UCRL-16363 Rev. corrected fig 5

University of California

Ernest O. Lawrence Radiation Laboratory

THE STRENGTH AND TOUGHNESS
OF DYNAMICALLY STRAIN AGED ALLOY STEELS

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

Berkeley, California

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 International Journal of Fracture

UCRL-16363 Rev.

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

AEC Contract W-7405-eng-48

THE STRENGTH AND TOUGHNESS OF DYNAMICALLY STRAIN AGED ALLOY STEELS

V. F. Zackay, W. W. Gerberich, R. Busch and E. R. Parker

July 1966

THE STRENGTH AND TOUGHNESS OF DYNAMICALLY STRAIN AGED ALLOY STEELS

V.F. Zackay, W.W. Gerberich,[†] R. Busch,[*] and E.R. Parker

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

The utilization of high strength in materials is precluded by their marginal toughness. An important merit of a structural material can be described by the relative values of the fracture toughness, K_c, and the yield strength σ_{ys}. For most available materials the reliability ratio K_c/σ_{ys} drops below unity at yield strengths above 200,000 psi. Thus, an important goal of the metallurgist becomes that of developing microstructures in alloys such that the reliability ratio is maintained at unity to higher strength levels. This note describes the production of such microstructures in alloy steels with yield strengths approaching 275,000 psi.

The strengthening process chosen for this study was that of dynamic strain aging, in which small strains are applied to martensitic steels in the range between room temperature and the tempering temperature. The reason for utilizing this process was two-fold: (a) Prior information on dynamically strain aged H-11 (5Cr-0.40 carbon die steel) indicated that large yield strength increases could be obtained without any loss of ductility and (b) stable load-elongation curves were obtained as opposed to the yield instability associated with conventional strain aging.

[†] Aerojet-General, Sacramento, California

[*] Battelle-Northwest, Richland, Washington

Three low alloy steels were studied in both the quenched and tempered and ausform conditions. The compositions are shown in Table I. The austenitizing temperatures were the same for both conditions: 900°C for Hy-Tuf and D6aC, and 1040°C for 5M21. The ausform steels, reduced 50% by rolling, were deformed at 595°C, 565°C, and 620°C for Hy-Tuf, D6aC, and 5M21, respectively, and oil quenched. The conventionally heat treated sheets were oil quenched directly from the austenitizing temperature. All steels were tempered twice for two hours at 205°C. The sheets were strained at selected temperatures by pack rolling in order to achieve uniform strain. The actual temperature during strain, as determined by a contact pyrometer, was estimated to be within ± 10°C of the reported value. Measured reductions in thickness were 2-1/2 ± 1% for the ausformed steels and 6 ± 1% for the quenched and tempered steels.

For screening purposes, pre-cracked Charpy specimens were tested for each condition. From these and the tensile data, conditions for "wide-plate" fracture toughness tests were selected. For the wide-plate tests, nominal 5" × 16" pieces were processed to the desired conditions. Both the ink[1] and calibrated displacement gauge methods were utilized. The results obtained with the ink method were approximately 30% lower than those obtained with the displacement gauge. The former results are reported here for comparison with published data.

Strength, ductility, and toughness were measured as a function of straining and tempering temperatures. Structural observations were made on the strained and unstrained steels.

The fracture toughness of the ausform steels as a function of strain temperatures is shown in Fig. 1. In the early stage of this investigation a high incidence of plastic instabilities in tensile tests was observed

TABLE I

	C	Cr	Mo	V	Ni	Mn	Si
Hy Tuf	0.25	0.30	0.39		1.74	1.35	1.25
D6AC	0.26	1.14	0.99	0.02	0.54	0.70	0.22
5M21	0.19	0.48	2.93		3.02	0.49	0.36

for those specimens strained at low temperatures. For this reason, no tests were made on statically strain-aged material. However, the observed trend of increasing K_c with decreasing strain temperature implies that the fracture toughness cannot be simply related to the stress-strain curve. These wide-plate results suggest that static strain aging should not be neglected as a useful strengthening process. The above conclusion is based on the results obtained with the relatively low strain rate of the wide-plate tests.

