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ABSTRACT

The softening which occurs on tempering AISI 4340 steel is shown to be retarded by additions of aluminum or combinations of aluminum and silicon. The "500°F embrittlement" phenomenon in AISI 4340 steel occurs at higher tempering temperatures in the presence of aluminum and aluminum plus silicon in the steel. Significant improvements in the fracture toughness of low/medium alloy heat treatable steels are possible without a loss in strength through aluminum or aluminum plus silicon additions.

INTRODUCTION

Recent research on low alloy steels has mainly focused on improving their fracture toughness at high strength levels. A number of different approaches have been taken to improve the fracture toughness. The most promising of these are:

(1) Improving the cleanliness of the steel;

(2) Modifying the heat treatment of existing steels; and

(3) Modifying the composition of the commonly used grades.

Studies directed toward improving the cleanliness of the steel have been aimed at reducing the size and content of nonmetallic inclusions and lowering the impurity concentrations. It has been shown by several investigators that substantial improvements in the fracture toughness can be obtained through these reductions.[1-2]

A further improvement in the mechanical properties can be achieved by the utilization of heat treatment modifications. Higher austenitizing treatments have been used to obtain microstructural features which improved the plane strain fracture toughness.[3-4] However, this increase in the K_{IC} fracture toughness can be accompanied by a loss in Charpy V-notch values.[5] More recently, isothermal transformations, following austenitization at the conventionally used lower temperatures, have been effective in improving the toughness.[6]

An increase in the fracture toughness at high levels of strength can also be achieved by modifying the composition of an existing steel. For example, modifications of AISI 4340, such as 300 M and HP 310, have been developed.[7-8] The major compositional modifications in these steels is the addition of Si and V. Silicon raises the embrittlement temperature range and allows tempering to be carried out at higher temperatures. It also retards the softening of the steel which normally occurs on tempering. Vanadium was added presumably to promote toughness by reducing the grain size.

The approach used in this investigation, for improving the fracture toughness, has been to utilize the effect of inexpensive alloy modifications. The following sections describe the results obtained.

CHOICE OF THE BASE STEEL AND ITS MODIFICATION

The base steel chosen was VAR AISI 4340. A commercial aircraft quality steel was used. The supplementary alloying additions employed were Al and Si. The effect of Si in this type of steel has already been mentioned.

The iron-aluminum phase diagram is similar to the iron-silicon diagram at the iron-rich end. Neither of these elements are carbide formers in steels.[10] It was considered reasonable to assume that Al might behave in a manner similar to Si in retarding the tempering of steel.

Additions of Al and Al plus Si were made to remelted AISI 4340 in a vacuum induction furnace. The compositions of the steels used in this investigation and the austenitizing temperatures used are shown in Table I. The M_s temperatures were measured by dilatometry and were all found to lie close to 300°C, which is the M_s for the base steel.[11] The combined additions of Al plus Si were made to study any possible synergestic effect on structure and properties.

TEMPERING RESPONSE OF THE MODIFIED STEELS

The effect of Al additions on the tempering response of AISI 4340, as indicated by hardness measurements, is shown in Fig. 1. Also plotted on the figure are similar data for AISI 4340. The effect of increasing amounts of Al additions on the retention of hardness at the higher tempering temperatures is clearly shown. This behavior is similar to that exhibited by other steels containing over 1% of silicon.[12-13] The hardness is seen to vary with the several steels in the as-quenched condition. The differences in hardness was attributed to differences in the carbon content and also to the different amounts of retained austenite found in these steels (3 to 7%).

Fig. 2 shows the tempering response of the Al plus Si modified steels. The general behavior is similar to that of the Al modified steels. However, higher hardnesses were obtained in these steels, compared to those containing Al. Also, there appeared to be an indication of a secondary hardness peak at higher tempering temperatures. The higher hardness of the Al plus Si modified steels was attributed to the greater strengthening effect of Si, especially at the higher tempering temperatures. The secondary hardening peak was evidently associated with the decomposition of the retained austenite.

Thus, it is clear that Al and combinations of Al plus Si lead to a retardation in the softening of AISI 4340 steel on tempering.

VARIATION IN TENSILE PROPERTIES WITH TEMPERING

The variation in the 0.2 pct. offset yield and the ultimate strength with tempering temperature for the 4340 + Al steels is shown in Fig. 3. Following an initial drop in the ultimate strength, a plateau in strength appears which extends to higher temperatures at high Al content. The precipitous drop in the ultimate strength of the AISI 4340 on tempering beyond 200°C is clearly not seen in the Al containing steels.

The 0.2 pct. offset yield strength increases with tempering temperatures up to a temperature of about 350-400°C, beyond which there is a sharp drop-off in both the ultimate and yield strength, as seen from the curves in Fig. 3. This sharp drop-off in strength is generally associated with the formation and rapid growth of cementite. The peak in yield strength occurs at higher tempering temperatures with increasing amounts of Al in the steel. Thus, it appears that the addition of Al to AISI 4340 has moved the temperature range for the formation of cementite to higher tempering temperatures.

The plateau in the ultimate strength was evidently the result of the transformation of retained austenite. The initial low yield strength in the as-quenched state is probably due to the presence of retained austenite.

A similar behavior was observed for the Al + Si modified steels. The results are shown in Fig. 4. A higher strength was obtained in the Al + Si steels than in the Al steels.

The tensile properties of three types of AISI 4340 modified steels are compared in Fig. 5. These are: 4340 + 2% Al, 4340 + 2% Si, and 4340 + 1% Al + 1.0% Si. The following conclusions were drawn:

(1) Additions of Al to AISI 4340 are not as effective as Si in raising the strength at similar weight percent additions; and

(2) A combination of Al plus Si raises the strength level above that obtained with an equivalent amount of Al addition, but not as much as with an equivalent amount of Si addition.

VARIATION OF FRACTURE TOUGHNESS WITH TEMPERING TEMPERATURE

As mentioned in a previous section, the reason for the addition of Al was to prevent the formation of cementite at lower tempering temperatures. This raises the temperature range needed to cause "500°F embrittlement", which is generally associated with the initial stages of the precipitation of cementite.[14] Consequently, a higher tempering temperature is possible in the Al and Al + Si modified steels. This could lead to an improvement in the fracture toughness without a concomitant loss in strength.

