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"FURTHER DISCUSSION ON THE EVALUATION OF TOUGHNESS IN AISI 4340 ALLOY STEEL AUSTENITIZED AT LOW AND HIGH TEMPERATURES"

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Authors' reply to 'Discussion of "Evaluation of Toughness in AISI 4340 Alloy Steel Austenitized at Low and High Temperatures"* by W. E. Wood'

Robert O. Ritchie, Benjamin Francis and William L. Server

The discussion of our paper[1] (RFS) by Wood raises several interesting points which we are pleased to comment upon. Firstly, the analysis that we presented was specifically limited to stress-controlled fracture. Accordingly, we chose to examine structures which primarily failed by transgranular cleavage or intergranular fracture, namely oil quenched AISI 4340 steel i) after conventional austenitization at 870°C, and ii) after step-quenching at 870°C following austenitization at 1200°C (denoted by 1200-870°C structure). Since direct oil quenching from 1200°C leads to failure by ductile rupture in this alloy,[2,4,5] we obviously did not consider this treatment in our analysis. Furthermore, based on Wood's own data,[2,3] also reported by Lai et al.,[4] we selected the structure step-quenched from 1200°C because this structure showed the highest plane strain fracture toughness (K_{Ic}) for as-quenched 4340, yet the lowest Charpy V-notch impact energy. In such situations, where failure mechanisms can be considered to be largely stress-controlled, there is little doubt that the marked improvement in K_{Ic} from high temperature austenitizing treatments is *not* paralleled with a corresponding improvement in Charpy energy.

However, much of the data quoted by Wood in his discussion refer to direct quenched and quenched and tempered structures where principally non-stress controlled fracture mechanisms, i.e. ductile rupture, occur. Here the results are more difficult to interpret. Certainly there appear to be advantages in using high austenitizing temperatures for the lower strength, lower carbon content AISI 4130 and 4330 steels, provided the tempering temperature is less than 300°C

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*R. O. Ritchie, B. Francis and W. L. Server: Met. Trans. A, 1976, Vol. 7A, pp. 831-838.

(see Figs. 1 and 2 of Wood's discussion). However, for the higher strength, higher carbon content 4340 and 300-M alloys, high temperature austenitization at 1200°C yields inferior Charpy V-notch impact energies compared to the conventional 870°C treatment, regardless of the tempering temperature or whether the material is direct or step-quenched after austenitizing (Fig. 3 of Wood's discussion). Ferguson et al.[5] have shown similar results for a Consteel En25 alloy. Furthermore, recent data by Ritchie and Horn[5] on a purer heat of 4340 show a consistent trend of *increasing* K_{Ic} and *decreasing* Charpy V-notch impact energy with increase in austenitizing temperature (all structures in this case were direct oil quenched except the step-quenched 1200-870°C treatment). Regardless of the strain rate of testing, the toughness evaluated in sharp fatigue precracked specimens (i.e. K_{Ic} and K_{Id}) was seen to increase, whereas the toughness evaluated in blunt V-notched specimens (i.e. slow-bend and impact Charpy) was seen to decrease, for both as-quenched 4340 (Fig. 1) and 4340 quenched and tempered at 200°C (Fig. 2). Not only were the differences in Charpy energy much larger here, but failure in all structures was by a non-stress-controlled ductile rupture, except those austenitized at 870°C or step-quenched from 1200°C in untempered steel. Thus, although the large majority of these results are not applicable to analysis by the RFS model for stress-controlled fracture, very similar trends are evident. In fact, recent analysis,[5] incorporating a strain-controlled fracture model, has shown that the decrease in Charpy impact energy with increase in austenitizing temperature, for failure by ductile rupture, is consistent with a decrease in ductility (uniaxial and plane strain) which is almost invariably seen following high temperature austenitizing treatments (see, for example, Fig. 3).