The yield strength of the strain aged ausform steels is shown as a function of the strain temperature in Fig. 2. The curves in the figure represent the upper and lower limits of the variation in yield strength with final tempering temperature. The mean value of the strength increase was about 40,000 psi or 25%.

A compilation of the fracture and strength data[2] on conventional quench and temper steels and the best commercially available ultra-high strength steels is shown in Fig. 3. A reliability plot of K_c/σ_{ys} versus the yield strength is shown with the data of this investigation superimposed. Two points are immediately apparent: (1) that above 250,000 psi the strength-toughness combination of the dynamically strain-aged ausform steels is superior to that of the best steels developed to date; (2) that the slope of

the curve is small, suggesting that high toughness might be maintained to strength levels as high as 300,000 psi.

Of the ausform materials with a yield strength greater than 247,000 psi, there were four with a plastic instability and four with normal work hardening behavior. For the former, the average yield strength was 268,000 psi and the average K_c was 259 ksi-in.$^{1/2}$, while for the latter the average values were 254,000 psi and 247 ksi-in.$^{1/2}$. Thus, within these experimental conditions, the reliability factor, K_c/σ_{ys} is not simply related to the shape of the static stress-strain curve.

The effect of dynamic strain aging on the yield strength of the quenched and tempered steels is shown in Fig. 4. By appropriate choice of strain and tempering temperatures, the strength of quenched and tempered steels was increased by about 40,000 psi, i.e., to the base strength of the ausform steels, as is shown for Hy-Tuf in Fig. 5.

The toughness of all materials was investigated with pre-cracked Charpy sheet specimens. For the ausform steels, where wide-plate results were available, there was no satisfactory correlation between the two types of tests. A detailed comparison of these results will be published.[3]

Preliminary structural studies using carbide extraction replicas indicated that a new carbide dispersion is produced by dyanmic strain aging. Micrographs of the unstrained and strained ausform D6aC are shown in Fig. 6. The observed particle spacings are too large to account for the strength by an Orowan-type mechanism. The role of these particles in the strain aged steel may be similar to that of alloy carbides formed during ausforming. Thomas et al.[4] suggest that the carbides act both as dislocation sources and as barriers, effectively increasing the dislocation density. Koh and Leslie[5] have observed in iron carbon alloys that dynamic strain aging

produces a finer carbide dispersion and a higher dislocation density than either quench aging or static strain aging. Thus, the primary strengthening mechanism in dynamic strain aging may be that of increased dislocation density rather than dispersion hardening.

ACKNOWLEDGMENT

The authors are indebted to the Crucible Steel Company for undertaking the difficult task of ausforming these low alloy steels.

This work was performed under the auspices of the United States Atomic Energy Commission.

REFERENCES

1. Fracture Testing of High Strength Sheet Materials, A Report of a Special ASTM Committee, ASTM Bulletin, January and February, 1960.
2. W. W. Gerberich, ASM Met. Eng. Quart., 5, No. 4, 1964 .
3. V. F. Zackay, W. W. Gerberich, R. Busch, and E. R. Parker, The Strength and Toughness of Dynamically Strain Aged Alloy Steels, International Conference on Fracture, Sendai, Japan, (1965).
4. G. Thomas, D. Schmatz and W. W. Gerberich, High Strength Materials, V. F. Zackay, Ed., John Wiley and Sons, New York, 1965; p. 251.
5. A. S. Keh and W. C. Leslie, Structure and Properties of Engineering Materials, H. H. Stadelmaier, Ed., Interscience, New York, 1964; p. 208.

FIGURE CAPTIONS

Fig. 1 The fracture toughness (K_c) of the ausform steels as a function of strain temperatures.

Fig. 2 The yield strength as a function of strain temperature for several tempering temperatures for the ausform steels.

