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by

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ABSTRACT

The fracture toughness of quenched and tempered steels, such as AISI 4340, AISI 4130, and 300M, can be increased by 50 to 100 percent by minor changes in heat treating procedures. Certain microstructural features, particularly blocky ferrite, upper bainite, and twinned martensite plates, are deleterious to fracture toughness. Similarly, the presence of undissolved carbides and sulfide inclusions, which act as crack nuclei, can lower fracture toughness by 25 to 50 percent. Other microstructural constituents, such as lower bainite, autotempered martensite, and retained austenite can enhance fracture toughness. By controlling the amounts and distributions of the microstructural constituents, the fracture toughness values of AISI 4340, AISI 4130, and 300M can be raised to the fracture toughness level of 18Ni maraging steel at equivalent values of yield strength.

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INTRODUCTION

Ultra-high strength steels, such as AISI 4340 heat treated to have a yield strength over 200,000 psi, are relatively brittle when crack-like defects are present. An extensive research program has been underway in the author's laboratory during the past several years, with the objective of identifying the elements of defect structure and microstructure that have major effects upon the plane strain fracture toughness. Some elements of structure enhance fracture toughness, while others degrade this important property. The highlights of the various investigations involved are reported herein.

By minimizing or eliminating those microconstituents that lowered fracture toughness, and increasing those that enhanced it, the fracture toughness could be increased 50 to 100 percent above the values obtained with commercially used heat treatments. The optimization of properties could be attained by either of two means--(1) changing the heat treating procedure, or (2) changing the chemical composition of the alloy.

EXPERIMENTAL PROGRAM

In the heat treatment of steel, austenitizing is a critical step. In general, use of low austenitizing temperatures is preferred because this procedure produces the smallest austenite grain size--and presumably the best combination of mechanical properties. In the present investigation, it was quickly found that low austenitizing temperatures did not provide the maximum fracture toughness (measured in accordance with ASTM standard procedures). In fact, the reverse was found to be true, with increases of 50 percent or more being obtained when high austenitizing temperatures were used. (However, as is well known, slightly better elongation and reduction in area are obtained in tensile test bars that have been subjected to low austenitizing temperatures). The compositions of the steels used in the present investigation are listed in Table I.

One of the important factors influenced by austenitizing temperature is the presence of undissolved carbides in the microstructure. This was clearly shown by the work of T. Tom[1], who used special steels containing 0.30C-5Mo and 0.41C-5Mo in his investigation. Both strength and fracture toughness were found to increase with increasing austenitizing temperature, as shown in Fig. 1. Metallographic examinations revealed that undissolved carbides were present below about 1050°C in the 0.30C-5Mo steel, but not above this temperature. The plane strain fracture toughness of the steel increased suddenly from 50 ksi-in$^{1/2}$ to 100 ksi-in$^{1/2}$ when the austenitizing temperature was raised from 1000°C to 1100°C. A similar, but more gradual, change was found for the 0.41C-5Mo steel. Experiments were made with several other steels of lower alloy content (e.g. 0.34C-1Mo and 0.35C-1Mo-3Ni). In these steels, all carbides were dissolved at 870°C and the fracture toughness values were found to be nearly independent of the austenitizing temperature (or grain size). These results are shown in Fig. 2.

Another important influence of austenitizing temperature is its effect on hardenability. Two factors affecting hardenability are the austenite grain size and the amount of carbon in solution. In steels of high hardenability, and in which all of the carbides are dissolved at low austenitizing temperatures, the grain size effect is not normally evident. This is so because the hardenability, even with the smaller grain size, is adequate to prevent the formation of ferrite and upper bainite during quenching. Low values of fracture toughness are generally associated with the presence of these transformation products. However, with steels of intermediate hardenability, such as AISI 4130, the effect of grain size (i.e. austenitizing temperature) may be very important[2]. In the present study when AISI 4130 steel was austenitized at 1200°C and ice-brine quenched, the fracture toughness was nearly twice as high as it was for the same steel oil quenched from 870°C. Oil quenching from 1200°C improved the fracture toughness relative to the lower temperature treatment, but less so than the more severe quench. The results are shown in Fig. 3. The tensile mechanical properties of as-quenched AISI 4130, AISI 4330 and AISI 4340 steels of the present investigation are listed in Table II. The microstructural features of AISI 4130 steel differed for the various treatments, with the 870°C oil quench producing a mixture of blocky ferrite and martensite that was partially autotempered. The microstructure of the 1200°C ice-brine quenched material had no blocky ferrite; it consisted entirely of martensite (partially autotempered). A similar correspondence between heat treatment, fracture toughness, and microstructure existed for AISI 4330 steel. Plots of room temperature plane strain fracture toughness vs tempering temperature for two austenitizing treatments are shown in Fig. 4.

