To be presented at the Third Intern.
Conference on the Strength of Metals
and Alloys, Cambridge, England,
August 20-25, 1973

LBL-1833

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May 1973

Prepared for the U.S. Atomic Energy Commission
under Contract W-7405-ENG-48

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INFLUENCE OF SOME MICROSTRUCTURAL FEATURES ON THE FRACTURE TOUGHNESS OF HIGH STRENGTH STEELS

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ABSTRACT

Relatively small amounts of embrittling microconstituents, often detectable only by a combination of careful optical microscopy and high resolution electron microscopy, have a considerable influence on the fracture toughness of ultra high strength steels. These embrittling microconstituents are commonly found in conventionally heat treated steels. Devising heat treating procedures to eliminate the undesirable microstructural features is an important aspect in the design of steels with improved fracture toughness. The present paper describes how undesirable microconstituents were detected by various metallographic techniques, and how these were eliminated or minimized by the design of appropriate heat treatments. In the first case, undissolved carbides were noted as the prime cause of low plane strain fracture toughness of a 5 Mo, 0.3 C steel. Their subsequent elimination by the use of high austenitizing temperatures resulted in a twofold increase in toughness. In AISI 4130 steel, conventionally used austenitizing treatments result in the formation of a large amount of free ferrite which considerably lowers fracture toughness. Minimizing the amount of free ferrite by the use of higher austenitizing temperatures and more rapid quenches than those conventionally used resulted in a significant enhancement of fracture toughness. Finally, the superior fracture toughness of AISI 4340 steel austenitized at higher than conventionally employed

temperatures was attributed to the presence of small amounts of retained austenite between martensite laths. It was concluded that in low and medium alloy steels unusual combinations of strength and toughness, comparable to those of the 18 Ni maraging alloys and approaching those of TRIP steels, can be attained.

INTRODUCTION

The evolution of a unified theory of fracture mechanics and the development of reliable test methods for obtaining an accurate value for the plane strain fracture toughness (K_{IC}) have provided the metallurgist with a quantitative method for evaluating the effects of microstructural details on the tendency of an alloy to fracture in a brittle manner. Studies of the relationship between the microstructure and the fracture toughness of ultra high strength steels have been especially rewarding. For example, the deleterious effects of sulfur and other trace impurities have been quantitatively determined.[1] Also, the relative merits of steels with bainitic or tempered martensitic microstructure have been well documented with respect to their strength and fracture toughness.[2] Steels are often rated according to their relative positions on master plots of plane strain fracture toughness vs yield strength.[3]

The assumption is generally made that the high hardenability of commercial quenched and tempered steels leads to uniform microstructures throughout the thickness of fracture toughness specimens. Elementary considerations of micromechanics of fracture lead to the conclusion that the fracture toughness of ultra high strength steels should be highly dependent on relatively small amounts of embrittling micro-constituents. The detection of minor amounts of austenite decomposition

products by either optical or electron microscopic techniques is deceptive in its apparent simplicity. The detection by optical microscopy, for example, of small amounts (of the order of one percent) of upper bainite in a 5/8 in. thick specimen consisting largely of lower bainite or autotempered martensite demands the utmost care and patience in all stages of specimen preparation. It is well known that high resolution electron microscopy is needed to distinguish between lower bainite and autotempered martensite. Unfortunately, the advantages of electron microscopy are offset by the disadvantage that large areas cannot be scanned readily. A combination of metallographic techniques is generally the most effective way to study the structures of heat treated steels. When metallographic techniques reveal the presence of embrittling structures in conventionally heat treated steels, alternate heat treatments should be devised to either eliminate, or at least minimize, such structures.

Recent studies at the University of California on a secondary hardening steel, 5 Mo-0.30, have suggested one way in which improvements in microstructural uniformity can be achieved.[4] Increases in fracture toughness of more than 50 percent were obtained in as quenched specimens by the use of high austenitizing temperatures. In this case, the improvement was attributed to the reduction of undissolved alloy carbides. In the present investigation several commercial steels were heat treated at different austenitizing and tempering temperatures and their strength and fracture toughness determined. The results obtained are reported herein.