The best combination of strength and toughness was obtained in the 4340 + 1.5 Al + 1.5 Si steel and in the 4340 + 2.0 Al + 2.0 Si steel. A description of the 4340 + 1.5 Al + 1.5 Si steel will be given below.

Variations in the tensile properties and the fracture toughness with tempering temperature are shown in Fig. 6 for AISI 4340 and for the 4340 + 1.5 Al + 1.5 Si steel. For the AISI 4340 steel, a plateau in the K_{IC} vs tempering temperature curve appears between 200°C and 300°C.[3] This behavior undoubtedly reflects the phenomenon of "500°F embrittlement". The rather dramatic improvement in the properties of the modified steel as compared to those of AISI 4340 is obvious at a tempering temperature of 300°C; at this temperature, the yield strength of the modified steel is about the same as the ultimate strength of AISI 4340, and yet the fracture toughness of the former steel is greater by about 20 ksi$\sqrt{in}$.

The fracture toughness of the modified steel is compared to that of 300 M in Fig. 7. At a tempering temperature of 300°C, both the steels have about the same ultimate and yield strengths. However, the 4340 + 1.5 Al + 1.5 Si steel has a higher fracture toughness as seen in Fig. 7. This difference in K_{IC} is maintained even at the higher tempering temperatures.

A summary of the results obtained to date for the modified steels used in this investigation is shown in Fig. 8, where the plane strain fracture toughness, K_{IC}, is plotted against the yield strength. The band for the maraging steels is the latest available in the literature and represents data obtained from high purity maraging alloys.[15] The bands for the AISI 4340 and 300 M are from the results obtained at this laboratory.[5,16] The improvement in the toughness and yield strength on tempering the modified steels is shown clearly in the figure. It thus appears possible to obtain higher strengths through alloy modification without a concomitant loss in the toughness.

In Fig. 9, the K_{IC} data are plotted against the ultimate strength. Due to the low work hardening rate of the maraging steel, the relative position of the modified 4340 steel band is favored in this type of a plot. At the higher strength levels, the bands for the experimental and the maraging steels merge.

The K_{IC} data have not yet been correlated with Charpy V-notch impact values. However, one data point for the 4340 + 1.5 Al + 1.5 Si steel is available for the 300°C tempered condition. The value obtained was 14 ft. lbs--a Charpy value comparable to that obtained for the maraging steels.

A microstructure study of the steels used in this investigation at the electron optical level is presently in progress.[11] A better understanding of the factors which influence the fracture toughness of these steels in the presence of Al and and Al + Si additions should be possible following this study.

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16. R. O. Ritchie, Unpublished Work, Lawrence Berkeley Laboratory.

FIGURE CAPTIONS

Fig. 1. Hardness (R_c) versus tempering temperature of AISI 4340 and 4340 + Al steels.

Fig. 2. Hardness (R_c) versus tempering temperature of AISI 4340 and 4340 + Al + Si steels.

Fig. 3. Variation in tensile properties (0.2 pct. offset yield strength and ultimate strength) of AISI 4340 and 4340 + Al steels with tempering temperature.

Fig. 4. Variation in tensile properties of AISI 4340 and 4340 + Al + Si steels with tempering temperature.

Fig. 5. A comparison of the tensile properties of (i) 4340 + 2.0 Al (ii) 4340 + 2.0 Si and 4340 + 1.0 M + 1.0 Si as a function of tempering temperature.

Fig. 6. The variation in tensile properties and plane strain fracture toughness, K_{IC}, with tempering temperature for AISI 4340 and 4340 + 1.5 Al + 1.5 Si steels.

Fig. 7. The variation in tensile properties and plane strain fracture toughness with tempering temperature for 300 M and 4340 + 1.5 Al + 1.5 Si steels.

Fig. 8. Plot of plane strain fracture toughness versus yield strength for some commercial high strength steels and the Al and Al + Si modified 4340 steels.

Fig. 9. Plot of plane strain fracture toughness versus ultimate strength for some commercial high strength steels and the Al and Al + Si modified 4340 steels.

Table I. Nominal composition, austenitization temperatures and M_s of modified AISI 4340 Steels.*

Alloy No.	wt% Al	wt% Si	Aust. Temp. °C	M_s °C
1	1.0	--	900	315
2	2.0	--	900	310
3	3.0	--	1100	310
4	1.0	1.0	900	295
5	1.5	1.5	950	310
6	2.0	2.0	1100	295

*Base Steel Composition: C-0.39, Cr-0.81, Mn-0.74, Ni-1.81, Si-0.2, P-0.005, S-0.003.