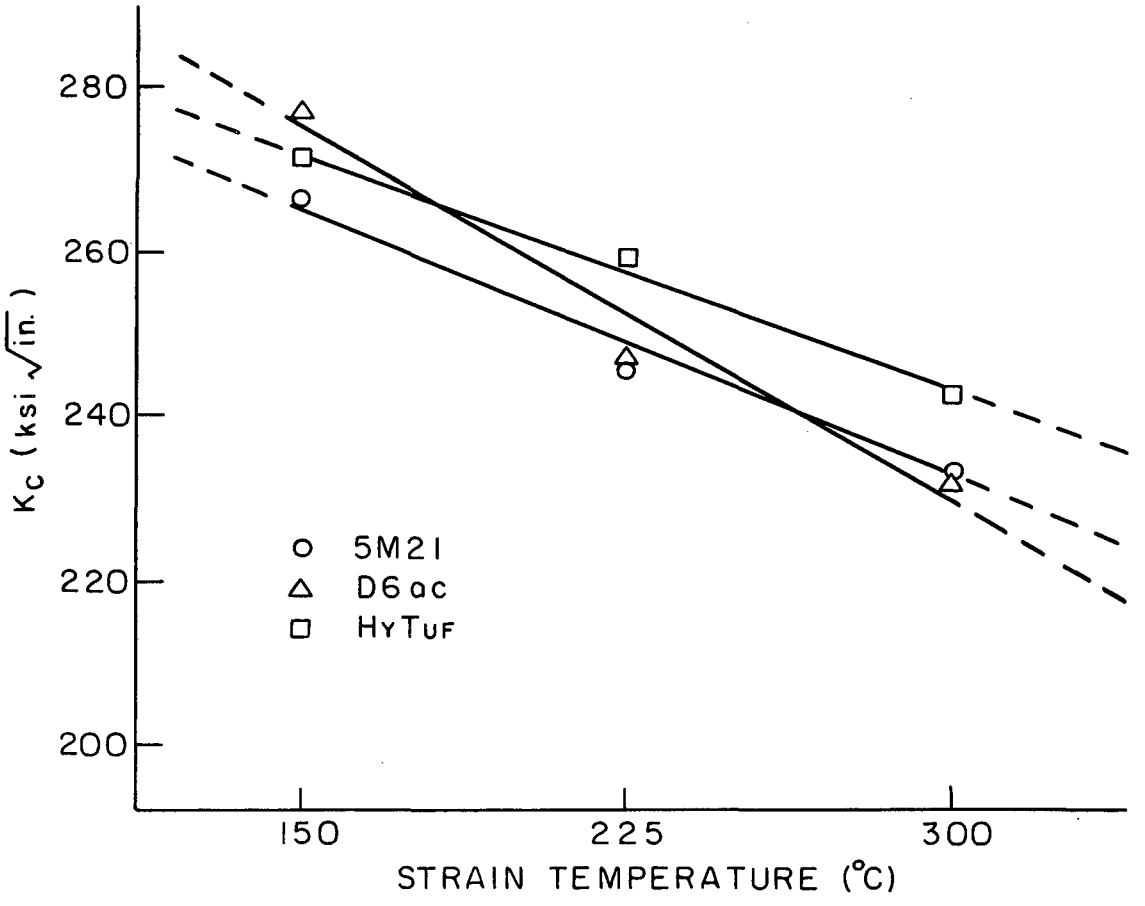
Fig. 3 Fracture resistance ratio (K_c/σ_{ys}) versus yield strength for the best commercially available ultra-high strength steels. Data points are from this investigation.

Fig. 4 The yield strength as a function of strain temperature for several tempering temperatures for the quenched and tempered steels.

Fig. 5 A comparison of the yield strengths of dynamically strain aged quenched and tempered and ausform Hy-Tuf as a function of strain temperature.