Secondly, Wood, referring to his own data, states that "it is doubtful that grain size *per se* is responsible for the observed behavior, since specimens with identical grain size exhibited varied Charpy V-notch properties as well as varied plane strain fracture toughness properties." In our paper (RFS) we tentatively associated the increase in K_{Ic} at high austenitizing temperatures with larger grain size, through an increase in the characteristic distance[7] *for stress-controlled cleavage and intergranular cracking.* In the situations to which Wood refers, such brittle fractures are not likely, and there is, of course, no reason to expect grain size *per se* to affect particle-controlled ductile rupture. Nevertheless, the increase in K_{Ic} can still be considered in terms of an increase in characteristic distance through coarsening of the microstructure, only this case by an increase in particle spacing for ductile rupture from dissolution of carbides at higher austenitizing temperatures.[4,8,11]

Finally we wish to emphasize our cautions with regard to the general use of high temperature austenitization treatments. First, although the fracture toughness (K_{Ic}) can be increased by such treatments,[1-6,8-11] the inferior Charpy V-notch impact energies shown by existing data on untempered and quenched and tempered 4340,[1,2,4,5,9] 300-M[2], En25[6] and Fe/Cr/C[11] steels are undeniable. Secondly, almost without exception, the ductility of low alloy steels austenitized at high temperatures is drastically reduced compared to conventional 870°C treatments[1,2,4,5,8,11] (e.g. Fig. 3). Thirdly, the considerably larger grain sizes resulting from such high temperature austenitization increases the danger arising from impurity-induced embrittlement. This is not simply a problem, as Wood states, of classical temper embrittlement at temperatures way above the normal tempering temperature, but embrittlement occurring at temperatures very close to the commercially used tempering temperatures, i.e. tempered martensite embrittlement.[12] In this regard it is noticeable in Figs. 1-4 of Wood's discussion that above a tempering temperature of 300°C the conventional 870°C treatment yields superior Charpy impact energies for all steels examined (i.e. 4130, 4330, 4340, 300-M and D6-AC). Furthermore, Ferguson et al.[6] have shown for En25 that, above this tempering temperature, the toughness of structures austenitized at 1200°C is inferior to those conventionally austenitized in *both* K_{Ic} *and* Charpy impact tests.

Clearly, a complete understanding of the influence of austenitizing temperature on the toughness of low alloy steels is still lacking, but this is not surprising in view of the complex nature of the microstructural and mechanical effects involved. It is unrealistic, however, to conclude that the usefulness of high temperature austenitization treatments can be simply assessed by improvements in K_{Ic}, while less impressive Charpy V-notch and ductility properties are ignored (as, for example, in refs. 3 and 10). Hence, we can only repeat our original conclusion that, at present, high temperature austenitization must be regarded with caution, and, as Wood himself concludes, until much additional research is performed, it is unwise to consider such heat-treatment procedures for commercial application in low alloy steels.

