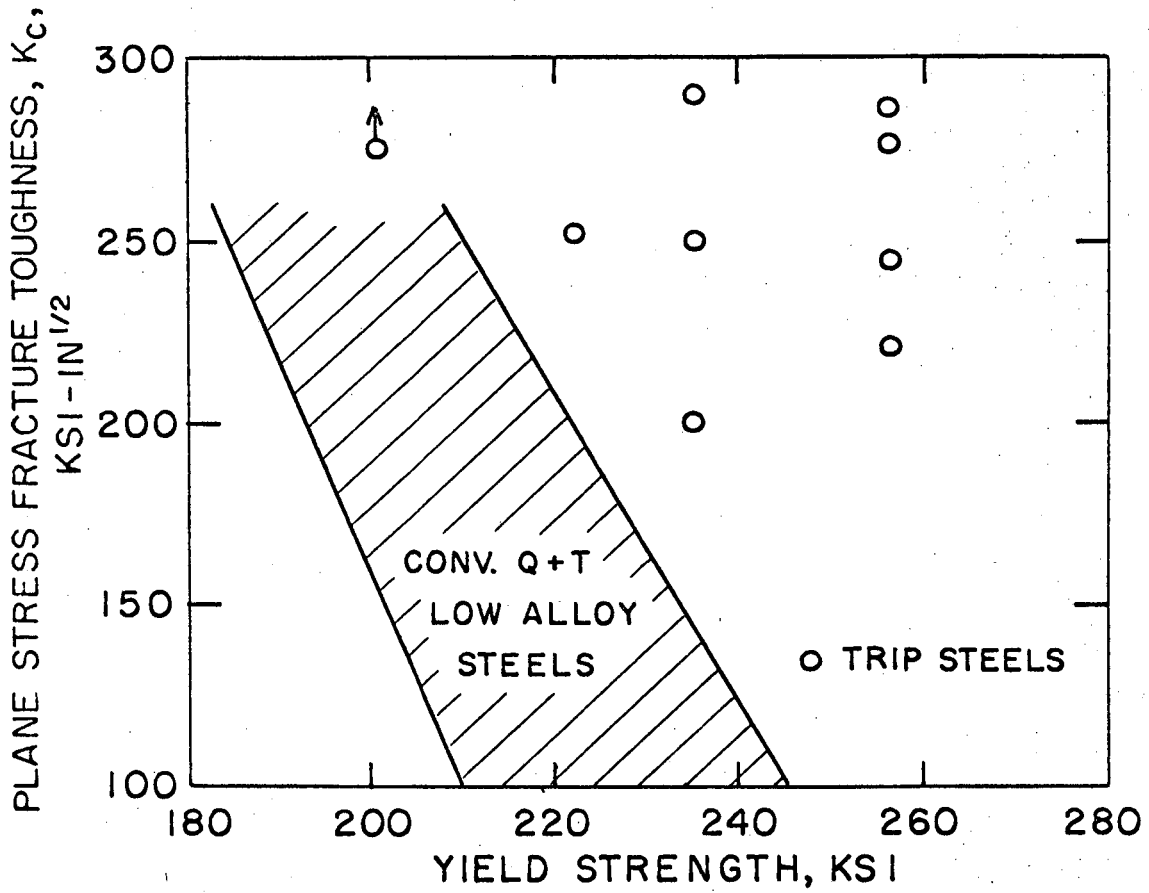
XBL 6811-6138

Fig. 3 Effect of strain-induced transformation on strength-elongation relationship



