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TOUGHNESS OF LATH VERSUS PLATE MARTENSITES

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Two general forms of martensite occur in iron-based alloys.[1] Lath martensite is characterized by a microstructure composed of many similar sized laths arranged in a parallel fashion to make up a packet. Several packets are generally found in a single austenite grain. In contrast, plate martensite develops in a non-parallel fashion and neighboring plates vary considerably in size. The substructure of the lath consists of a high density of tangled dislocations while that of plate martensite is made up of twins and/or dislocation tangles.

The differences found in the morphology and dislocation substructure of the two forms of martensite has led many past investigators[2,3] to the belief that differences in the mechanical properties and particularly in the fracture resistance should exist also. Although crystallographic analysis[5] and microstructural evidence[1,6] for reduced ductility and susceptibility to microcrack formation in plate martensite structure have been given, no conclusive evidence has yet been offered to show that either the lath or the plate morphology possessed the higher fracture toughness. The present study was initiated in order to resolve this question.

One Fe-Ni composition which clearly forms lath martensite (24% Ni), one which forms the plate morphology (32% Ni) and one which falls between

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the two structures (28% Ni) were selected for study. Titanium and aluminum amounting to 0.10 and 0.05 wt.% respectively were added to combine with certain of the interstitial and metalloid elements normally present in 99.9+% iron and nickel.* This precaution was taken because these elements are known to cause serious degradation to the fracture toughness if left as free solutes or if allowed to combine with iron (e.g. FeS).[7] In each alloy the C+N+O content was less than 0.008%; S was less than 0.004% and P less than 0.005%.

The choice of the carbon free Fe-Ni system for investigation of the mechanical behavior of the two martensites was principally made so as to avoid those complicating factors associated with carbon partitioning and precipitation and carbide interaction with dislocations and grain boundaries. If present, these factors could easily mask the role played by the martensite morphology alone, However, one disadvantage resulted in not being able to use the compact single-edge-notch tension specimen that is normally used to measure fracture toughness. These specimens became experimentally infeasible to apply because of the very high fracture toughness-yield strength ratio of the Fe-Ni alloys. (Rough calculations showed that specimens in excess of several inches in thickness were required in order to achieve plain strain conditions.) Instead, standard Charpy V-notch specimens were impact tested and from the upper shelf energy levels, K_{IC} fracture toughness values were calculated using a correlation for low strength steels introduced by Rolf, Barsom and Gensamer.[8]

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*Note: The Ti and Al added to the 24, 28 and 32% Ni alloys combined with the impurities to form second phase particles with interparticle spacing of 50.5, 54.5 and 52.2 μm respectively. This variation in inclusion content between alloys was not considered significant with respect to the relative mechanical properties obtained.

Figure 1 shows the microstructures produced by each of the three compositions when austenitized at 1000°C and quenched to LN temperature. The lath martensite of the 24% Ni alloy and the predominantly lath martensite of the 28% Ni alloy are shown in Figs. 1a and b. The 24% Ni alloy contained no retained austenite when examined by X-rays,[9] however, the 28% Ni alloy and the 32% Ni plate martensite alloy (Fig. 1c) contained 5 and 10% austenite respectively for each of three austenite grain sizes ranging from 100 to 10 μm. The 100 μm grain size was obtained in each alloy by austenitizing at 1000°C for 2 hr; 25 μm at 800°C for 2 hr; and 10 μm by cycling three times for 1 hr at between 650 and 625°C. Standard Charpy V-notch specimens and flat 3.2 mm (0.125) in. × 6.4 mm (0.250 in.) tensile specimens of 25.4 mm (1 in.) gauge length were machined from heat treated blanks.