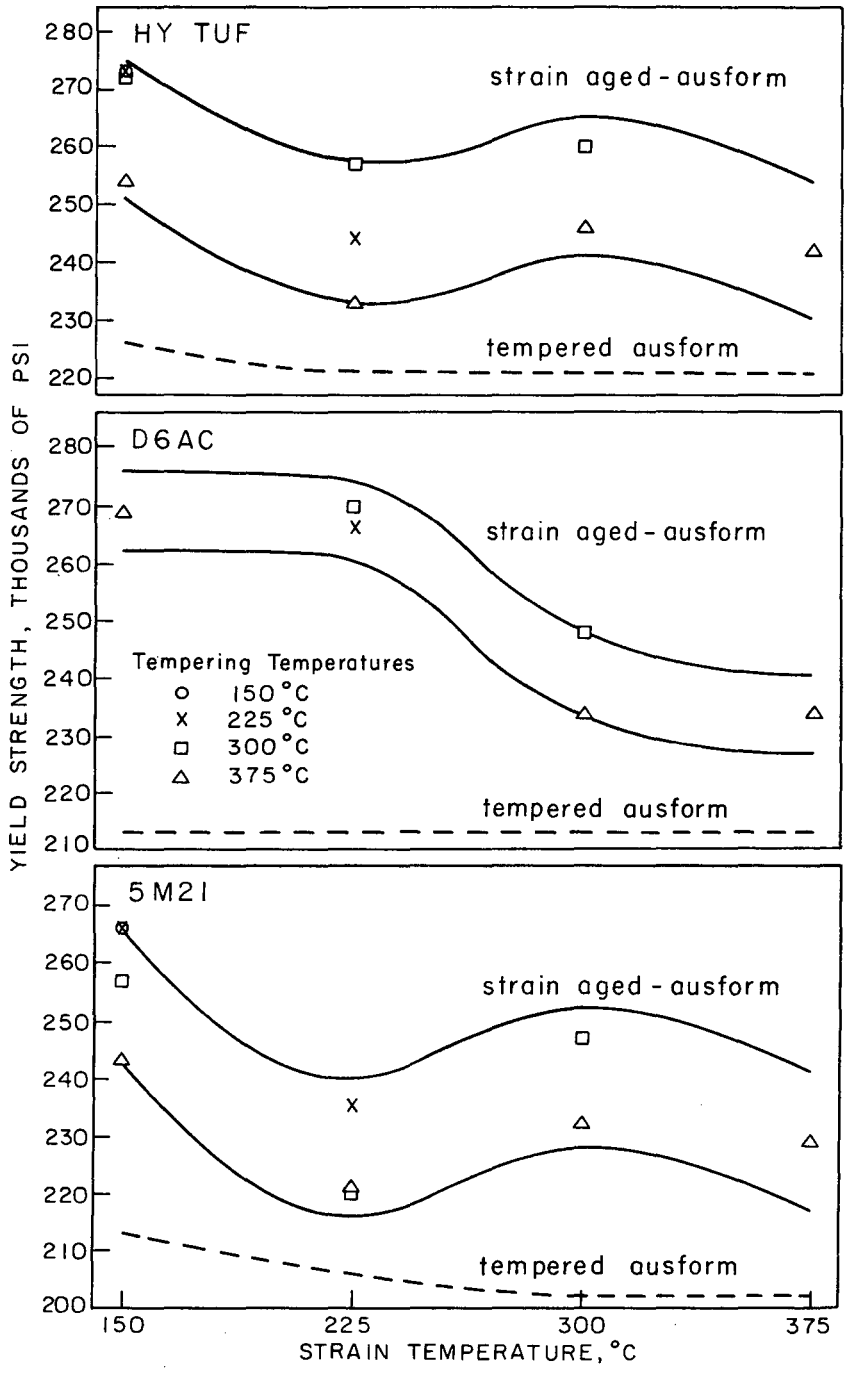
Fig. 6 Carbide extraction replicas of ausform D6aC: left-unstrained; right-strained at 225°C.