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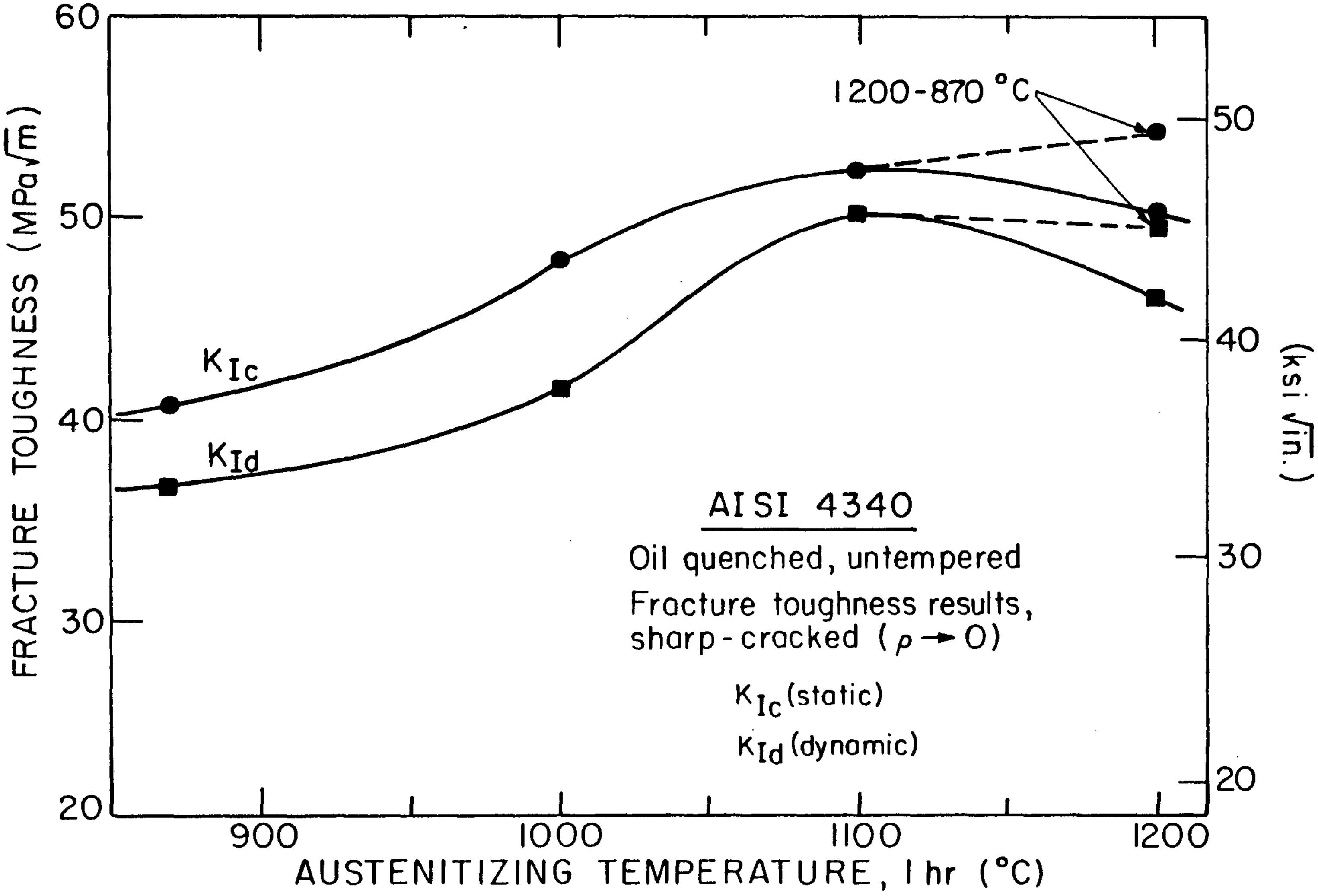
Figure Captions

Fig. 1 Influence of austenitizing treatment on the toughness of as-quenched, untempered AISI 4340 steel, showing toughness evaluation a) using sharp-cracked specimens for static K_{Ic} and dynamic K_{Id} tests, and b) using blunt-notched (root radius $\rho \approx 0.25$ mm) specimens for static slow-bend and dynamic impact Charpy tests. Also shown is evaluation of toughness using area under stress-strain curve from uniaxial tensile tests. All structures are direct oil quenched after austenitization, except the 1200-870°C treatment which was step-quenched from 1200°C by holding at 870°C before final oil quenching. (after Ritchie and Horn[5]).