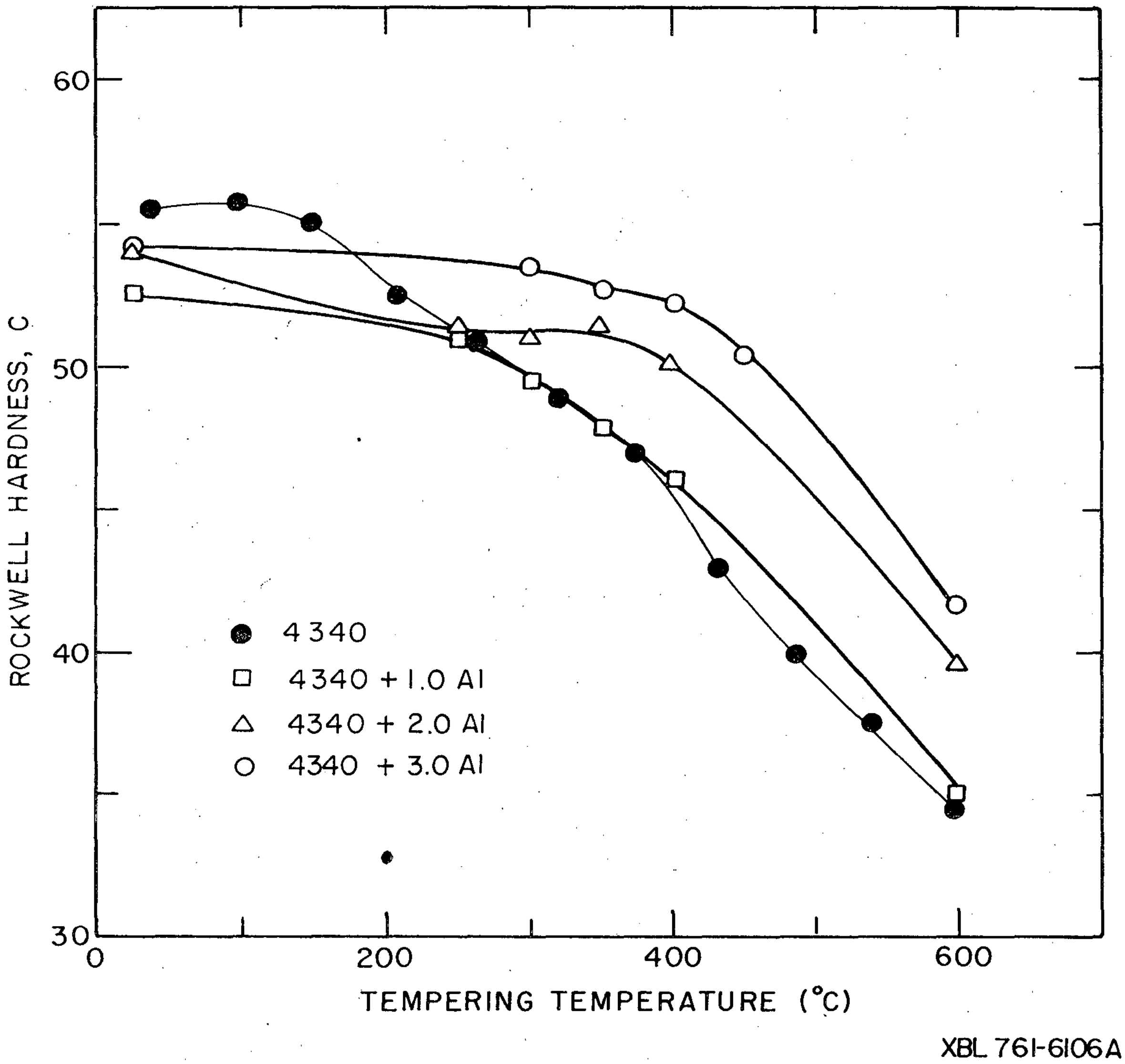

60
50
40
30
0
200
400
600
ROCKWELL HARDNESS, C
TEMPERING TEMPERATURE (°C)
4340
4340 + 1.0 Al
4340 + 2.0 Al
4340 + 3.0 Al
XBL 761-6106A

Figure 1.