The use of high austenitizing treatments for steels having high hardenabilities, such as AISI 4340, also resulted in substantially higher K_{IC} values, even though there were no undissolved carbides, blocky ferrite, or upper bainite present in the microstructure resulting from the use of lower (870°C) quenching temperature. The room temperature fracture toughness of AISI 4340 steel is shown in Fig. 5 as a function of tempering temperature for two austenitizing temperatures. The preferred heat treatment involves a step-quench, i.e. cooling slowly from 1200°C to 870°C before oil quenching. Quenching directly into oil from 1200°C tended to cause cracking, as did ice-brine quenching from 870°C. Step-quenching (1200°→870°C OQ) nearly doubled the as-quenched (870°C OQ) fracture toughness.

Optical metallographic examination failed to reveal any significant microstructural difference resulting from the two austenitizing treatments (other than differences in austenite grain size). Transmission electron microscopy was employed to reveal additional small-scale structural differences. It was found that the 1200°C material had a significant amount of retained austenite in the form of 100-200Å thick films between martensite laths, whereas the 870°C material had very few austenite films[5], as shown in Fig. 6. Austenite is tough and crack resistant. The beneficial effect of the higher temperature treatment was therefore attributed mainly to the presence of the austenite films. However, there was another distinct microstructural difference observed in the transmission electron microscope studies. The packets of lath martensite were similar for both austenitizing treatments, but the material heat treated at 870°C also had twinned martensite plates. Das and Thomas[3] and Thomas[4] have shown that the presence of twinned martensite plates causes the fracture toughness to be lower than with lath martensite alone. This additional difference in microstructure is believed to have been partially responsible for the higher fracture toughness of the step-quenched steel.

Additional investigations of the effects of heat treatments and variations in chemical composition are continuing. Preliminary results indicate that even greater improvements in fracture toughness may be forthcoming.

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REFERENCES

[1] T. Tom, Microstructural Variables and Fracture Toughness of High Strength Mo and Mo-Ni Steels. D. Eng. Thesis, LBL-1856, University of California, Berkeley, Calif., Sept. 1973.

[2] W. E. Wood, E. R. Parker, and V. F. Zackay, An Investigation of Metallurgical Factors Which Affect the Fracture Toughness of Ultra-High Strength Steels, LBL-1474, Lawrence Berkeley Laboratory, Berkeley, Calif., May 1973.

[3] S. K. Das and G. Thomas, Structure and Mechanical Properties of Fe-Ni-Co-C Steels, Trans. ASM 62, 659-676, 1969.

[4] G. Thomas, Electron Microscopy Investigations of Ferrous Martensite. Met. Trans. 2, 2373-2385, 1971.

[5] G. Y. Lai, W. E. Wood, R. A. Clark, V. F. Zackay, and E. R. Parker, Effect of Austenitizing Temperature on the Amount of Retained Austenite in AISI 4340 Steel, To be submitted to Met Trans., 1974.