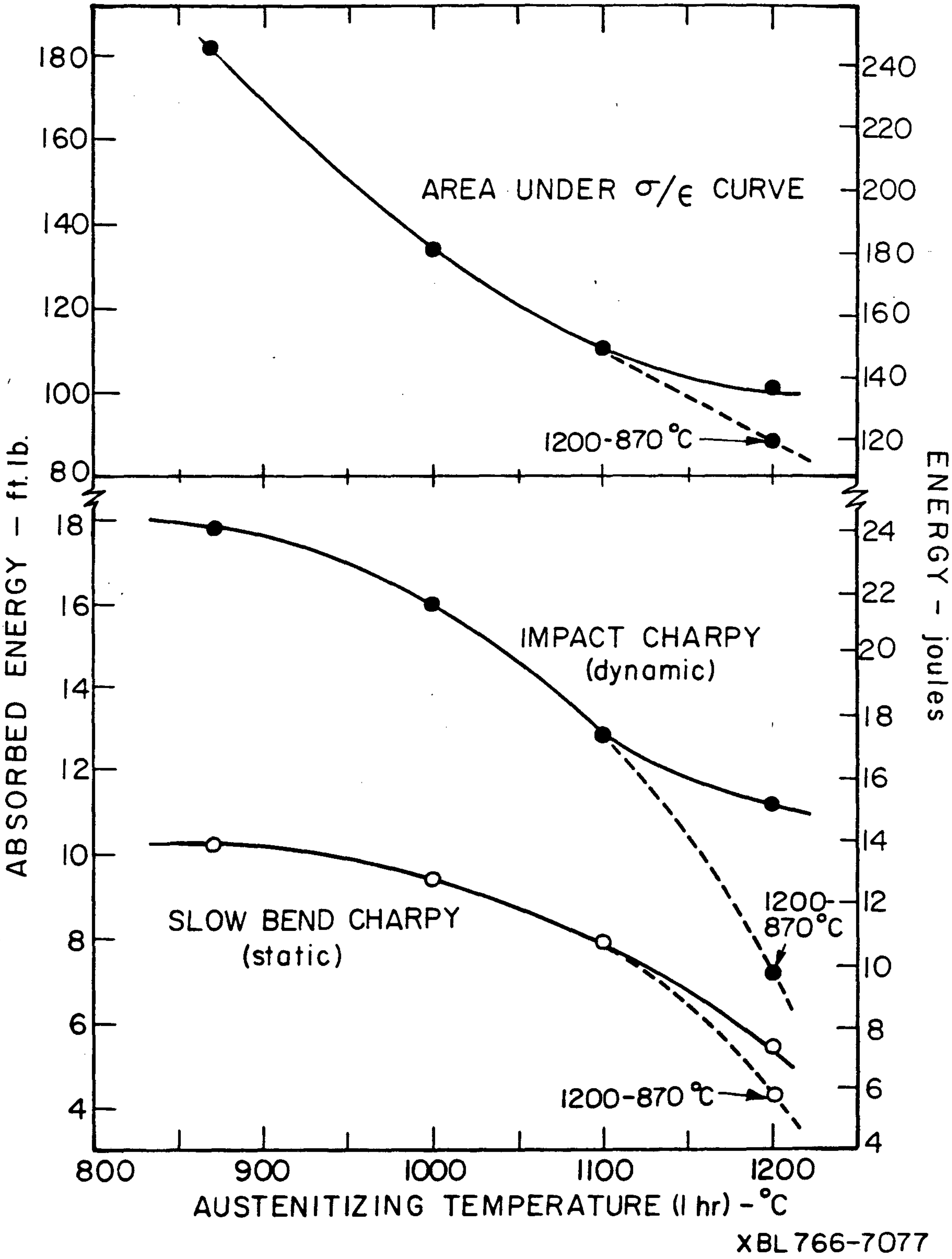
Fig. 2 Influence of austenitizing treatment on the toughness of AISI 4340 steel, oil quenched and tempered at 200°C, showing evaluation a) using sharp-cracked K_{Ic} tests, and b) using blunt-notched ($\rho \approx 0.25$ mm) slow-bend and impact Charpy tests, and area under stress-strain curves (after Ritchie and Horn[5]).

Fig. 3 Influence of austenitizing treatment on the uniaxial ductility (pct. elongation and reduction in area) of as-quenched AISI 4340 steel (after Ritchie and Horn[5]).