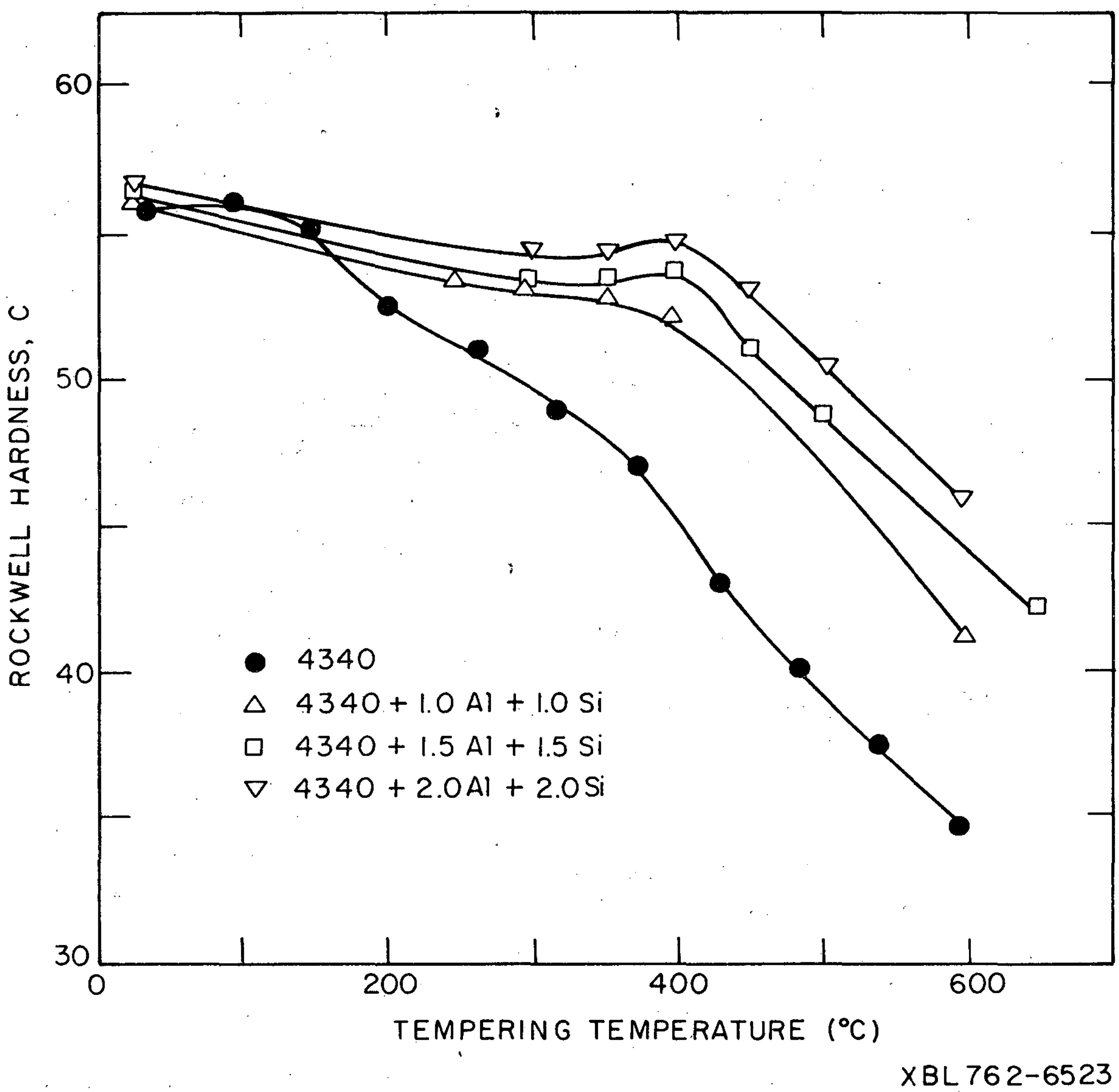
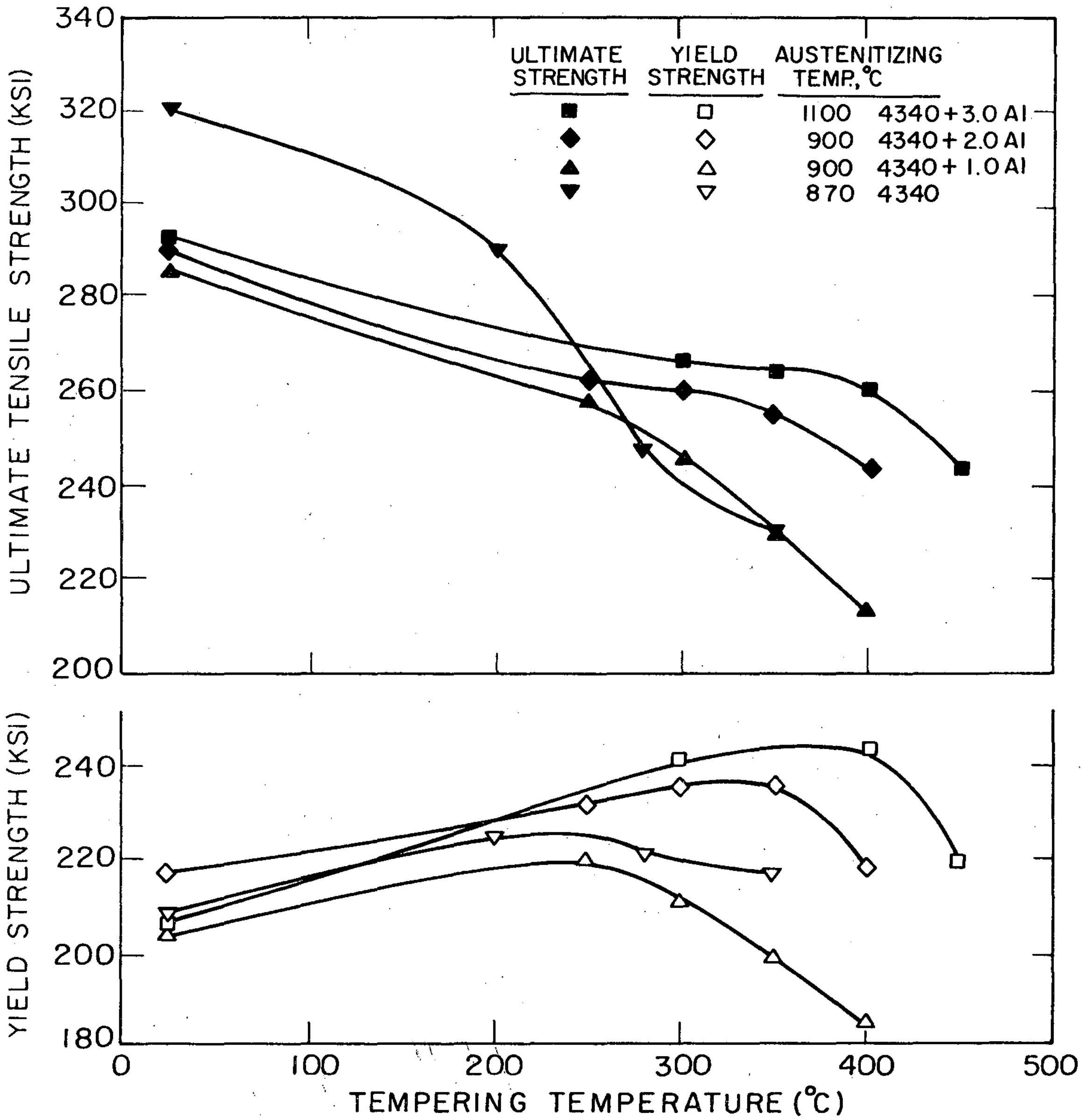

60
50
40
30
0
200
400
600
ROCKWELL HARDNESS, C
TEMPERING TEMPERATURE (°C)
4340
4340 + 1.0 Al + 1.0 Si
4340 + 1.5 Al + 1.5 Si
4340 + 2.0 Al + 2.0 Si
XBL 762-6523

Figure 2.



ULTIMATE STRENGTH
YIELD STRENGTH
AUSTENITIZING TEMP., °C
1100 4340+3.0 Al
900 4340+2.0 Al
900 4340+1.0 Al
870 4340
ULTIMATE TENSILE STRENGTH (KSI)
YIELD STRENGTH (KSI)
TEMPERING TEMPERATURE (°C)
340
320
300
280
260
240
220
200
180
0
100
200
300
400
500
XBL 762-6527

Figure 3.