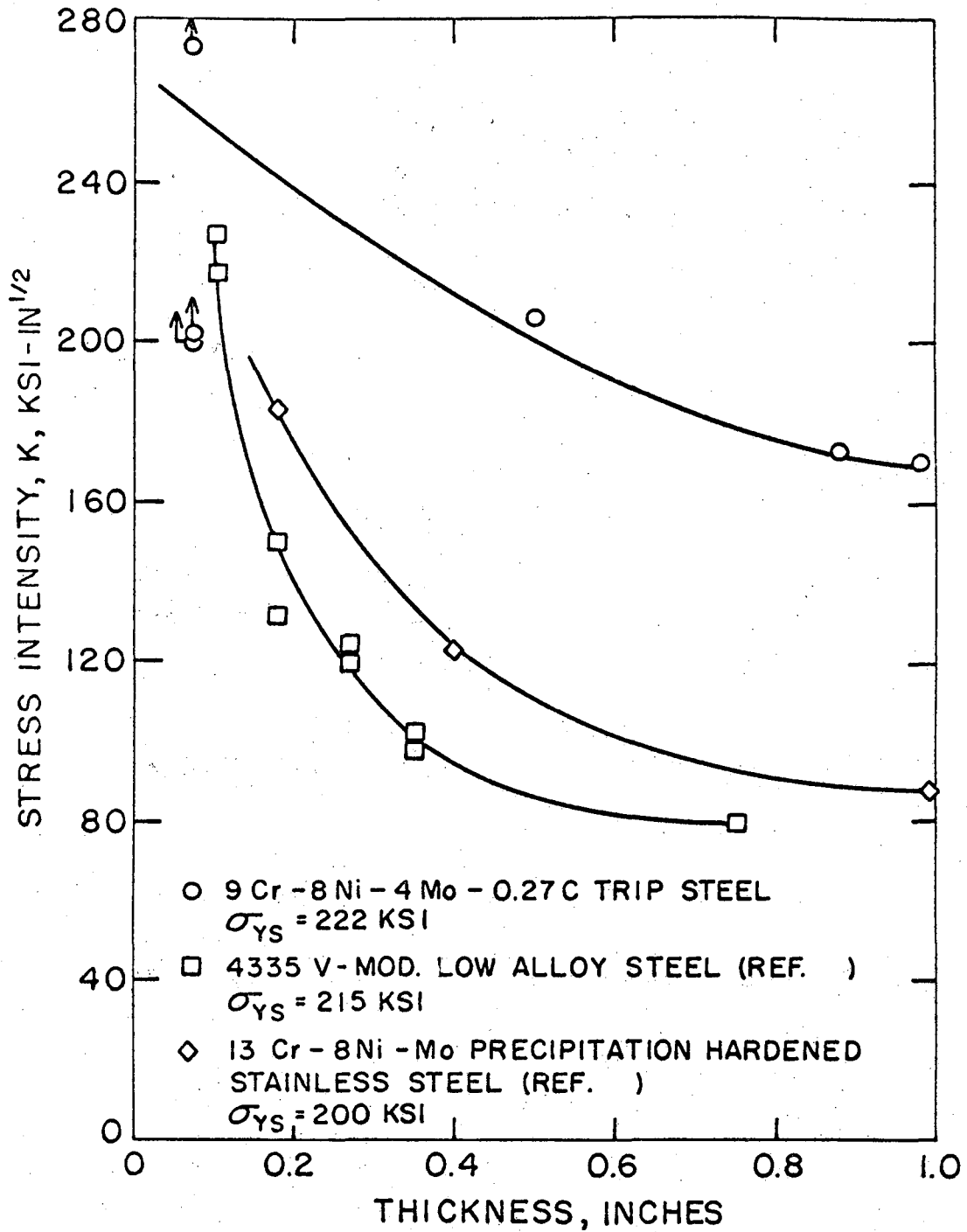
XBB 689-5383

Fig. 4 Plastic zone at the tip of a crack in TRIP steel.