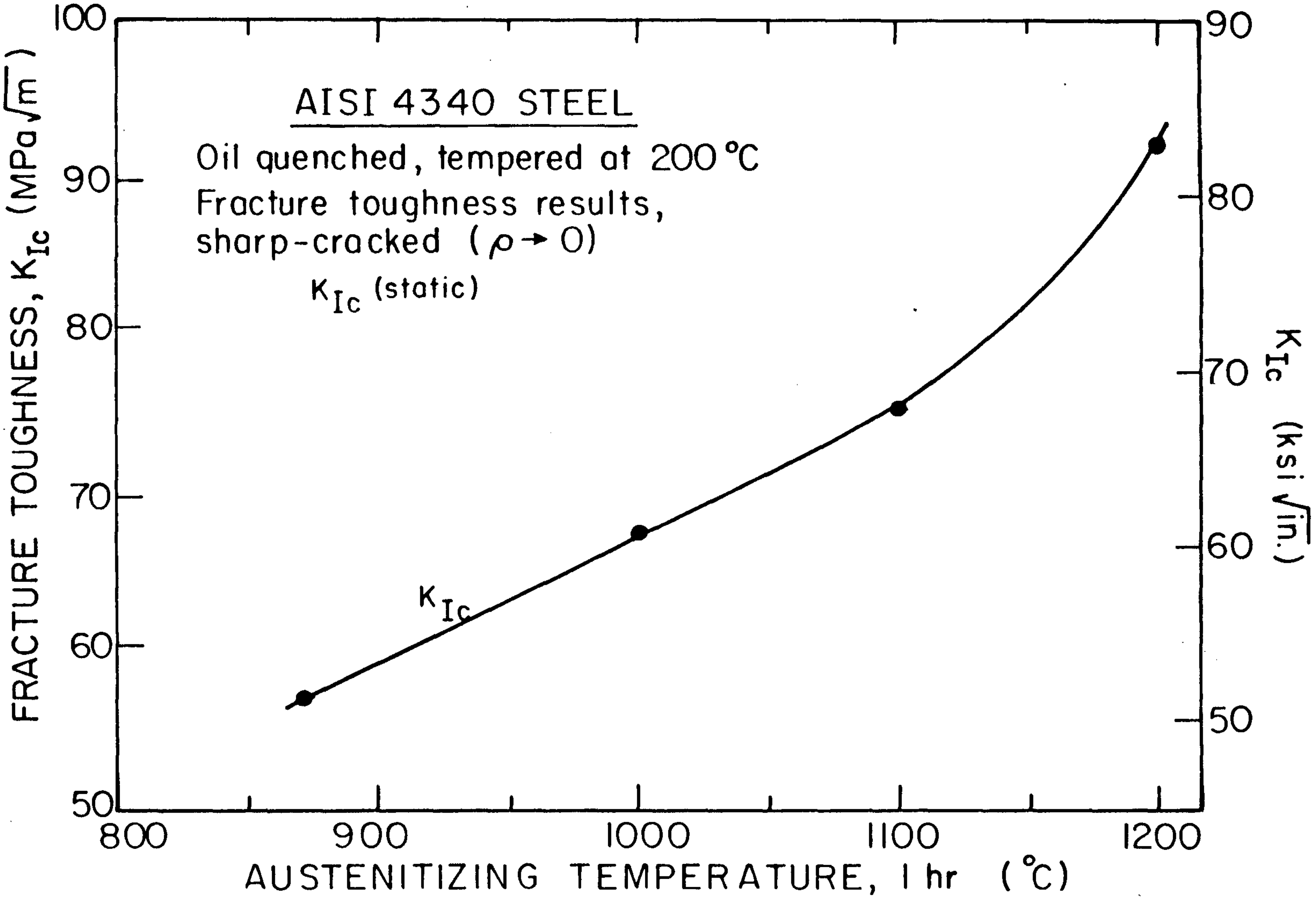
XBL 764-6725

Fig. 1a



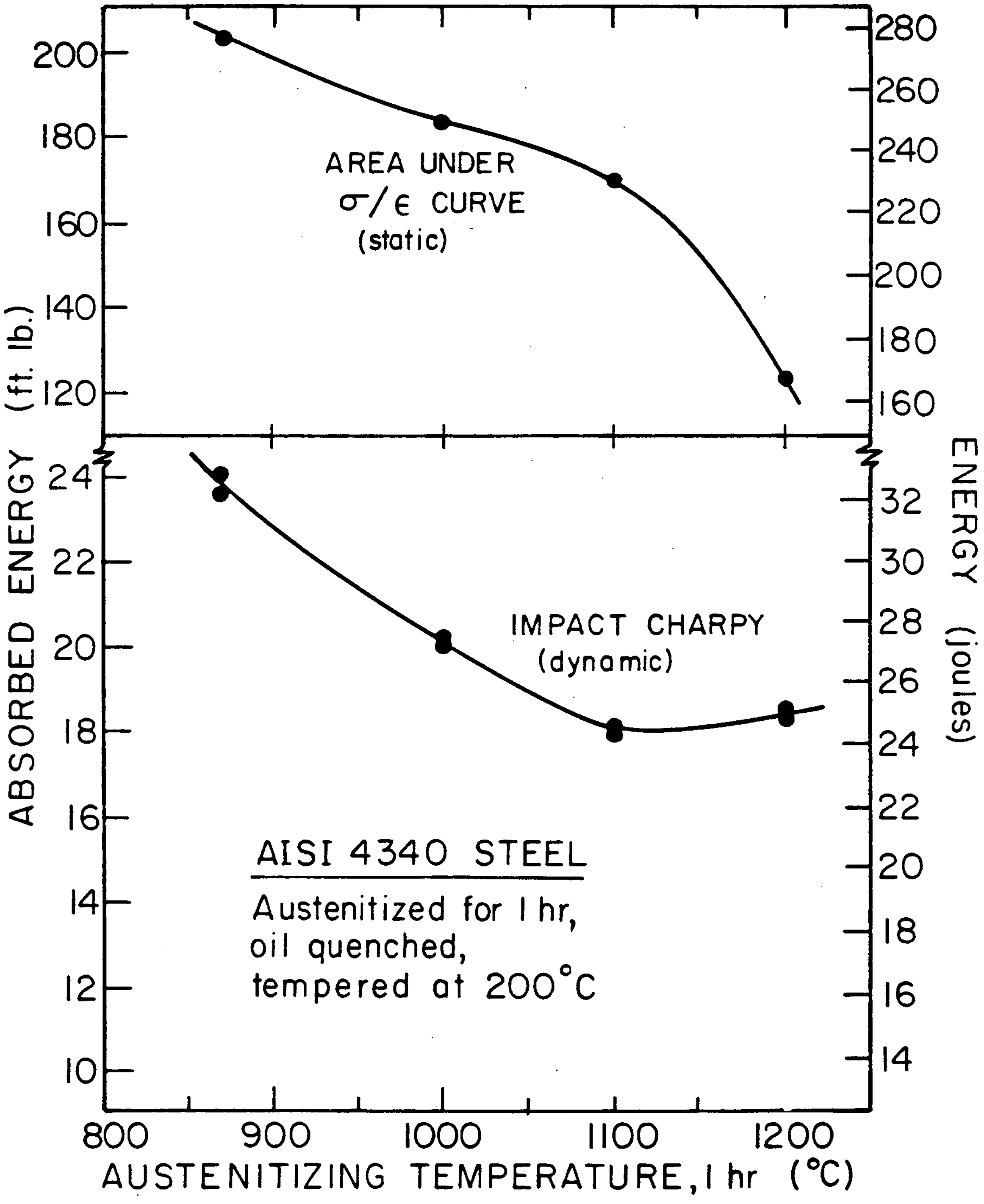
AREA UNDER σ/ε CURVE
IMPACT CHARPY
(dynamic)
SLOW BEND CHARPY
(static)
1200-870°C
1200-870°C
1200-870°C
180
160
140
120
100
80
18
16
14
12
10
8
6
4
240
220
200
180
160
140
120
24
22
20
18
16
14
12
10
8
6
4
800
900
1000
1100
1200
ABSORBED ENERGY – ft. lb.
ENERGY – joules
AUSTENITIZING TEMPERATURE (1 hr) – °C
XBL 766-7077