0 0 0 0 4 5 0 3 3 9 6

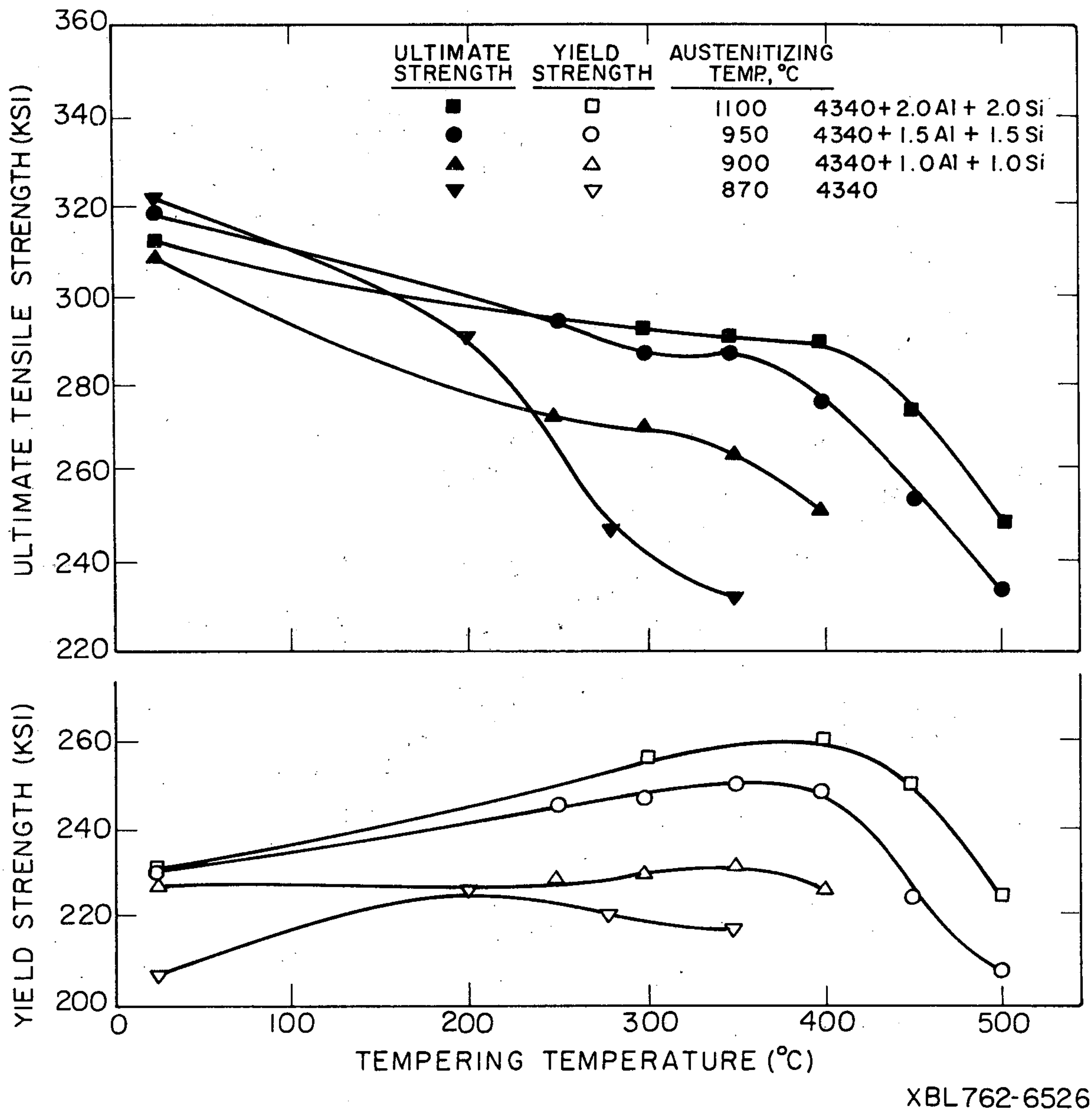


Figure 4.