TABLE I Chemical Compositions of Steels

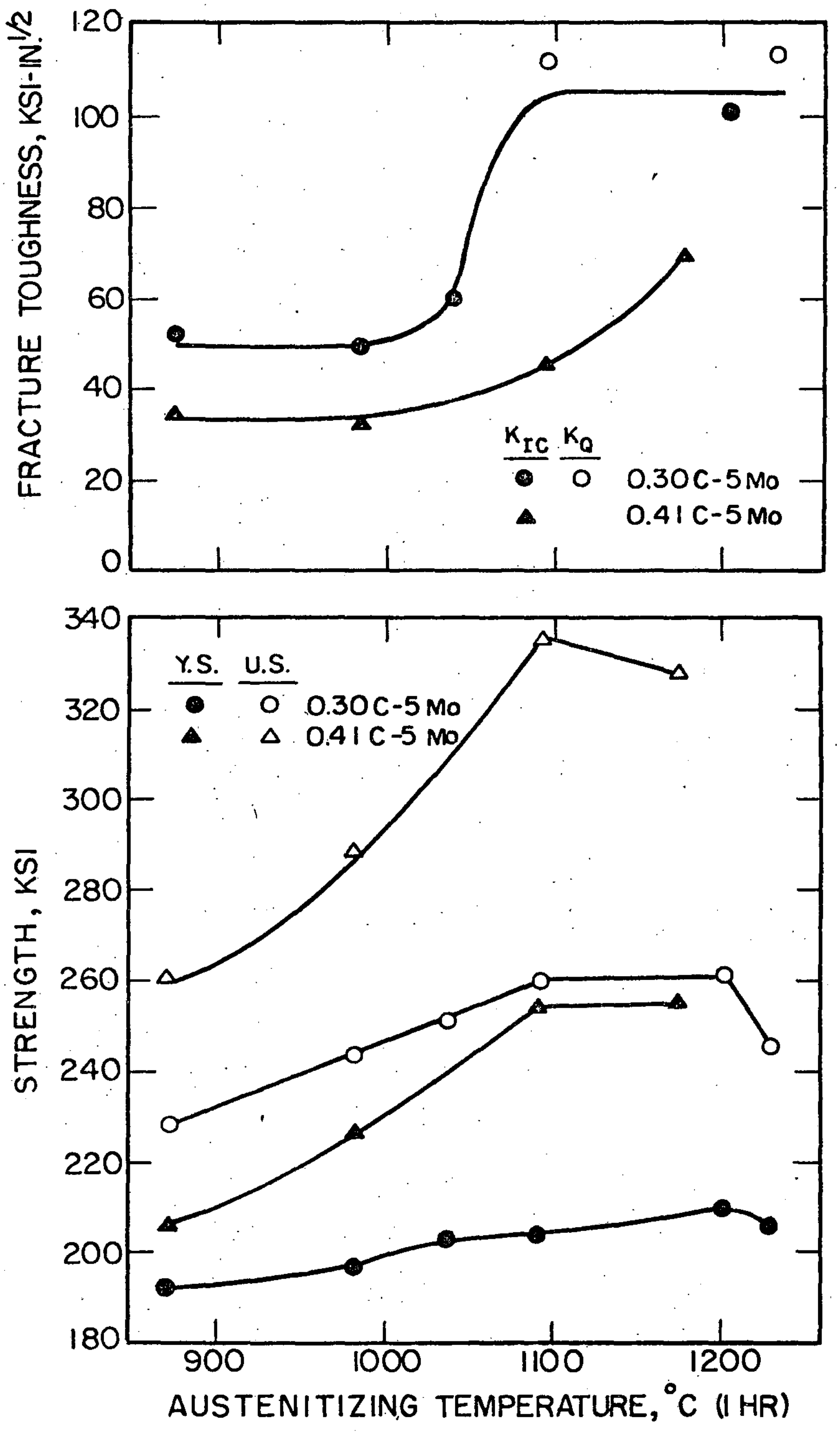
Designation	Compositions, Wt%								
	C	Cr	Mn	Mo	Ni	P	S	Si	V
0.30C-5Mo	0.30	-	0.60	5.03	-	0.008	0.005	<0.02	-
0.41C-5Mo	0.41	-	0.51	4.93	-	0.007	0.005	<0.02	-
0.34C-1Mo	0.34	-	0.63	0.95	-	0.008	0.005	<0.02	-
0.35C-1Mo-3Ni	0.35	-	0.61	0.95	3.1	0.007	0.005	<0.02	-
AISI 4130-A	0.31	0.85	0.57	0.18	0.15	0.008	0.009	0.28	<0.005
AISI 4130-B	0.33	0.90	0.63	0.18	0.15	0.008	0.009	0.27	<0.005
AISI 4330	0.28	0.85	1.02	0.40	1.80	0.009	0.005	0.28	0.07
AISI 4340	0.40	0.72	0.85	0.24	1.73	0.004	0.010	0.22	<0.005

TABLE II Tensile Properties of As-quenched AISI 4130, AISI 4330 and AISI 4340 Steels

Steel	Austenitizing Temp. (°C) and Quenching Medium	0.2% Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elong. %	Red. in Area %
AISI 4130	870, Oil	201	284	11.4	32.9
	1200, Oil	205	276	5.6	9.9
	1200, Ice-brine	215	249	1.6	6.6
AISI 4330	870, Oil	234	284	13.1	43
	1200, Ice-brine	210	222	0.6	3.4
AISI 4340	870, Oil	231	322	9.0	30.8
	1200→870, Oil	231	318	3.2	7.8