EXPERIMENTAL RESULTS AND DISCUSSION

The compositions and properties of the steels used in the present investigation are shown in the Table. Specimens for optical and electron microscopy were taken from the fracture toughness specimens which had been designed and tested in accordance with ASTM recommended practices. Sufficient sampling was done to ensure that representative microstructures were obtained.

The effect of austenitizing temperature on the fracture toughness of as quenched specimens of the 5 Mo,0.3 C steel is shown in Fig. 1. The abrupt increase in fracture toughness at a critical austenitizing temperature was associated with an increase in grain size (ASTM 7-8 to 1); the grain size change was concomitant with complete solution of the alloy carbides.

Several different microstructural features were responsible for the lower fracture toughnesses of the three steels when they were austenitized at the conventionally used temperature (870°C). The optical micrographs of AISI 4130 steel, oil quenched from 870°C, clearly showed grains of ferrite and many regions of upper bainite. The remainder of the structure was identified by transmission electron microscopy as being lower bainite and autotempered martensite. When the austenite grain size was increased by first heating the steel to 1200°C (then furnace cooled to 870°C before oil quenching), there were no ferrite grains visible in the optical micrograph, and the amount of upper bainite was substantially lower than that formed during the direct quench from 870°C. The fracture toughness was increased about 30 percent by the 1200°C treatment.

TABLE

Austenitizing and Tempering Temperatures, Fracture Toughness and Yield Strength of the Steels

Steel (Composition)	Austenitizing Temperature, °C	Quenching Medium	Tempering Temperature, °C	0.2% Yield Strength ksi	Fracture Toughness, ksi-in$^{1/2}$
5Mo-0.60Mn-0.30C	870	Iced Brine	As Quenched	194	52
(Laboratory heat)	1200	Iced Brine	As Quenched	214	100
	1200	Iced Brine	150	210	104*
	1200	Iced Brine	225	196	109*
AISI 4130	870	Oil	As Quenched	201	57
(0.30C-0.85Cr-	1200→870**	Oil	As Quenched	210	73
0.46Mn-0.20Mo)	1200	Iced Brine	As Quenched	214	100
(Commercial steel)	1200	Iced Brine	200	210	110
AISI 4340	870	Oil	As Quenched	231	35
(0.40C-0.72Cr.	1200→870**	Oil	As Quenched	231	63
1.73Ni-0.80Mn-	870	Oil	200	235	62
0.24Mo)	1200→870**	Oil	200	230	75
(Commercial steel)					

*K_Q, rather than K_{IC}, values.

**Specimens cooled slowly from 1200°C to 870°C before quenching to maintain quenching conditions identical with 870°C austenitized specimens.

Free ferrite grains and ferrite plates in upper bainite are regions that are mechanically weak. They can fail readily by either plastic flow or by cleavage, and thus they tend to initiate microcracks at relatively low levels of plastic strain. This results in low values of fracture toughness, even when dimpled rupture occurs, as scanning electron microscopy revealed was the case for this steel. In additional experiments, fracture toughness specimens were quenched into iced brine directly from 1200°C. The cooling rate in this case was fast enough to suppress the formation of upper bainite, although small amounts of a bainitic product were visible in isolated regions in optical micrographs. The remainder of the microstructure appeared to be autotempered martensite. Specimens given the iced brine quench had exceptionally high fracture toughness (100 ksi $\sqrt{\text{in.}}$).

Annother microstructural feature that can have a marked influence on fracture toughness is retained austenite. The presence of austenite films has been observed by other investigators, and there has been some speculation about its influence on toughness.[5] In the case of AISI 4340 steel, the presence of retained austenite in oil quenched specimens with the larger austenite grains appeared to markedly enhance the fracture toughness. Optical micrographs did not reveal the structural nature of this steel in any of the conditions investigated. Transmission electron micrographs were required to show that the structure was primarily autotempered martensite with small amounts of lower bainite and untempered martensite for both the 870°C, and the 1200° to 870°C austenitizing conditions. The only significant difference observable in the two steels was that a film of austenite, 100 to 200 Å thick, surrounded a majority of the martensite laths in the specimens that had been heated to 1200°C,

as can be seen in the dark field electron micrograph of Fig. 2, whereas there was only a trace of retained austenite visible in the specimens heated to 870°C. Additional dark field microscopy showed that the retained austenite did not transform when specimens were cooled to liquid nitrogen temperature.