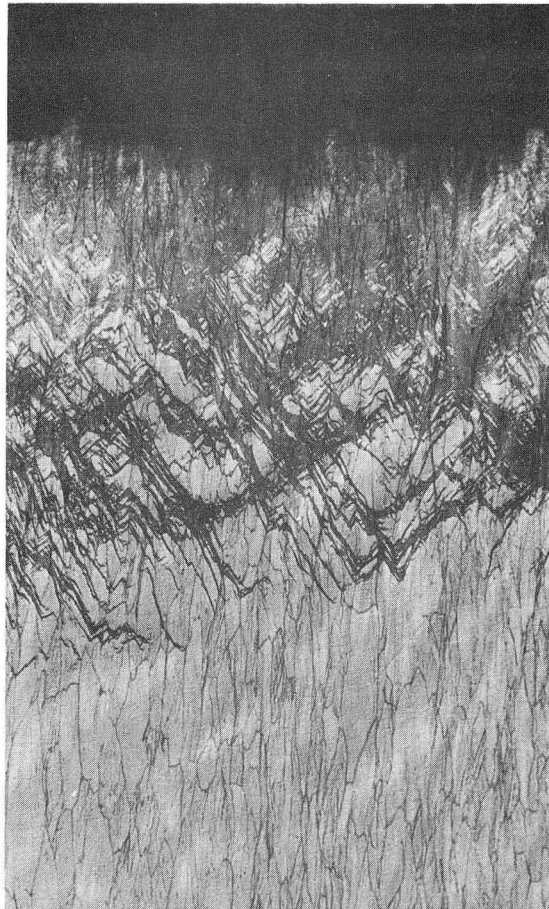
XBL 6811-6137

Fig. 5 Toughness in thin sheet for TRIP steels as compared to conventional low-alloy steels.



XBL 6811-6136

Fig. 6 Effect of thickness on toughness transition of TRIP steel and two conventional steels.