Figure 2 shows the Charpy impact toughness plotted versus the yield strength for the three sets of alloys at room temperature. As can be seen, each of the alloys experienced a decrease in yield strength and an increase in Charpy impact toughness as the grain size was increased. This behavior is similar to the increase in fracture toughness experienced in 4340 low alloy steels[3] when high austenitizing temperatures were used to promote austenite grain growth.[*] Also, note the lower level of impact toughness produced in the 32% Ni plate martensite alloy compared to the 24% Ni lath martensite alloy. Besides morphology, these two alloys also differ in their Ni content as well as in the amount of retained austenite. Each of these factors can contribute to the impact toughness of the alloys.

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[*] Note that Lai et al.[3] found the Charpy impact energy to decrease rather than increase with increasing grain size, but this was thought to have resulted because the data was obtained at room temperature where the impact transition occurs for 4340.[4] Toughness comparisons between alloys should only be made using upper shelf energy values.

Plotted in Fig. 3 are two curves which show the role played by retained austenite on the impact toughness and yield strength of the 32% Ni alloy with a grain size of 100 μm. The different amounts of retained austenite were obtained by quenching to different temperatures below the Ms. The extrapolated values at zero percent austenite from Fig. 3 can then be used to correct the Charpy toughness-yield strength curve in Fig. 2. Likewise a similar correction can be made for the 28% Ni alloy. The corrected curves are shown dotted in Fig. 2. Note that the plate martensite morphology still shows a lower level of toughness compared to the lath martensite structures.

Nickel content, the other parameter which varies between the alloys is known to greatly affect the toughness of Fe alloys. The above alloys vary in Ni content from 24 to 32% Ni. Figure 4 shows how the Charpy energy and yield strength vary with Ni content with the austenite grain size held constant at 100 μm. In the lath martensite composition range from 8 to 24% Ni,[10] the yield strength increases and the Charpy energy slowly decreases as nickel content is increased. This result is primarily due to solid solution strengthening of the BCC lattice.[11] Beyond 24% Ni where plate martensite beings to form, the yield strength begins to decrease as was also found by Speich and Swann.[11] Part of this decrease is due to the retained austenite in these alloys but when corrected for its presence, the 28 and 32% Ni alloys containing plate martensite still shows a decreasing yield strength with increasing Ni. This result suggests that the presence of plate martensite in the structure lowers the yield strength but without a corresponding increase in the impact toughness as occurs with increasing amounts of retained austenite (Fig. 3).

In other words, a lower level of impact toughness results for comparable strength levels for plate martensite structures.

For low strength alloy steels the Rolfe, Gensamer, Barsom[8] empirical relationship between plane strain fracture toughness (K_{IC}) and Charpy V-notch impact toughness can be used.

$$\left(\frac{K_{IC}}{\sigma_y}\right)^2 = \frac{A}{\sigma_y}\left(CVN - \frac{\sigma_y}{B}\right)$$

where A = 5, B = 20 when K_{IC} and σ_y are given in ksi$\sqrt{\text{in.}}$ and ksi and CVN in ft-lbs units.

In Fig. 5 the calculated K_{IC} is plotted against the yield strength and shows that the fracture toughness of lath martensite should also be superior to that of plate martensite for comparable strengths.

Causes for the higher fracture toughness of the lath martensite can be suggested, such as its more uniform substructure and the absence of twins. Kelly and Nutting[5] have suggested that a decrease in ductility should result in plate martensite structures containing internal twins because the available deformation systems are in effect reduced by a factor of four. In addition, deformation twinning is frequently found to occur where units of plate martensite forming at angles to one another impinge. Marder and Benscoter[6] show examples of microcracking occurring at such impingement points in an Fe-1.4%C alloy.