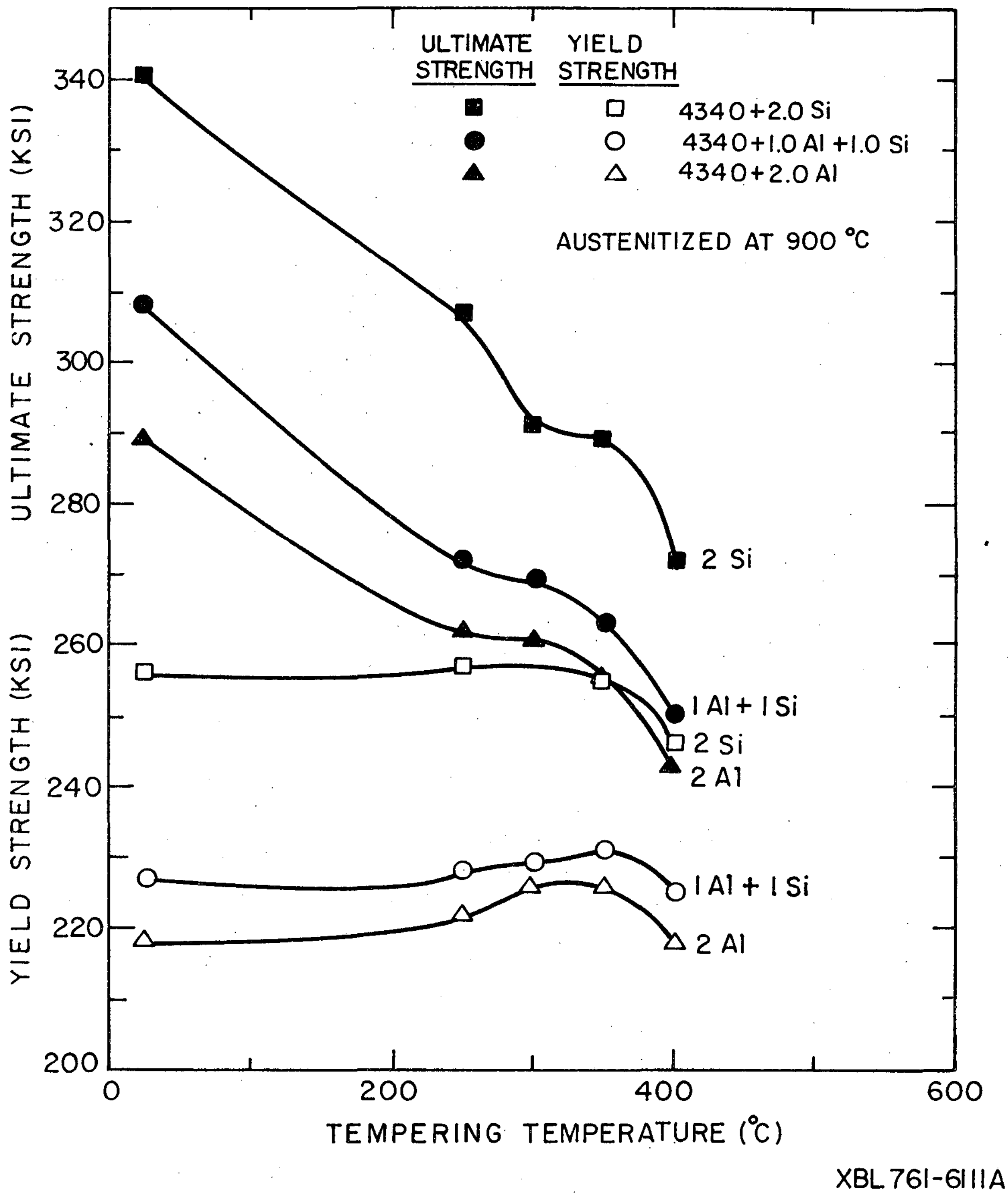

ULTIMATE STRENGTH
YIELD STRENGTH
4340+2.0 Si
4340+1.0 Al +1.0 Si
4340+2.0 Al
AUSTENITIZED AT 900 °C
2 Si
1 Al + 1 Si
2 Si
2 Al
1 Al + 1 Si
2 Al
ULTIMATE STRENGTH (KSI)