FRACTURE
SURFACE

STRAIN INDUCED
MARTENSITE

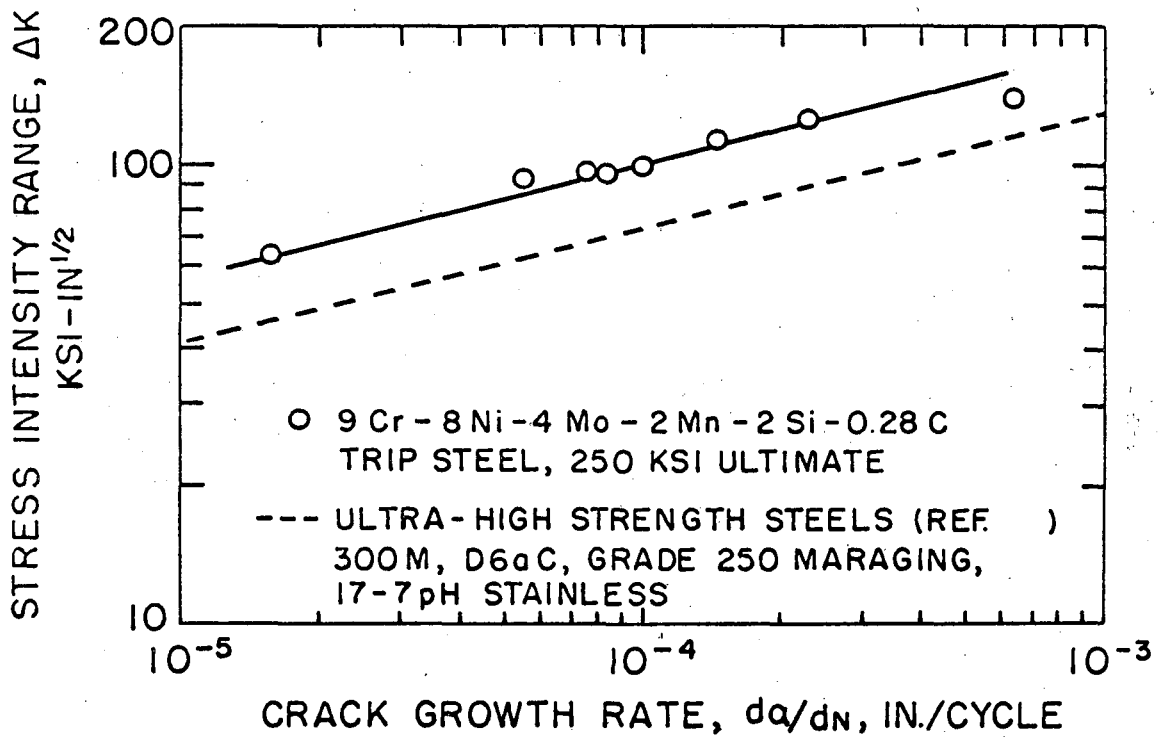
EXTENT OF
PLASTIC ZONE

AUSTENITE

80 X

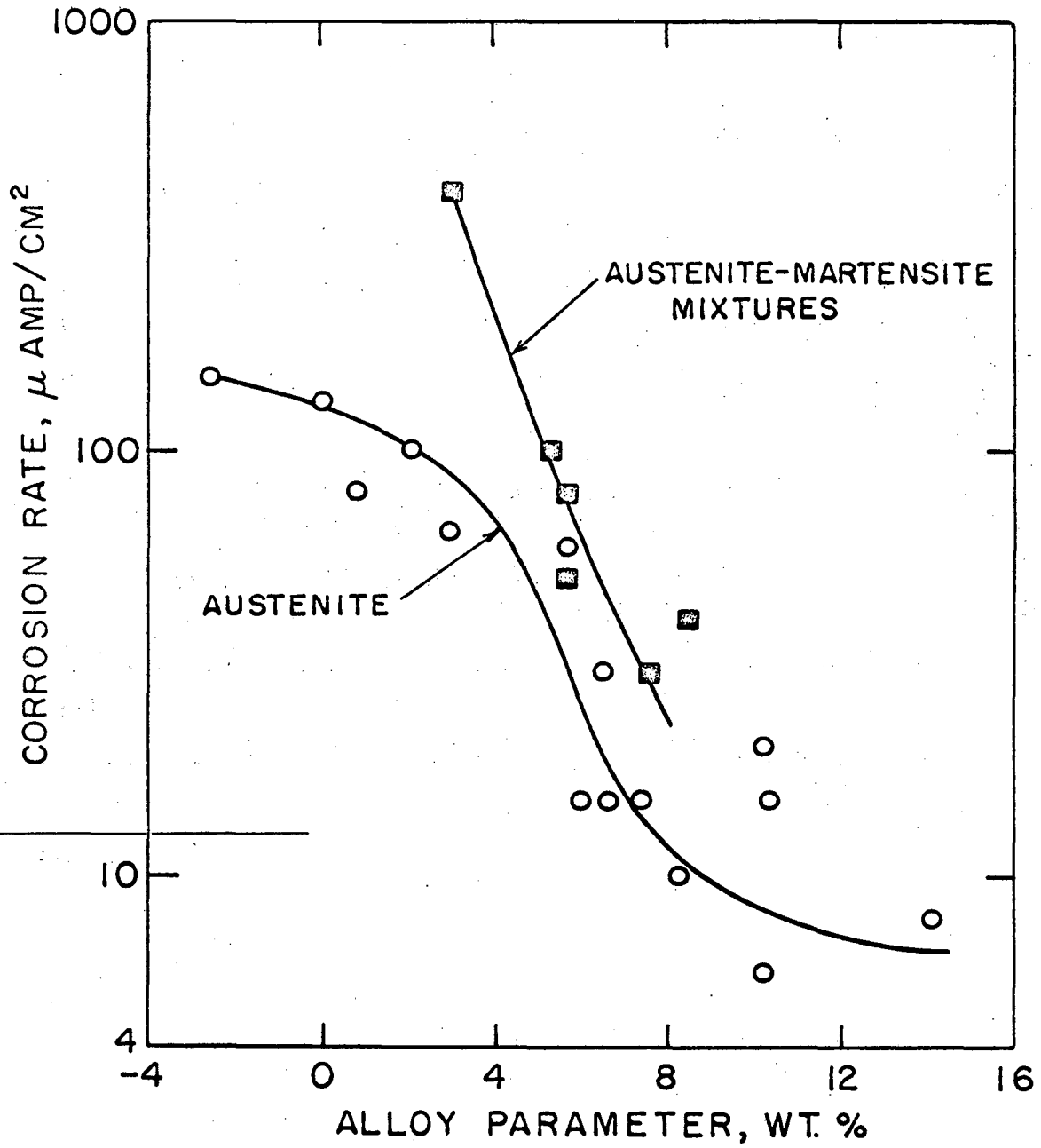
XBB 6811-6881

Fig. 7 Strain-induced martensite occurring around a crack in a thick sample tested at -196°C .



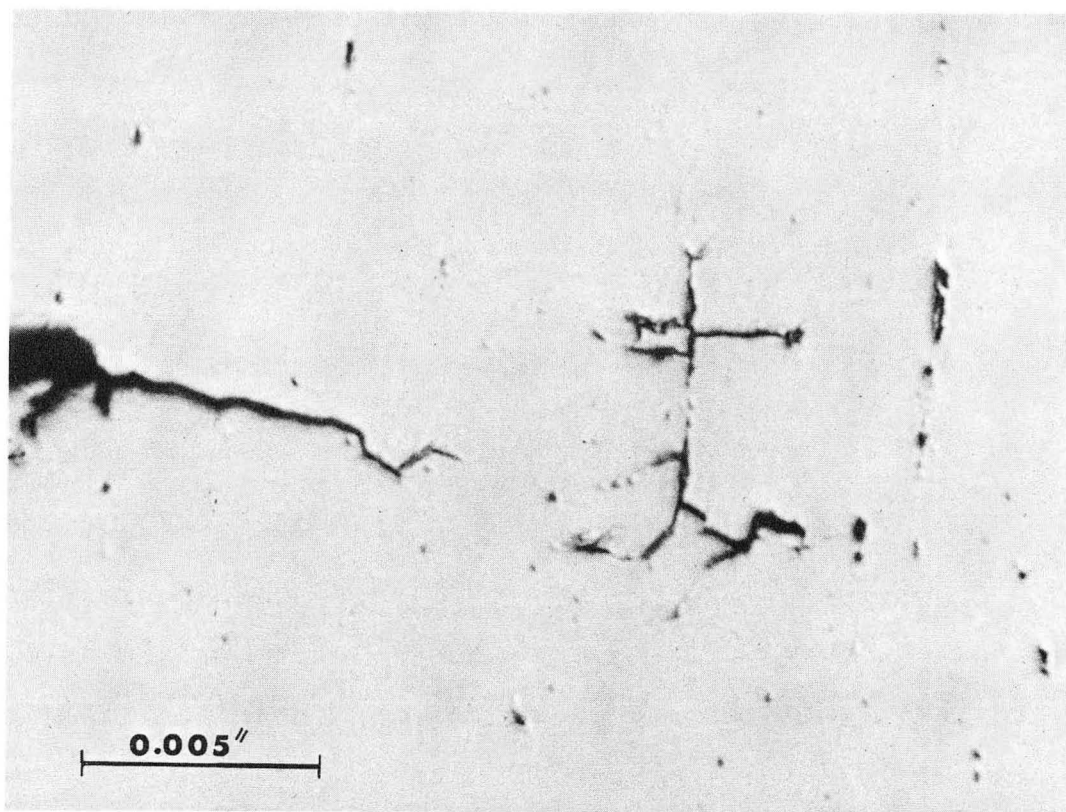
XBL 6811-6135

Fig. 8 Fatigue crack propagation rate as a function of stress intensity.



XBL 6811-6134

Fig. 9 Effect of alloy content on corrosion behavior of TRIP steel.



XBB 6811-6880

Fig. 10 Observation of hydrogen-induced cracking in martensite that has been cathodically charged.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or*
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.*

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720