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Figure Captions

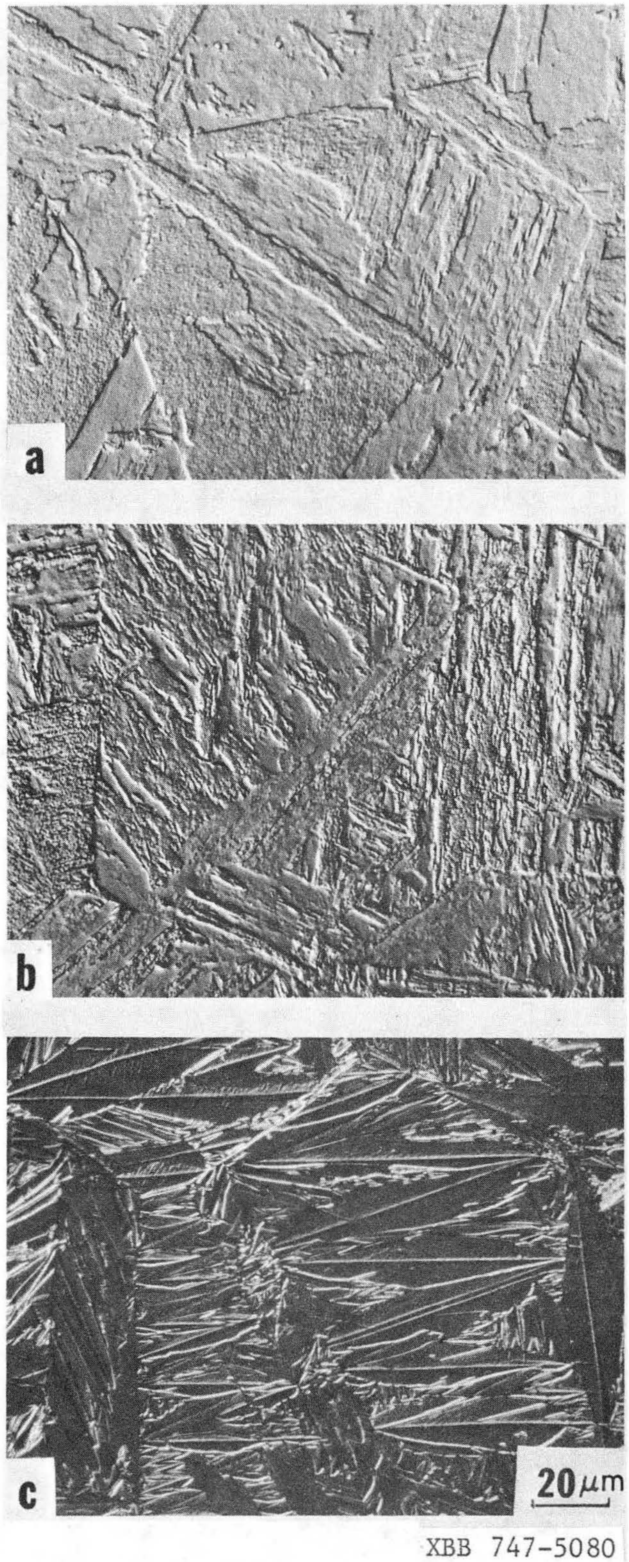
Fig. 1. Light micrographs of 1000°C austenitized and LN quenched (a) Fe-24% Ni (b) Fe-28% Ni, (c) Fe-32% Ni.

Fig. 2. Charpy impact toughness versus yield strength.

Fig. 3. Yield strength and Charpy impact toughness versus retained austenite in Fe-32% Ni.

Fig. 4. Yield strength and Charpy impact toughness versus % nickel for a constant grain size of 100 μm.

Fig. 5. Calculated K_{IC} vs yield strength.