Austenite is not sensitive to high local stress concentrations and does not fail by cleavage, as does ferrite. Consequently, it seemed reasonable to conclude that in this case, the presence of another phase, properly dispersed, can actually enhance the fracture toughness.

CONCLUSIONS

It is clearly evident that low fracture toughness of a quenched and tempered steel is associated with the presence of certain types of microstructural features. It is well known that sulfide inclusions act as microcrack nuclei and therefore induce microfracture at relatively low strains in fracture toughness specimens. Similarly, as reported herein, carbide particles undissolved during austenitizing lower toughness. Free ferrite, whether present as separate grains or as platelets in upper bainite in ultra high strength steels, lowers fracture toughness by a substantial amount.

Autotempered martensite formed during the quenching operation, lower bainite, and tempered martensite free from lath boundary films of carbides, are tough and fracture resistant microstructural constituents. The presence of retained austenite films around autotempered laths of martensite adds substantially to the inherent toughness of the autotempered martensitic structure.

Figure 3 summarizes the results of our tests to date on steels that had been given the 1200°C austenitizing treatment. The fracture toughness, K_{IC}, is plotted against the yield strength. In this figure there are two bands plotted which show the ranges of yield strength and fracture toughness values reported in the literature for commercial AISI 4340 steel and the 18 Ni maraging alloy. The maraging steels are usually considered to have the highest value of plane strain fracture toughness obtainable at a given yield strength. As the figure shows, it is possible to increase the fracture toughness of quenched and tempered steels, through microstructural control, so that their toughness values are in, or very near, the maraging steel band. Furthermore, there are good reasons to believe that fracture toughnesses well above the maraging steel band can be obtained with quenched and tempered steels through modifications of chemical composition and thermal treatments.

Figure 4 shows the approximate range of results obtained with TRIP steels and how the fracture toughness values compare with those of quenched and tempered, and maraging steels. The TRIP steels are metastable austenitic ultra high strength steels that transform martensitically when plastically deformed. These steels contain 0.3 percent carbon or more, and the martensite that forms provides an additional strengthening mechanism. A volume change of approximately 3 percent (corresponding to a linear change of 1 percent) is associated with the transformation. The linear strain augments the ductility and adds to the fracture toughness. The volumetric expansion tends to reduce the three dimensional tensile stresses that are developed during plastic straining near the apex of a notch. This changes the stress state toward a condition which favors a more ductile performance of a fracture toughness specimen.

It seems reasonable to postulate that steels with lower alloy content than TRIP steels, but with some TRIP characteristies, can be designed. The fracture toughness values for such steels should fall in the region between the maraging and the TRIP steels.

ACKNOWLEDGEMENTS

The authors are grateful to Professor Gareth Thomas for his helpful suggestions, to Mr. Thomas Tom and Dr. George Lai for the use of unpublished data, and to Mr. Dilip Bhandarkar for assistance in preparing this manuscript. This research was supported by the Atomic Energy Commission and by the Army Materials and Mechanics Research Center.

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FIGURE CAPTIONS

Fig. 1. Influence of austenitizing temperature on the room temperature plane strain fracture toughness, K_{IC}, of as quenched 5 Mo, 0.3 C steel.

Fig. 2. Transmission electron micrograph of AISI 4340 steel heated to 1200°C before oil quenching, (a) bright field image, (b) dark field image, showing reversal of contrast at austenite films between martensite laths.

Fig. 3. Plots of fracture toughness, K_{IC}, vs yield strength. The two shaded bands represent the range of values found in the literature for AISI 4340 and maraging steels. The circles are data points from the present investigation.

Fig. 4. Plots of fracture toughness vs yield strength. Bands for commercial steels (K_{IC}) and metastable austenitic TRIP steels (K_C).