FIGURE CAPTIONS

1. Plots showing the influence of austenitizing temperature on room temperature fracture toughness (K_{IC} or K_Q), yield strength (Y.S.), and ultimate strength (U.S.) of 0.30C-5Mo and 0.41C-5Mo Steels.
2. Plots of room temperature plane strain fracture toughness vs prior austenite grain size (indicated by ASTM grain size number) for as-quenched 0.34C-1Mo and 0.35C-1Mo-3Ni steels.
3. Plots of room temperature plane strain fracture toughness vs tempering temperature for AISI 4130 steel. Austenitizing temperatures and quenching media are indicated. (IBQLN is an abbreviation for ice-brine quenching followed by refrigeration in liquid nitrogen.)
4. Plots of room temperature plane strain fracture toughness vs tempering temperature for AISI 4330 steel. Austenitizing temperatures and quenching media are indicated.
5. Plots of room temperature plane strain fracture toughness vs tempering temperature for AISI 4340 steel. Austenitizing temperatures and quenching media are indicated.
6. Transmission electron micrographs of as-quenched AISI 4340 steel: Bright field (a) and dark field of austenite reflection (b) for the 870°C austenitized specimen, and bright field (c) and dark field of austenite reflection (d) for the 1200°C→870°C austenitized specimen.