YIELD STRENGTH (KSI)
340
320
300
280
260
240
220
200
0
200
400
600
TEMPERING TEMPERATURE (°C)
XBL 761-6111A

Figure 5.

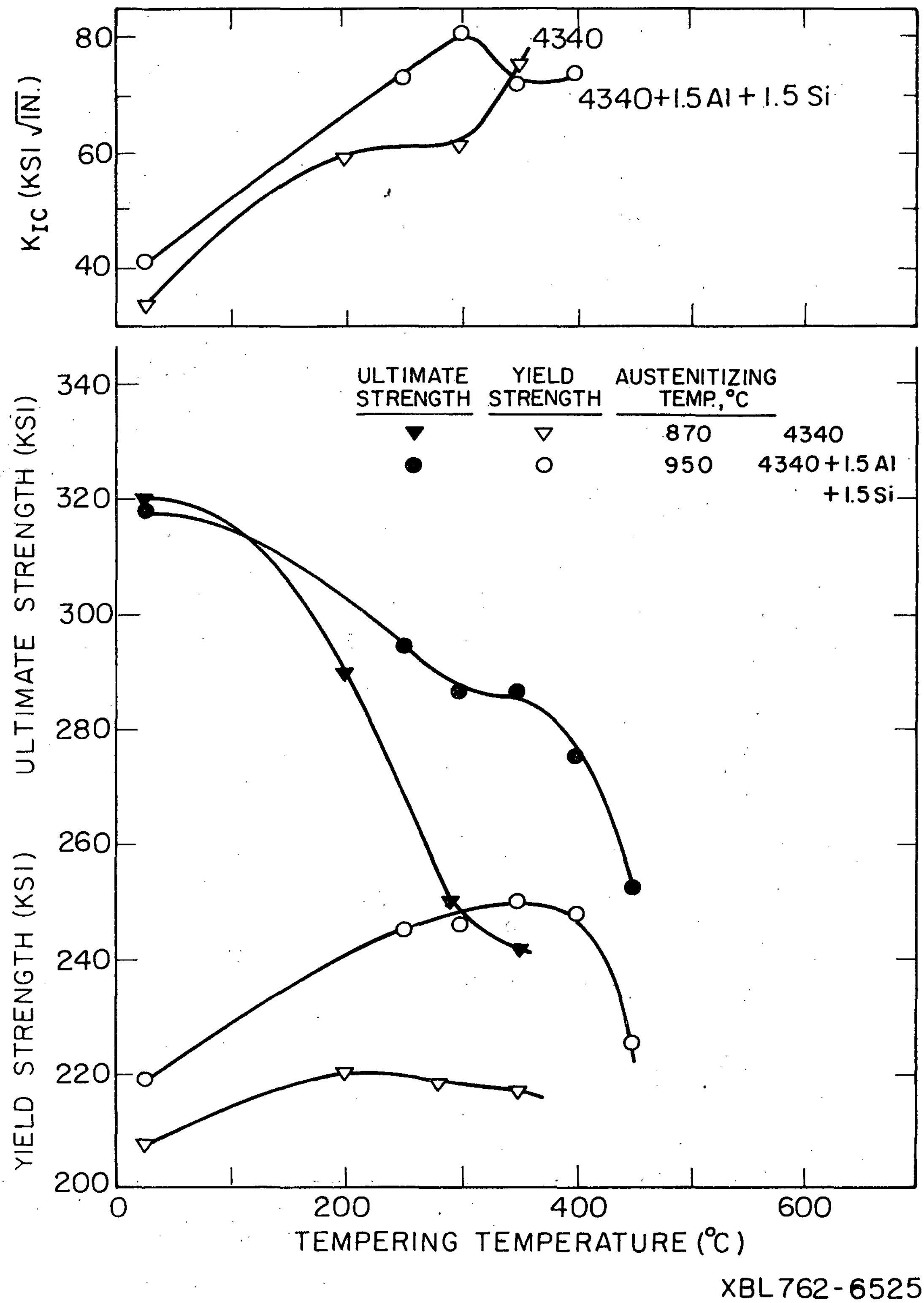
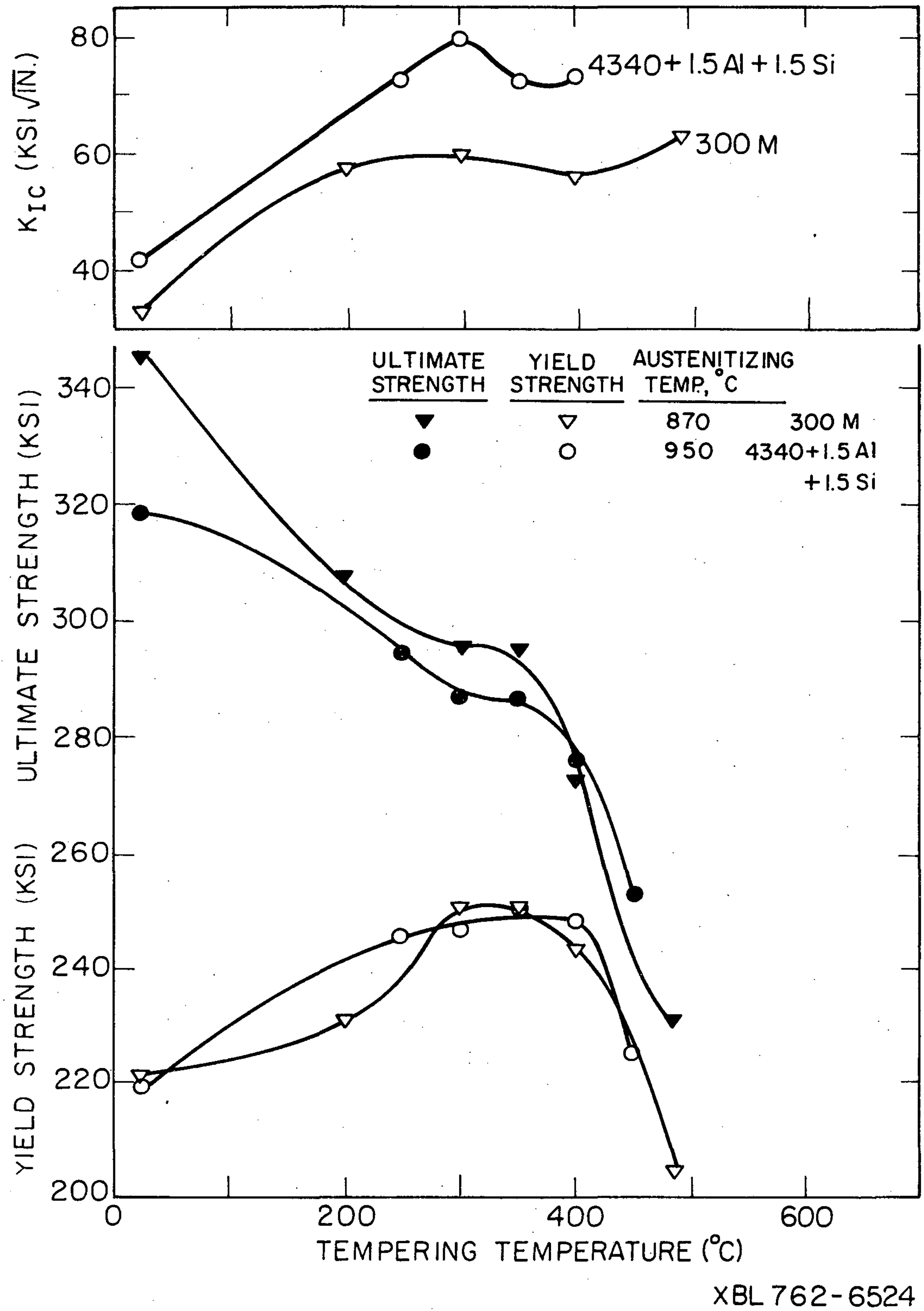