Fig. 1b



XBL 767-7212A

Fig. 2a



XBL767-7211A

Fig. 2b

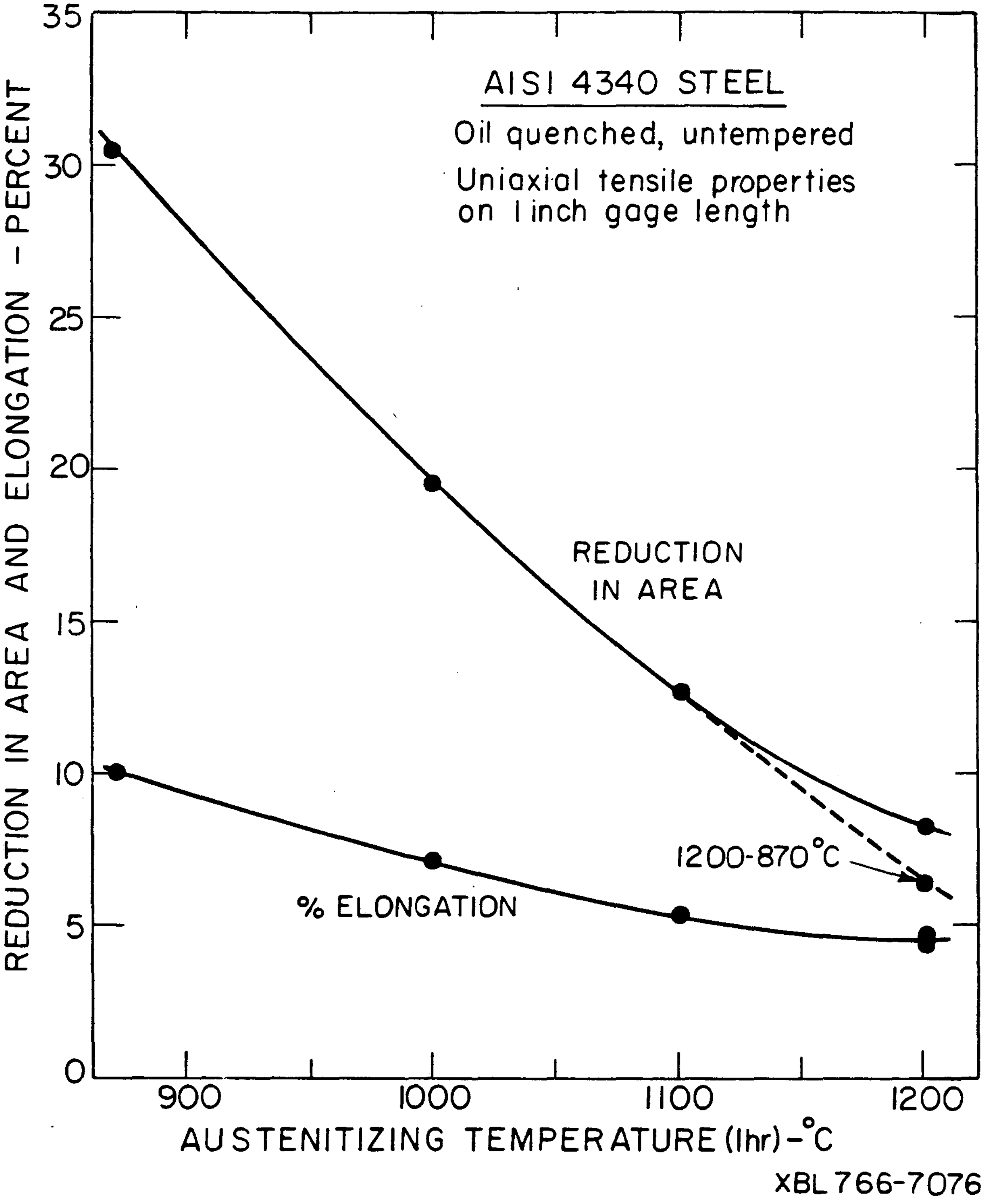

AISI 4340 STEEL
Oil quenched, untempered
Uniaxial tensile properties
on 1 inch gage length
REDUCTION IN AREA
% ELONGATION
1200-870°C
REDUCTION IN AREA AND ELONGATION - PERCENT
0
5
10
15
20
25
30
35
900
1000
1100
1200
AUSTENITIZING TEMPERATURE (1hr) - °C
XBL 766-7076

Fig. 3

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