XBB 747-5080

Fig. 1

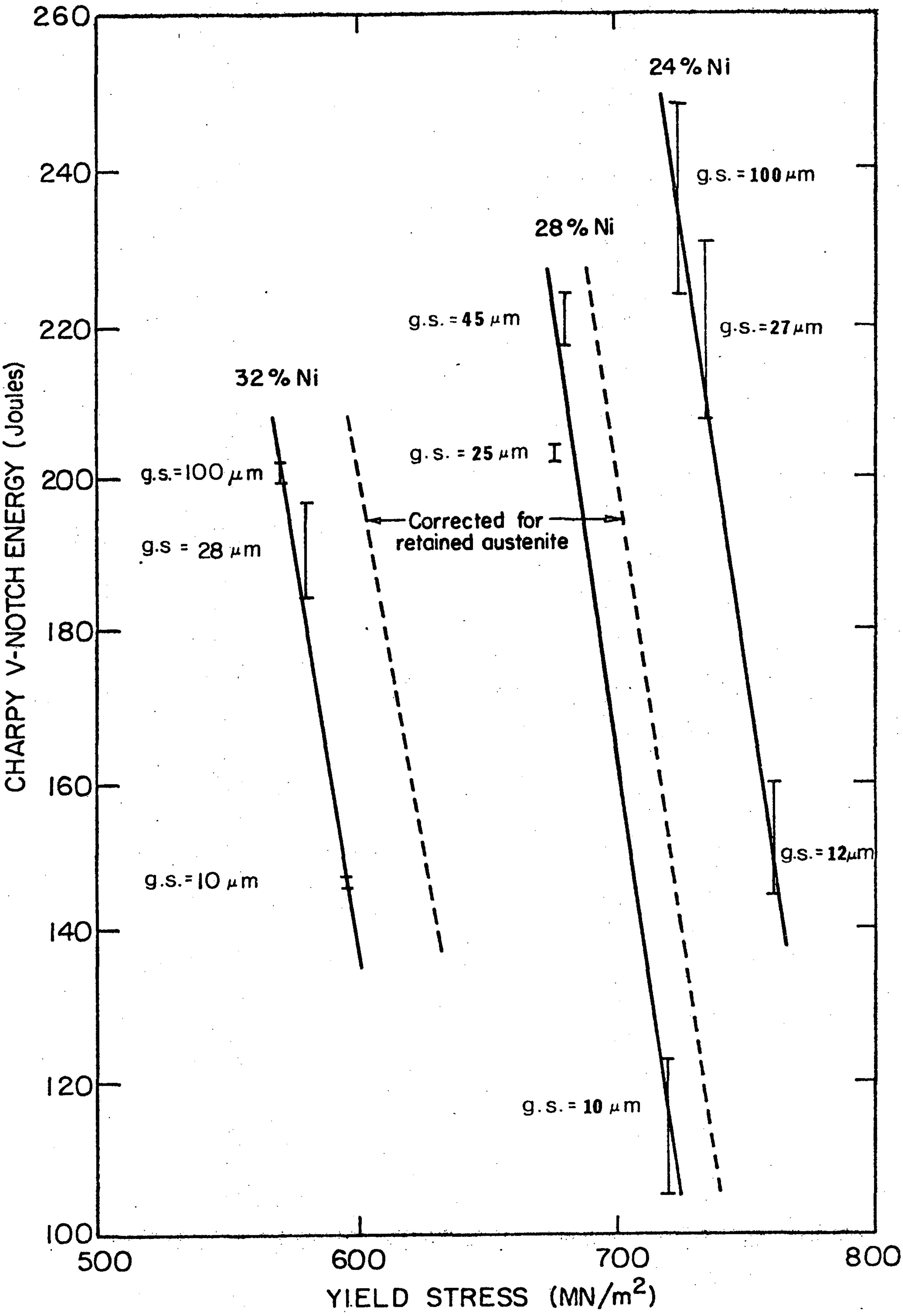