TABLE I Composition of Alloys



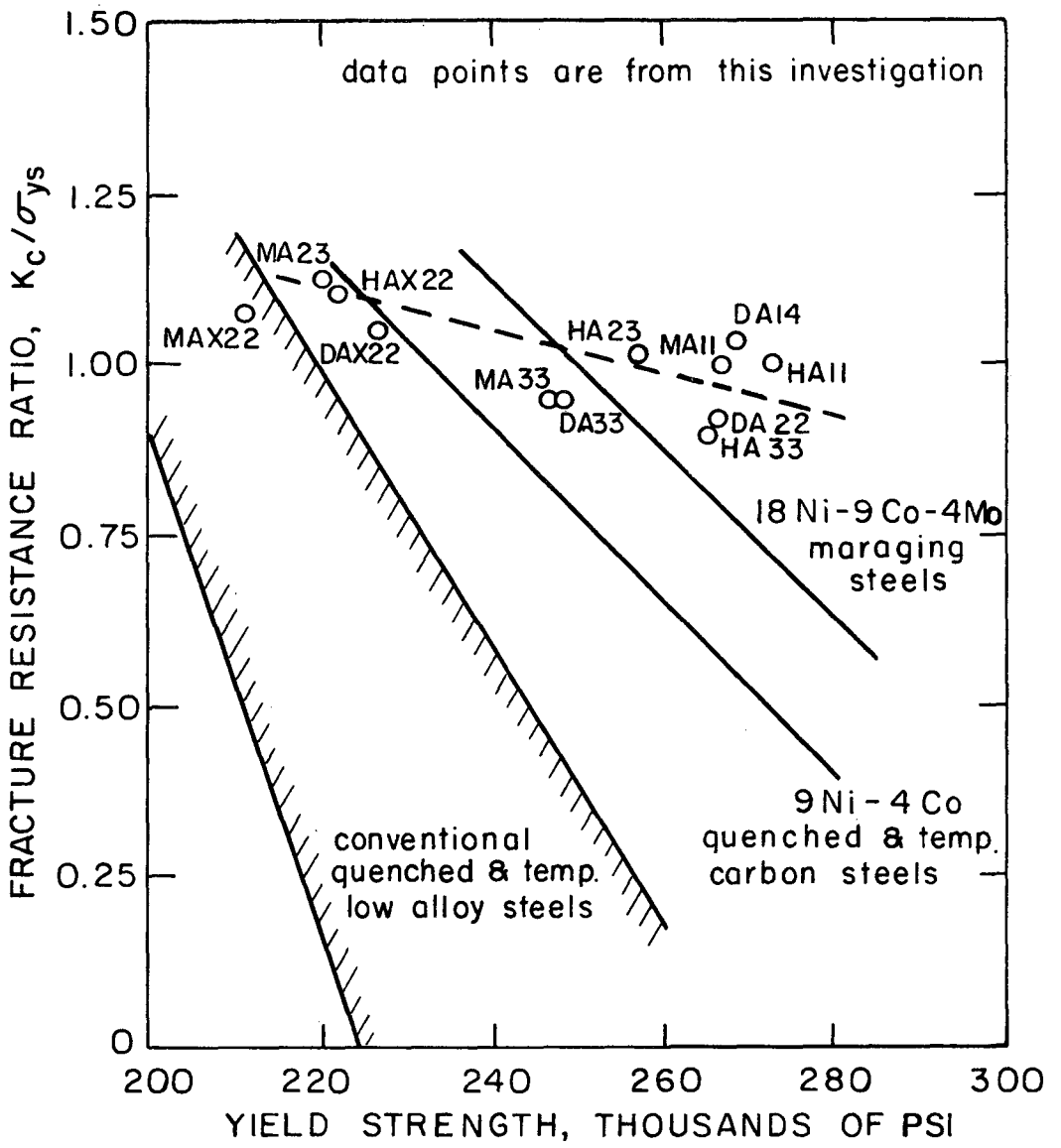
MUB-11647

Fig. 1