XBL737-6460A

Fig. 1

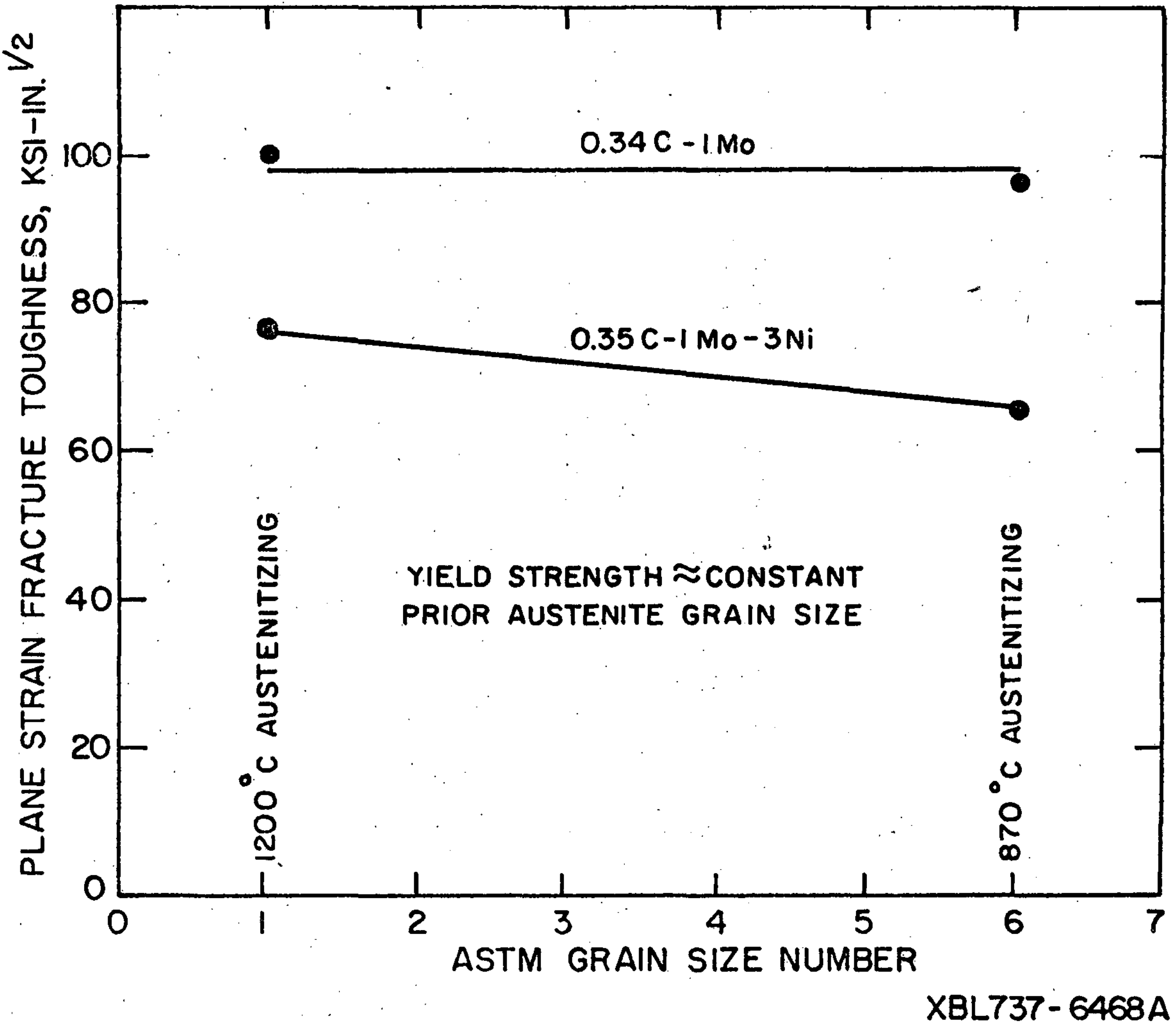
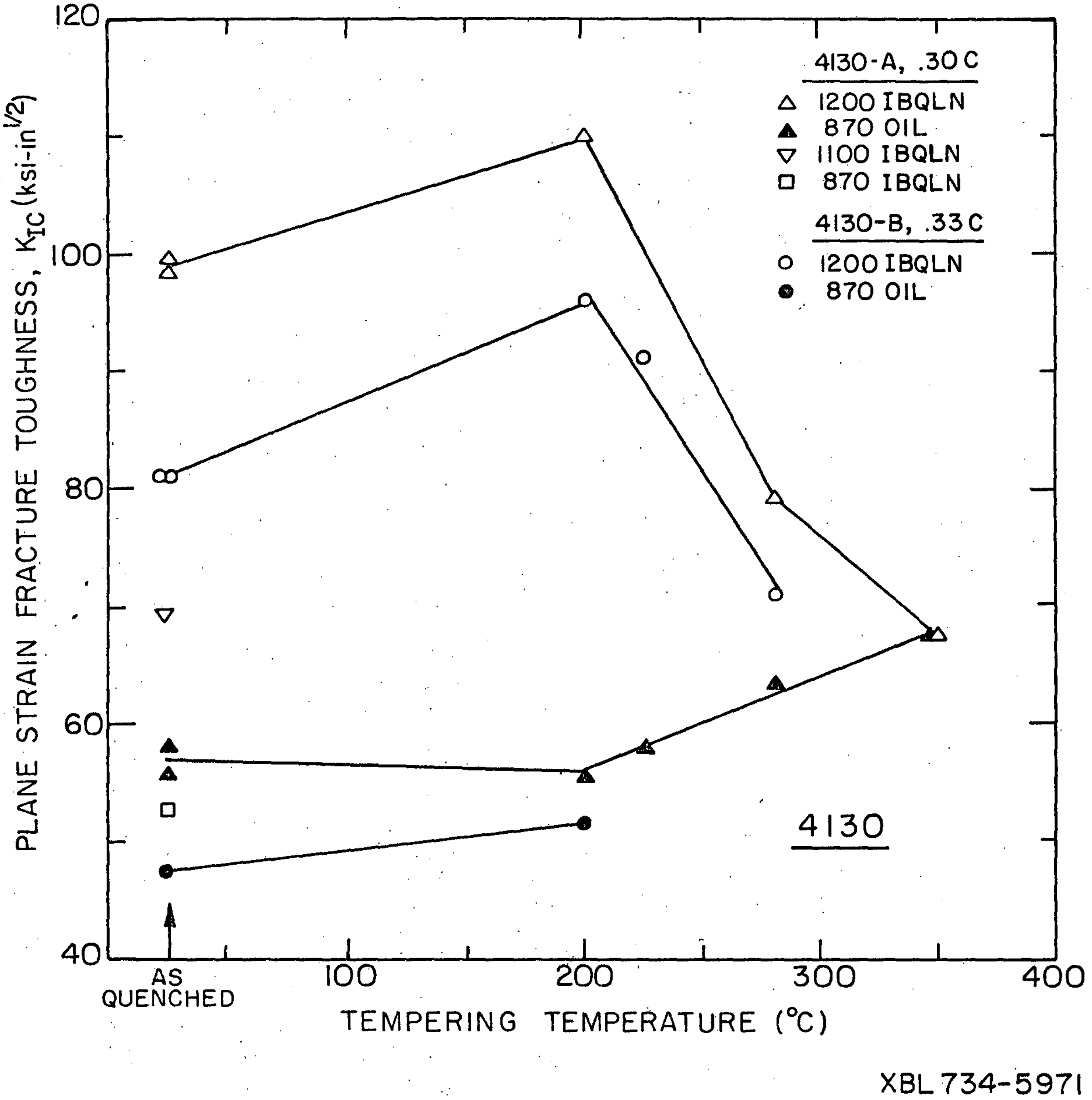