0 0 0 0 3 9 0 6 3 6 1

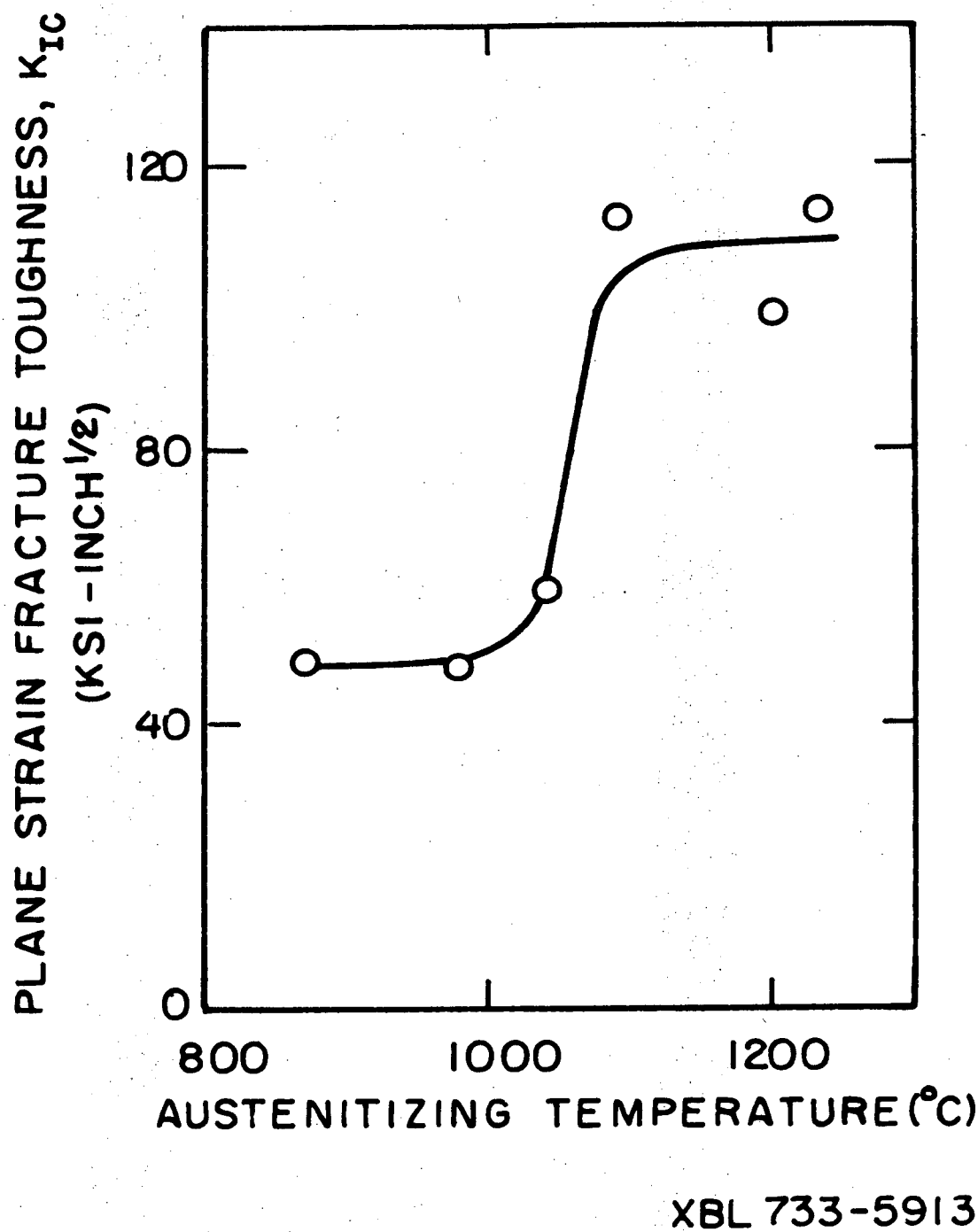

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