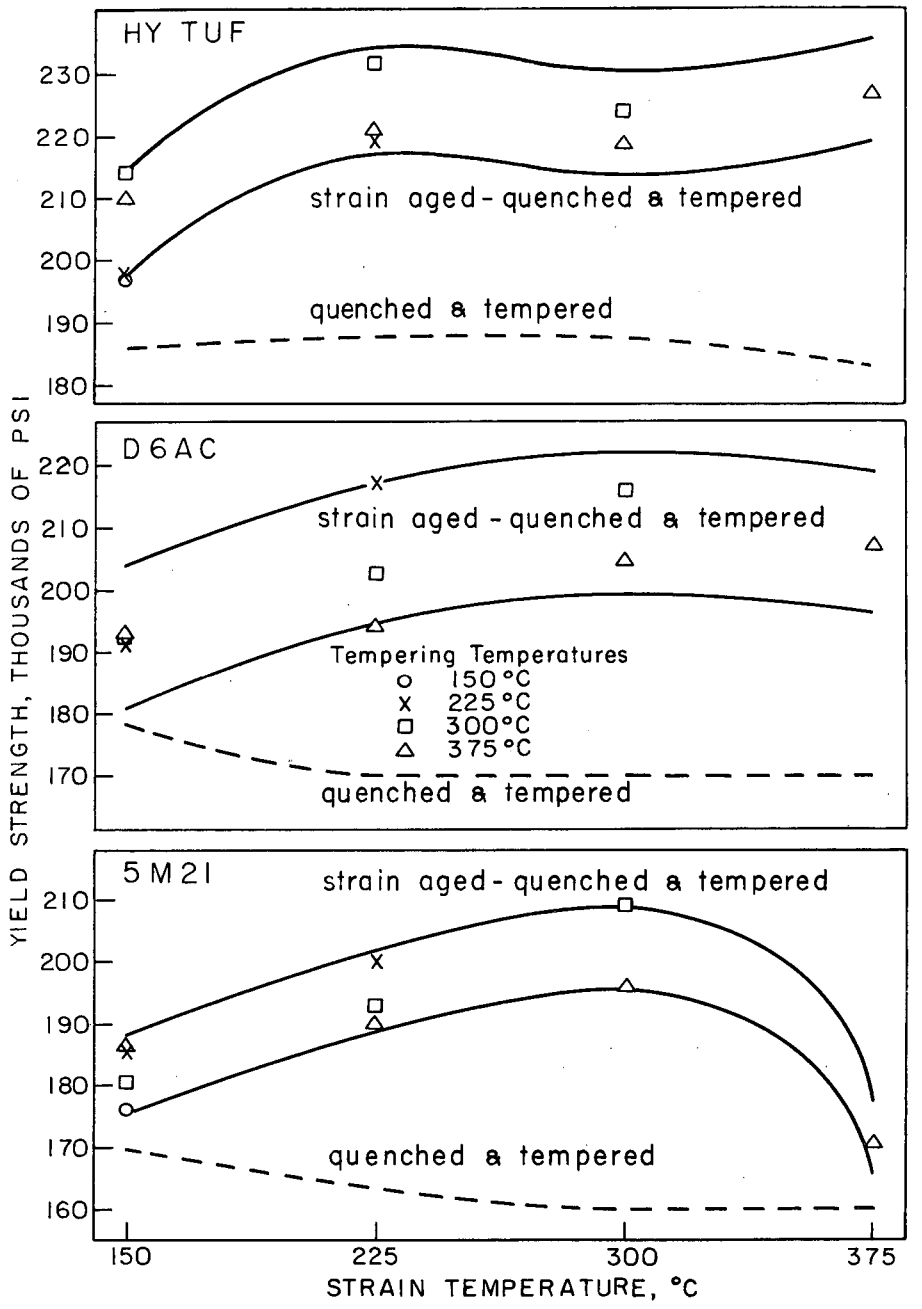
MUB-7483

Fig. 2



MUB-7536

Fig. 3



MUB-7481