PLANE STRAIN FRACTURE TOUGHNESS, KSI-IN.$^{1/2}$
0
20
40
60
80
100
0
1
2
3
4
5
6
7
ASTM GRAIN SIZE NUMBER
0.34 C - 1 Mo
0.35 C - 1 Mo - 3 Ni
1200 °C AUSTENITIZING
870 °C AUSTENITIZING
YIELD STRENGTH ≈ CONSTANT
PRIOR AUSTENITE GRAIN SIZE
XBL737-6468A

Fig. 2



120
100
80
60
40
PLANE STRAIN FRACTURE TOUGHNESS, K_{IC} (ksi-in$^{1/2}$)
AS QUENCHED
100
200
300
400
TEMPERING TEMPERATURE (°C)
4130-A, .30 C
△ 1200 IBQLN
▲ 870 OIL
▽ 1100 IBQLN
□ 870 IBQLN
4130-B, .33 C
○ 1200 IBQLN
● 870 OIL
4130
XBL 734-5971

Fig. 3

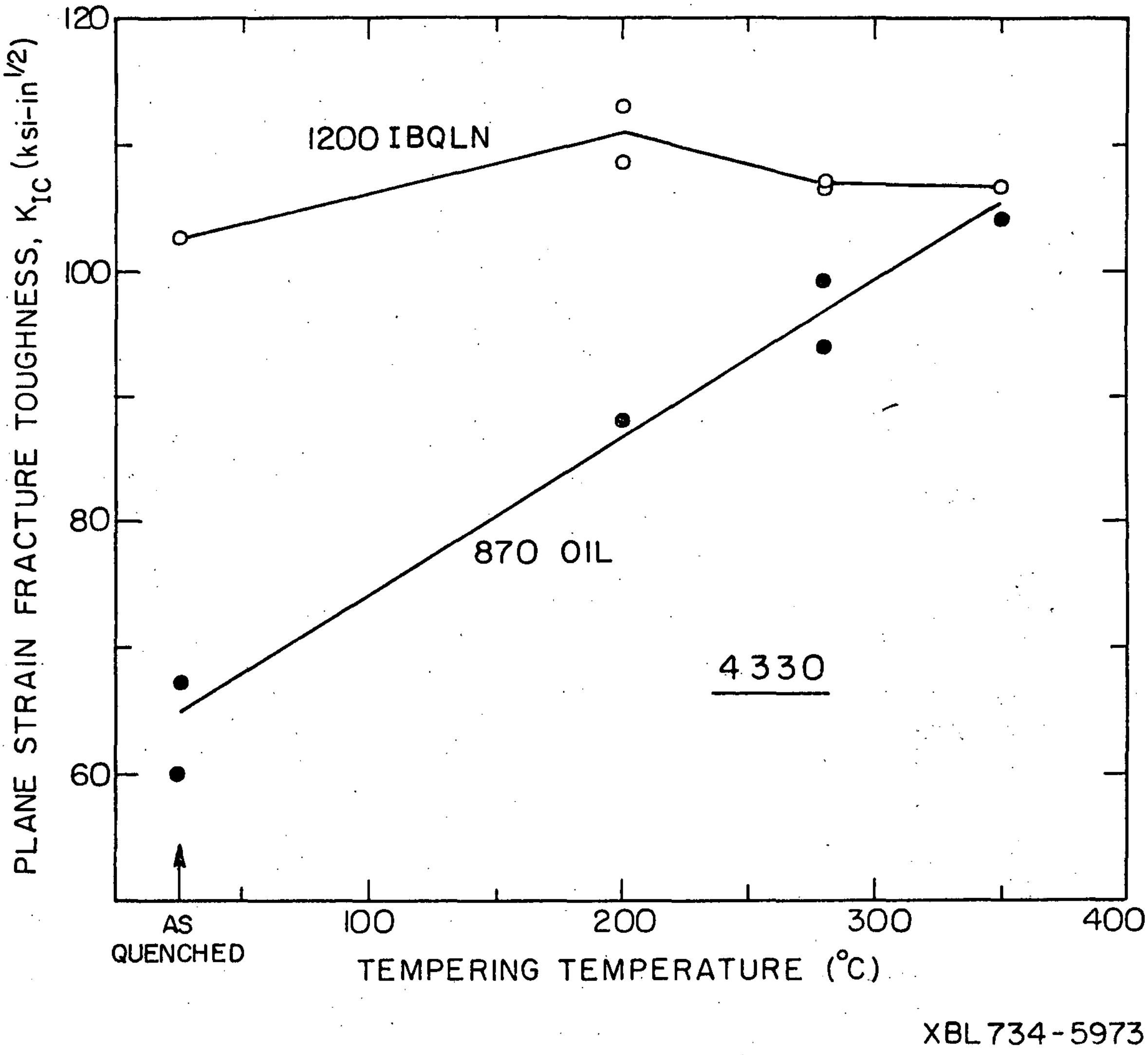
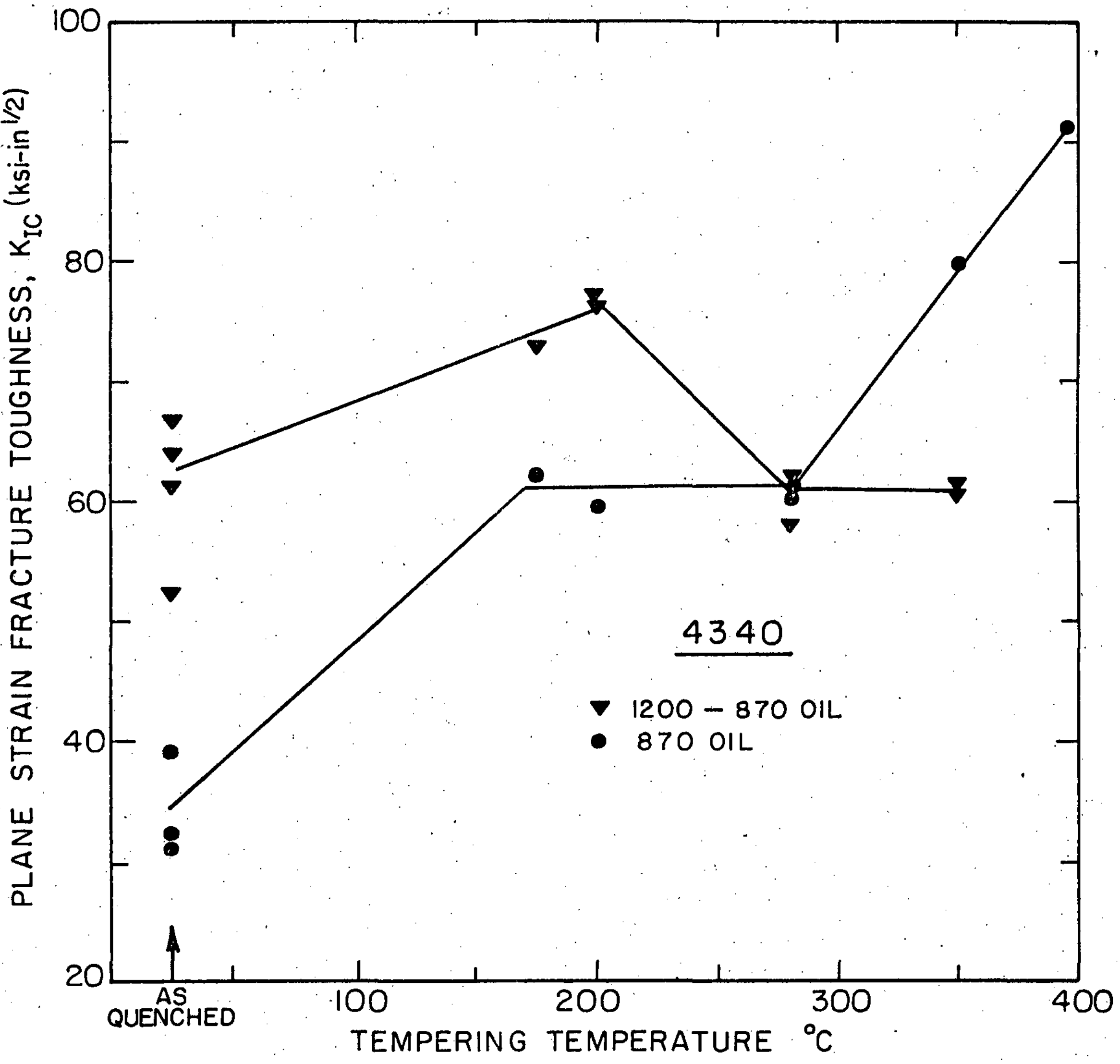