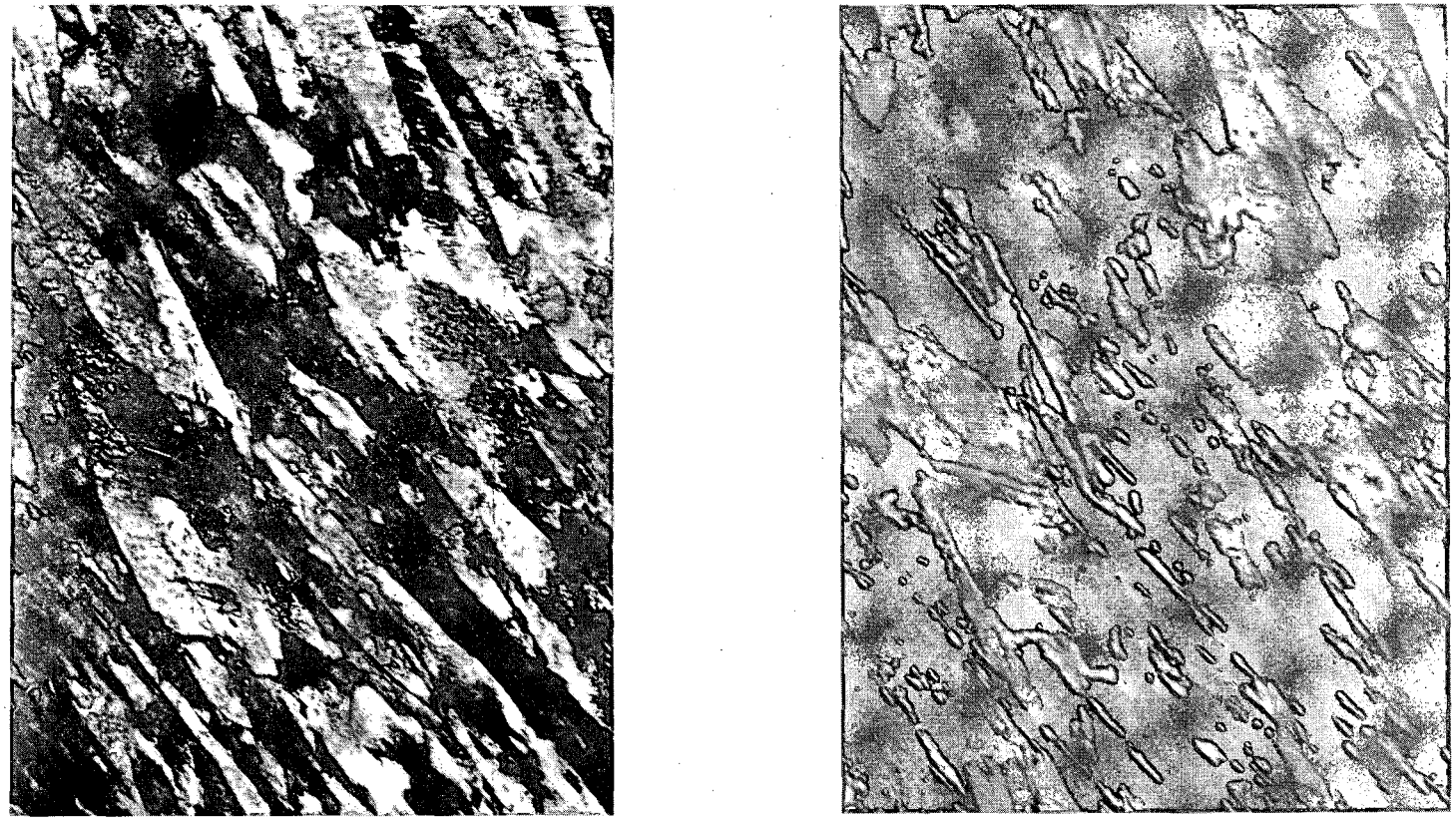
Fig. 1



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(a) (b)