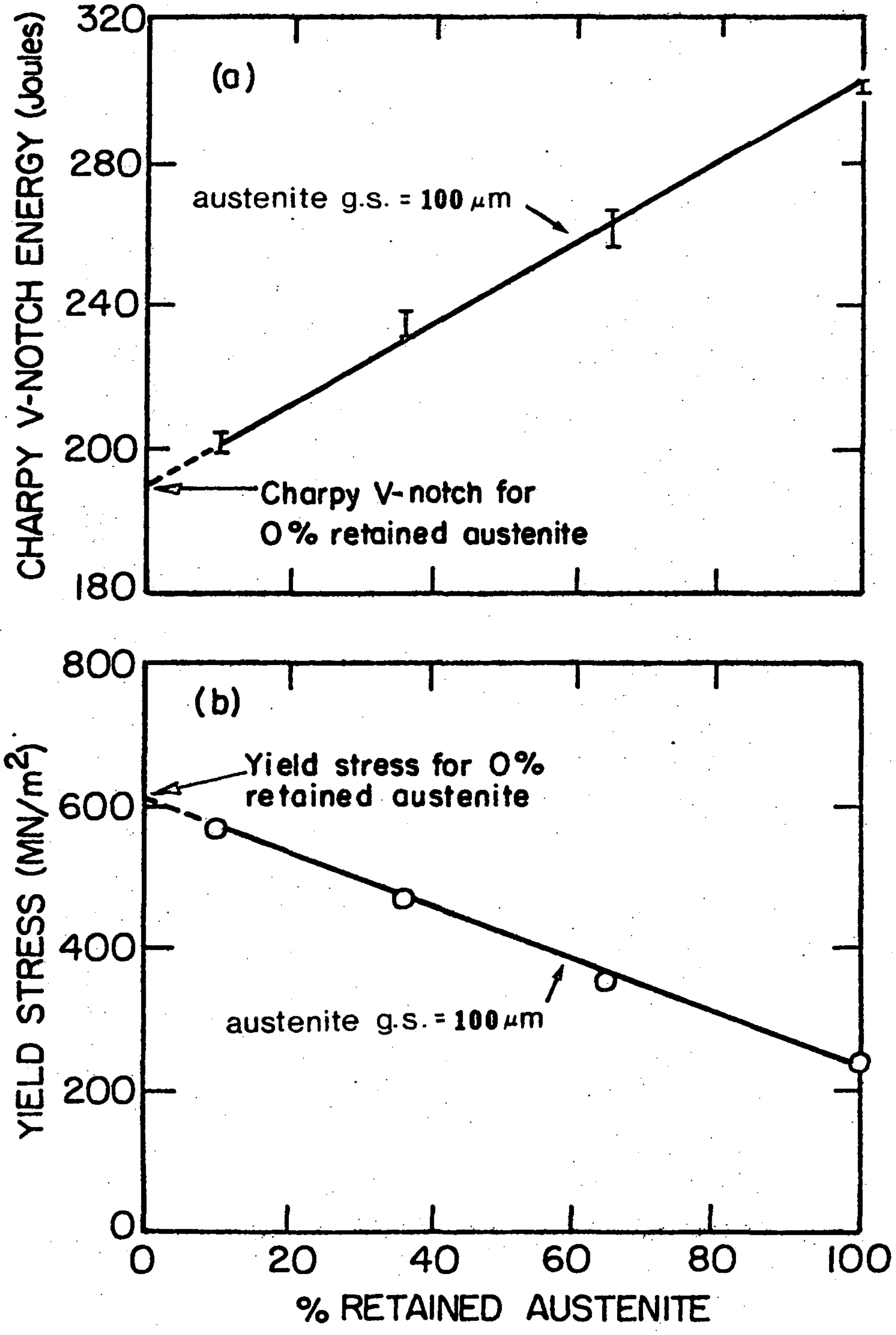