80
60
40
K_{IC} (KSI $\sqrt{IN.}$)
4340
4340+1.5 Al + 1.5 Si
340
320
300
280
260
240
220
200
ULTIMATE STRENGTH (KSI)
YIELD STRENGTH (KSI)
ULTIMATE STRENGTH
YIELD STRENGTH
AUSTENITIZING TEMP., °C
870
4340
950
4340+1.5 Al +1.5 Si
0
200
400
600
TEMPERING TEMPERATURE (°C)
XBL 762-6525

Figure 6.



80
60
40
K_{IC} (KSI $\sqrt{IN.}$)
4340+ 1.5 Al + 1.5 Si
300 M
ULTIMATE STRENGTH
YIELD STRENGTH
AUSTENITIZING TEMP, °C
870
300 M
950
4340+1.5 Al +1.5 Si
340
320
300
280
260
240
220
200
ULTIMATE STRENGTH (KSI)
YIELD STRENGTH (KSI)
0
200
400
600
TEMPERING TEMPERATURE (°C)
XBL 762-6524

Figure 7.

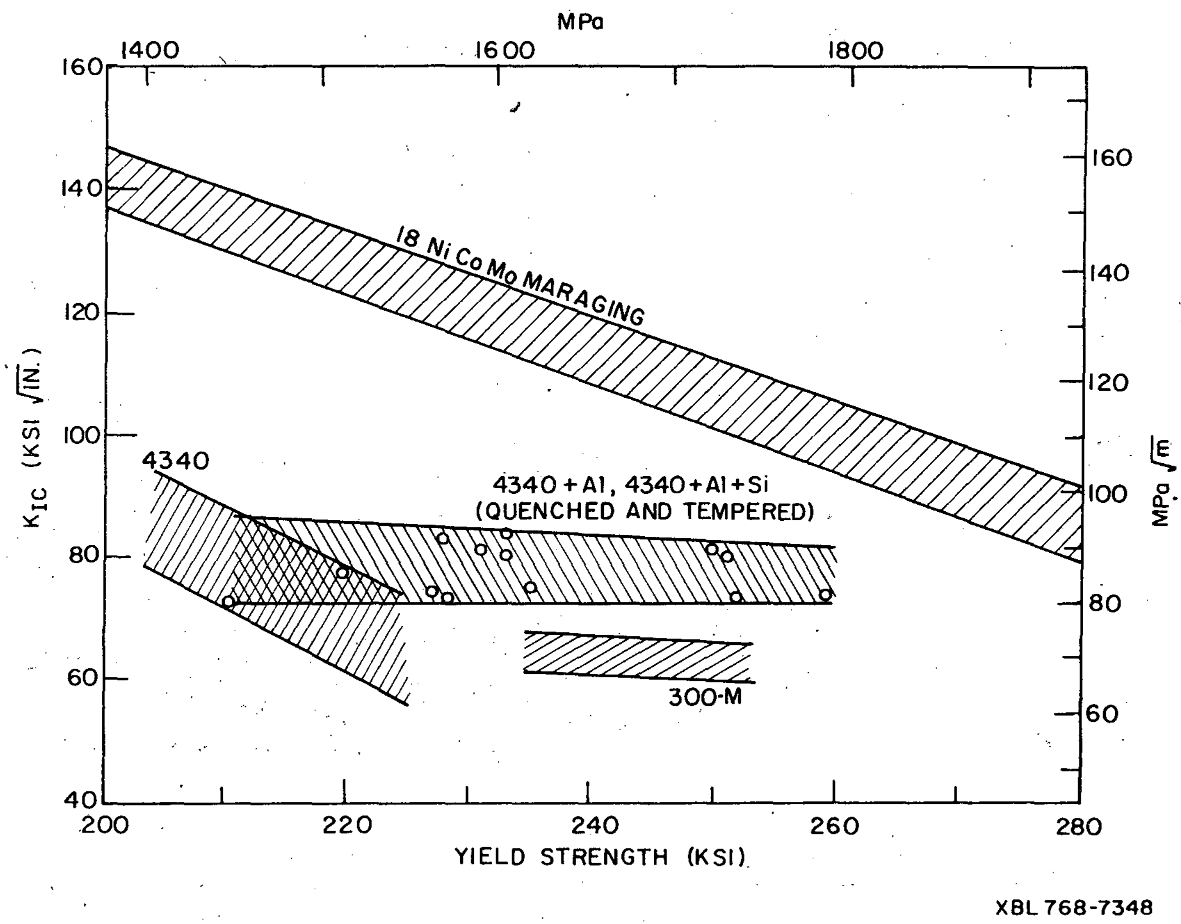

MPa
1400
1600
1800
160
140
120
100
80
60
40
160
140
120
100
80
60
K_{IC} (KSI $\sqrt{IN.}$)
MPa $\sqrt{m}$
18 Ni Co Mo MARAGING
4340
4340 + Al, 4340 + Al + Si
(QUENCHED AND TEMPERED)
300-M
200
220
240
260
280
YIELD STRENGTH (KSI)
XBL 768-7348

Figure 8.

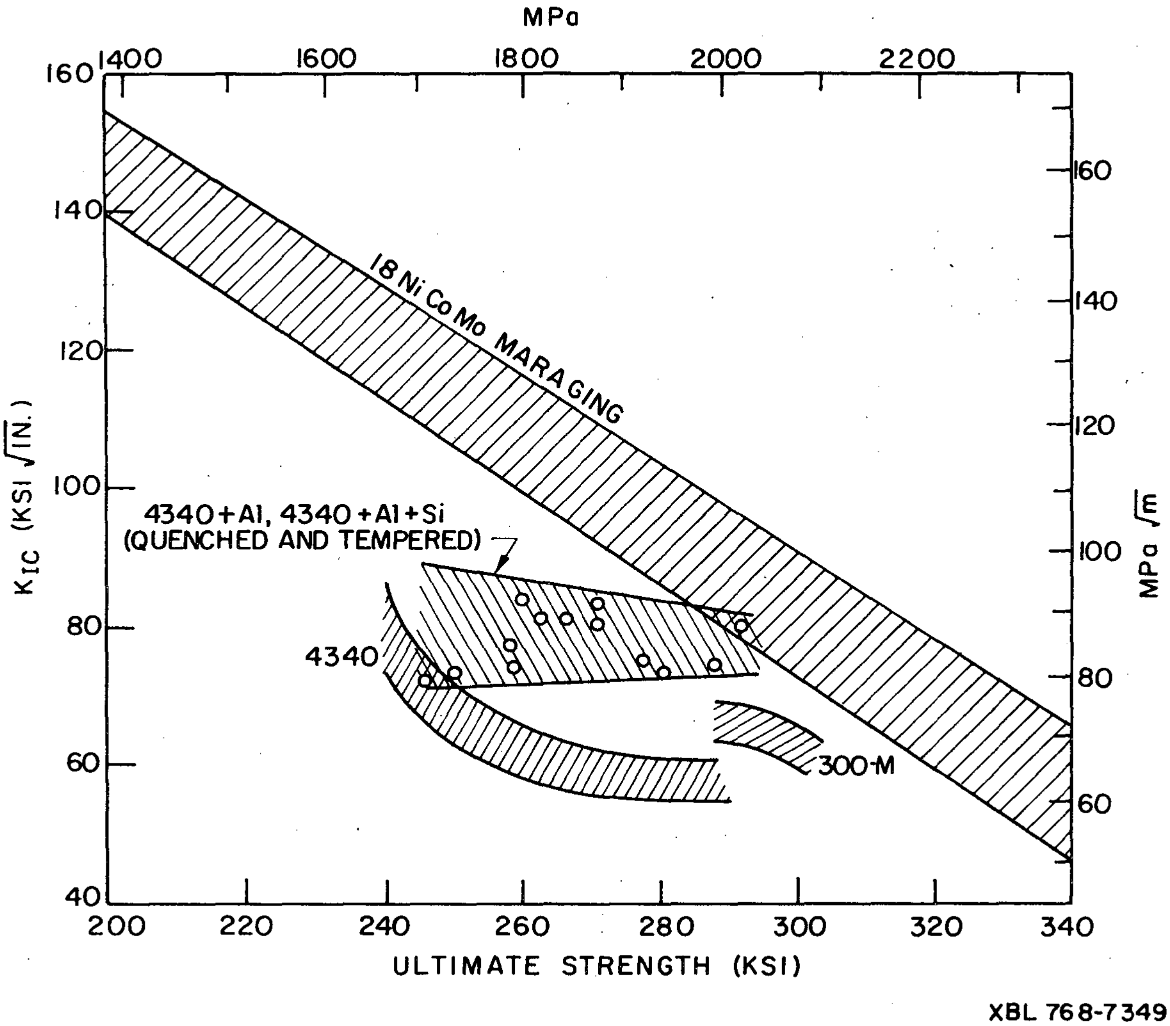

MPa
1400
1600
1800
2000
2200
160
140
120
100
80
60
40
160
140
120
100
80
60
18 Ni Co Mo MARAGING
4340+Al, 4340+Al+Si
(QUENCHED AND TEMPERED)
4340
300-M
K_{IC} (KSI $\sqrt{IN.}$)
MPa $\sqrt{m}$
200
220
240
260
280
300
320
340
ULTIMATE STRENGTH (KSI)
XBL 768-7349

Figure 9.

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