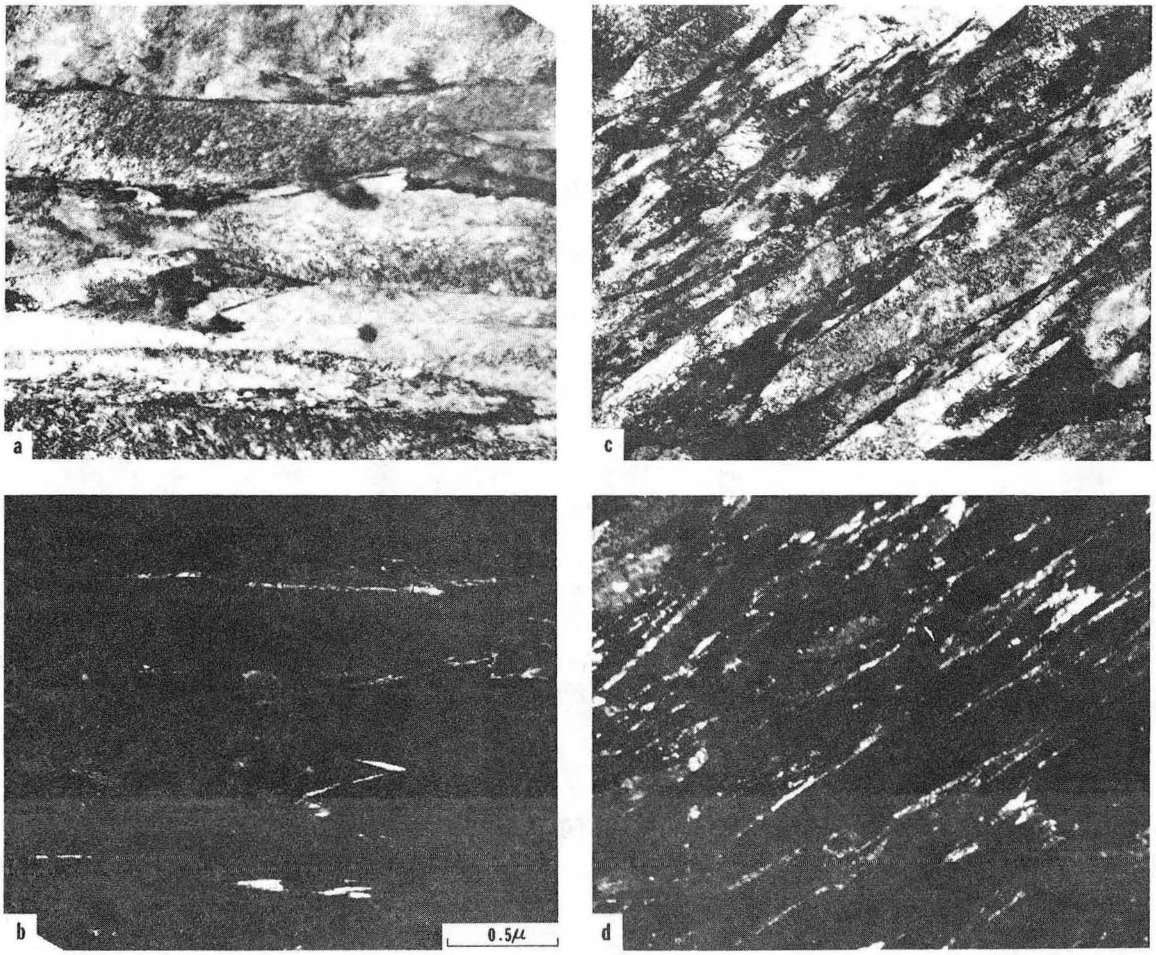

PLANE STRAIN FRACTURE TOUGHNESS, K_{IC} (ksi-in$^{1/2}$)
120
100
80
60
1200 IBQLN
870 OIL
4330
AS QUENCHED
100
200
300
400
TEMPERING TEMPERATURE (°C)
XBL 734-5973

Fig. 4



XBL734-5974

Fig. 5



XBB 738-5026

Fig. 6

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