Fig. 4

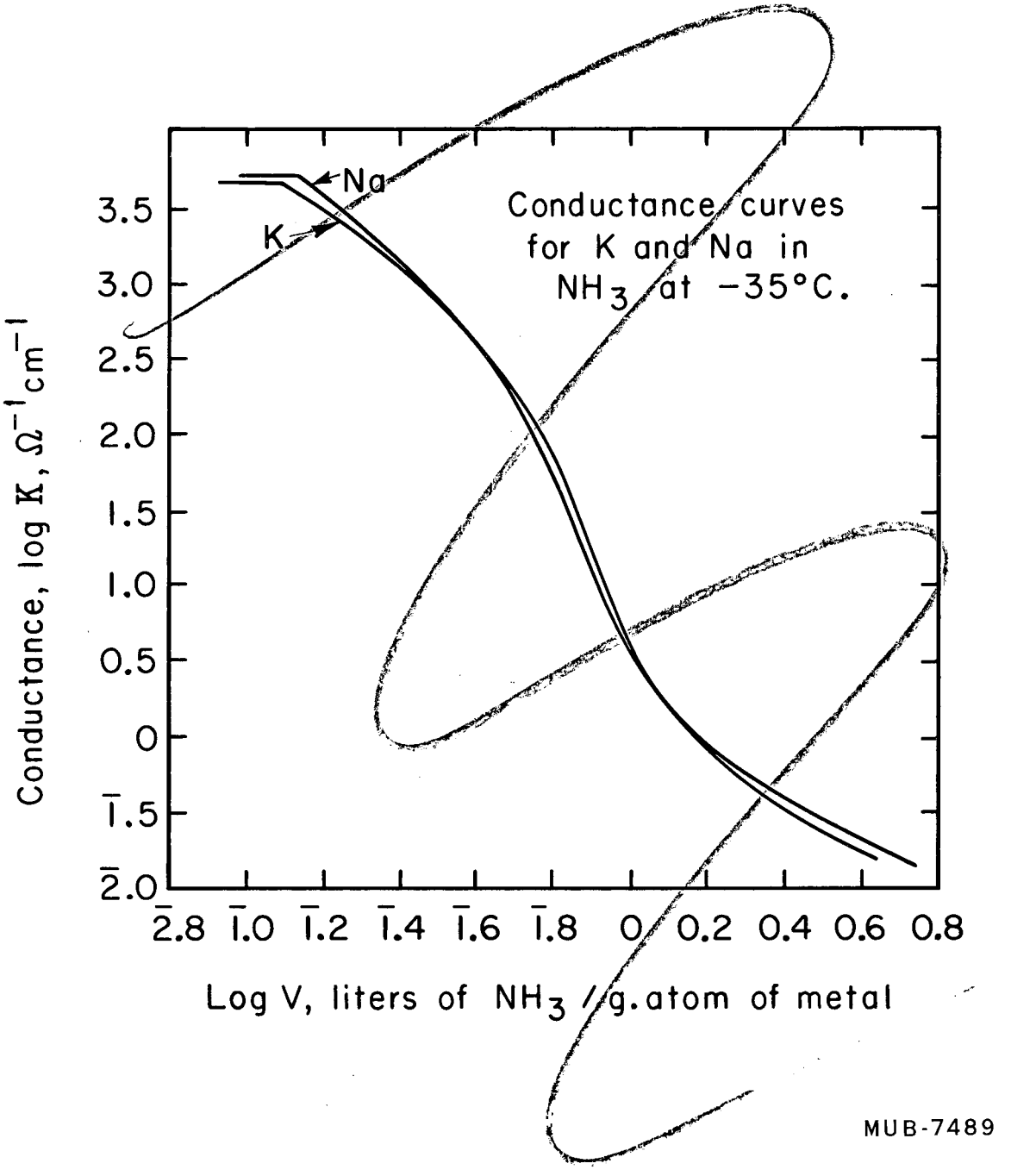
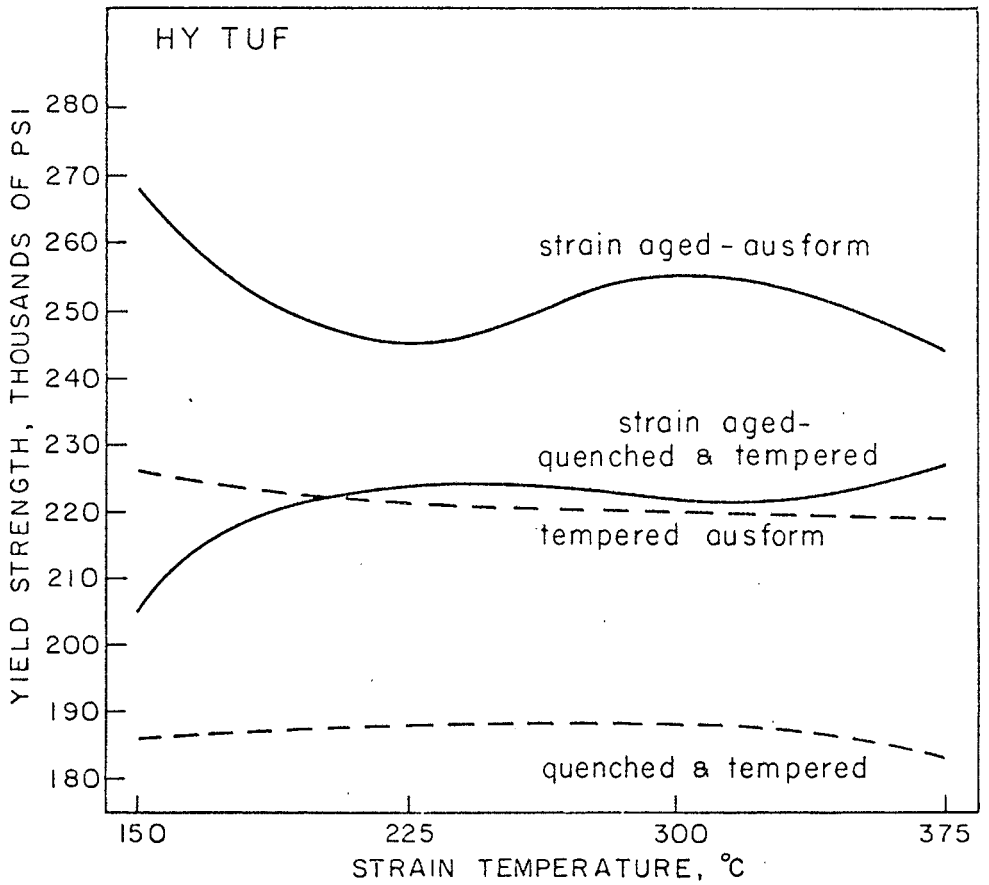