1μ

Fig. 2

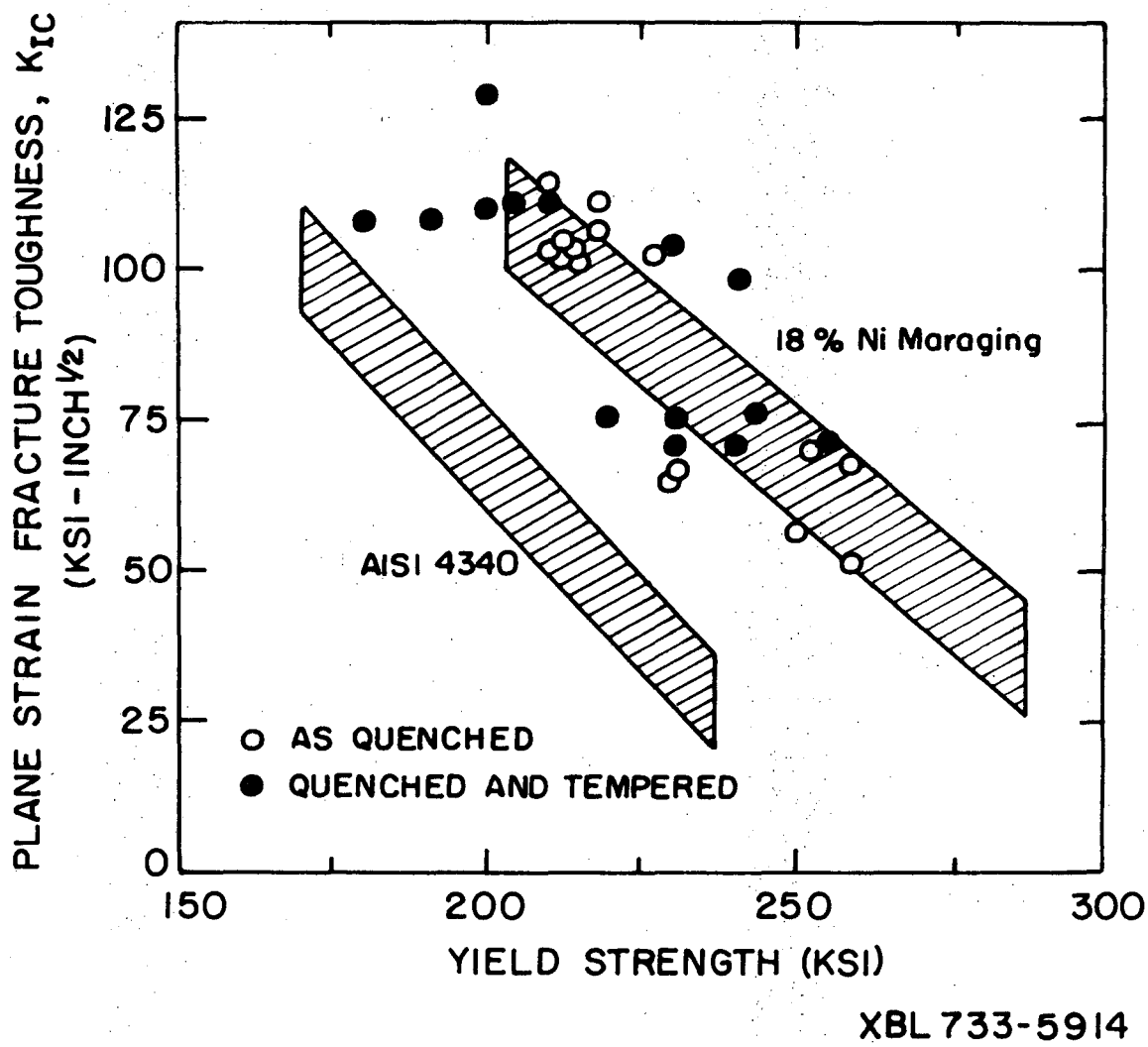
PLANE STRAIN FRACTURE TOUGHNESS, K_{IC}
(KSI - INCH$^{1/2}$)
125
100
75
50
25
0
150
200
250
300
YIELD STRENGTH (KSI)
18 % Ni Maraging
AISI 4340
AS QUENCHED
QUENCHED AND TEMPERED
XBL 733-5914