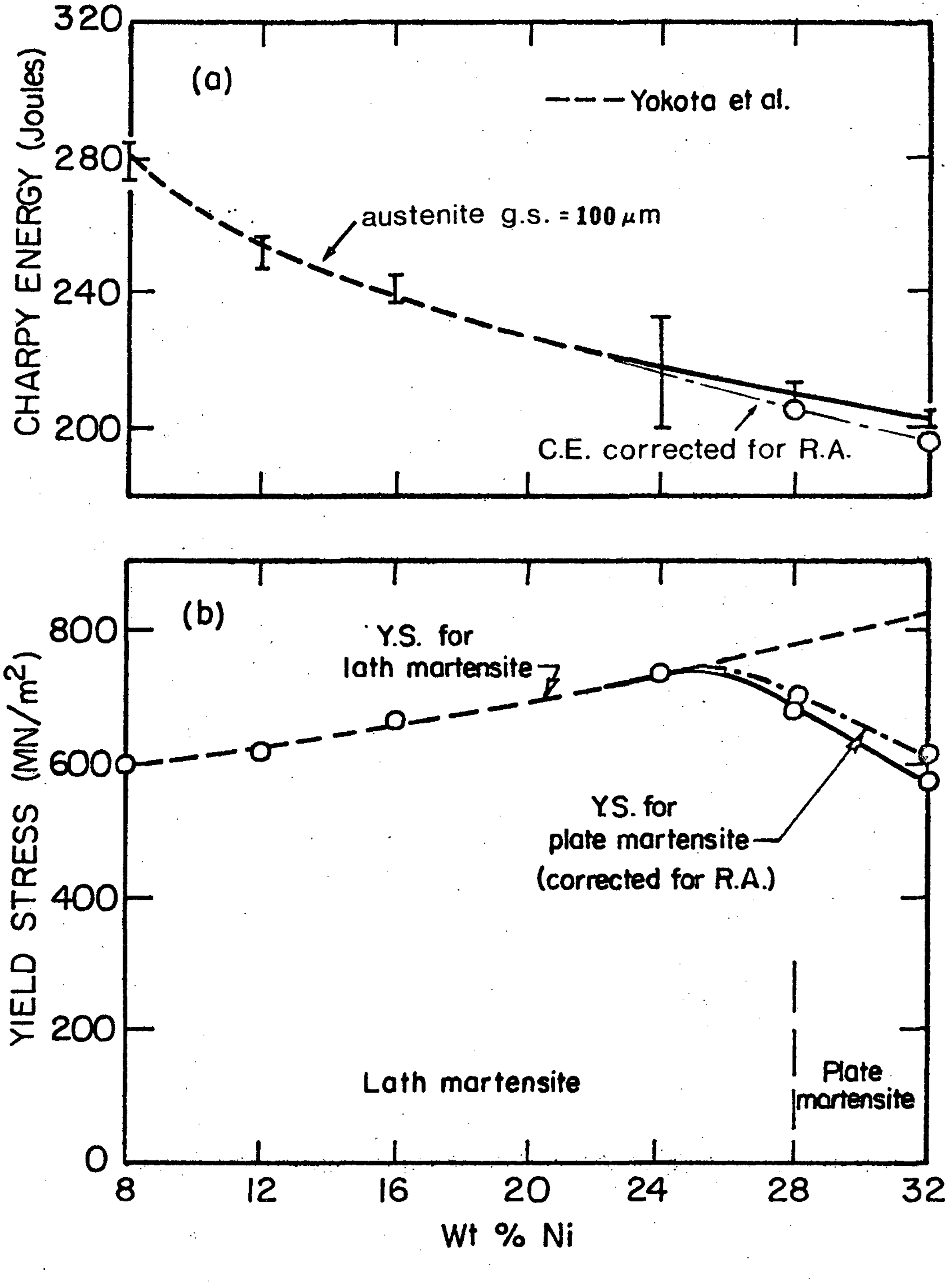
Fig. 2

XBL 749-7121



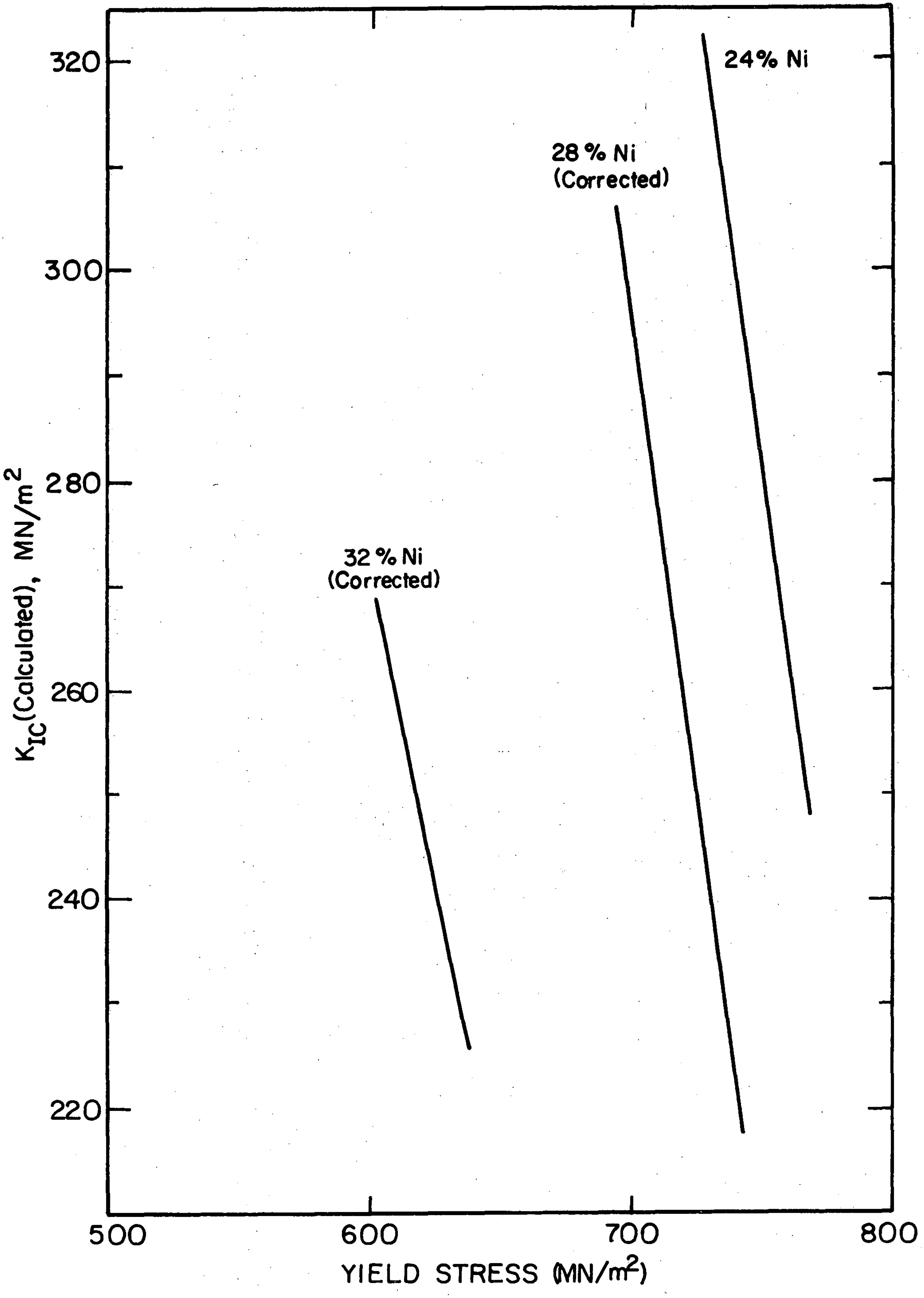
XBL749-7122

Fig. 3



XBL749-7123

Fig. 4


24% Ni
28 % Ni
(Corrected)
32 % Ni
(Corrected)
320
300
280
260
240
220
K_{IC}(Calculated), MN/m^2
500
600
700
800
YIELD STRESS (MN/m^2)

XBL749-7124