Na
K
Conductance curves
for K and Na in
NH3 at −35°C.
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
$\bar{1}.5$
$\bar{2}.0$
Conductance, log K, $\Omega^{-1}cm^{-1}$
$\bar{2}.8$ $\bar{1}.0$ $\bar{1}.2$ $\bar{1}.4$ $\bar{1}.6$ $\bar{1}.8$ 0 0.2 0.4 0.6 0.8
Log V, liters of NH3 /g.atom of metal
MUB-7489

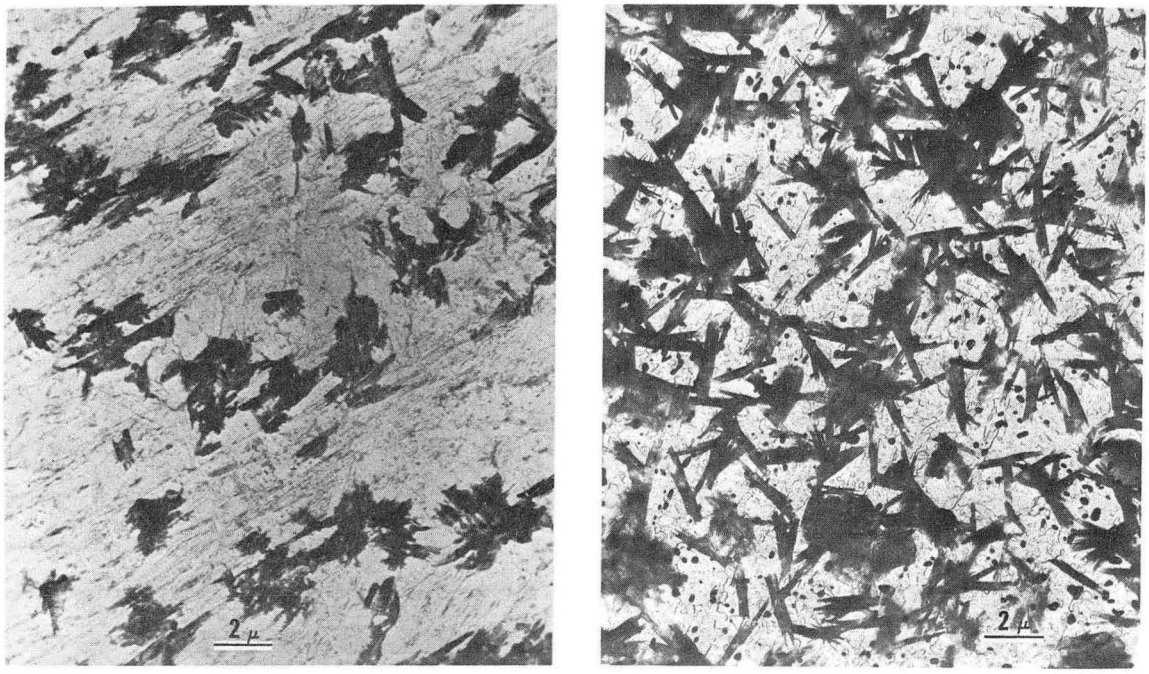
Fig. 5

16363 Rev



MUB-7498

Fig. 5



ZN-5247

Fig. 6

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.