Fig. 3

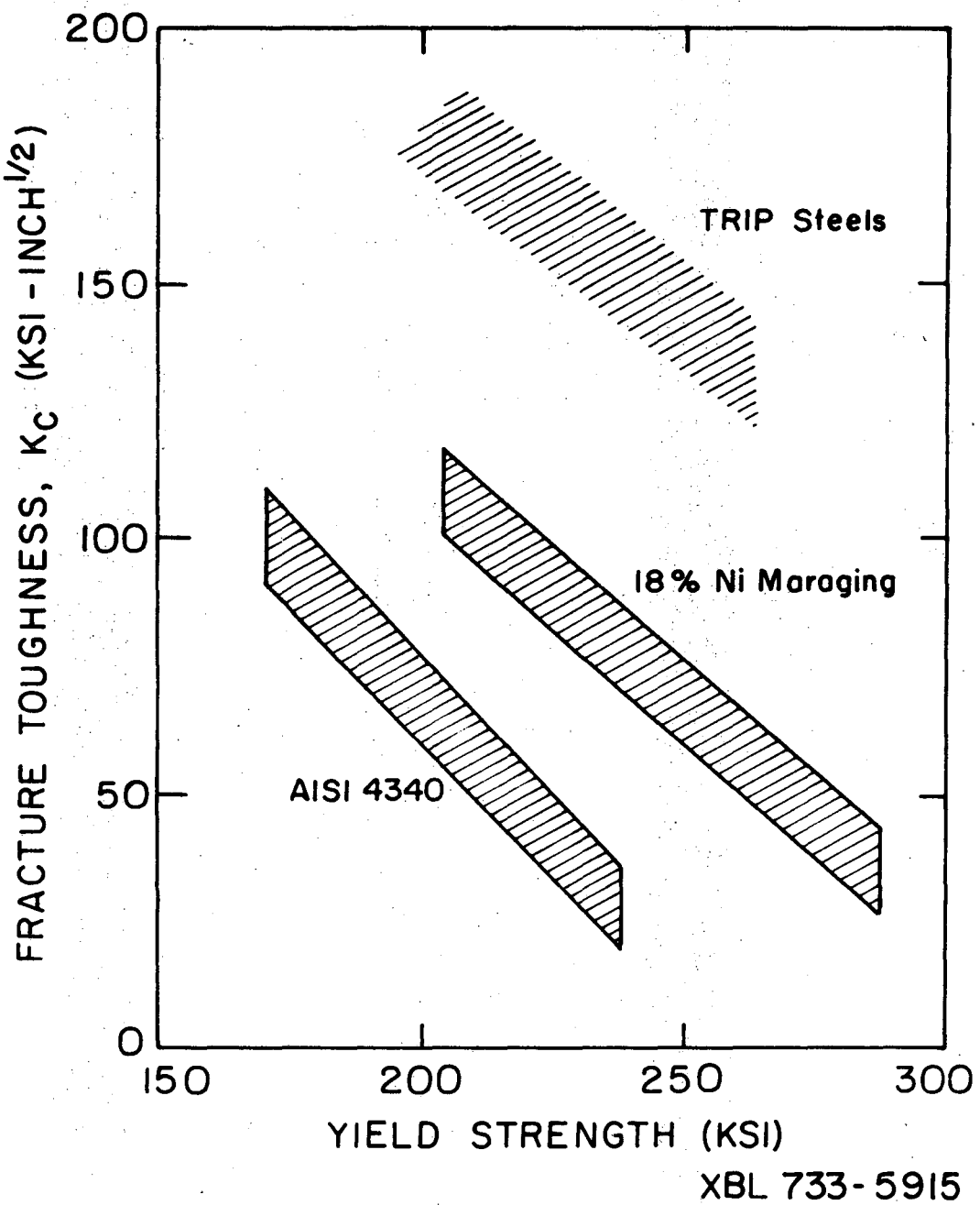
200
150
100
50
0
FRACTURE TOUGHNESS, K_C (KSI - INCH$^{1/2}$)
TRIP Steels
18% Ni Maraging
AISI 4340
150
200
250
300
YIELD STRENGTH (KSI)
XBL 733-5915

Fig. 4

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