Title

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Various authors[1,2] have attempted to make some quantitative correlation between uniaxial tensile properties (such as yield stress, work hardening rate, and ductility) and fracture toughness as measured in a notched specimen. The criterion for fracture is taken to be the attainment of a limiting value of stress or strain or energy at or near the crack tip. The predicted fracture toughness based on such models depends only on the mechanical properties as measured in a tensile test, i.e., materials with similar tensile behavior should have similar values of fracture toughness. The purpose of the present study was to investigate the relationship between fracture toughness and uniaxial tensile properties in a high strength steel and to study those microstructural features which might have a marked influence on this relationship.

Following the work of Raymond et al.[3] and Gerberich[4] a modified H-11 steel was chosen for the study. The composition is given as follows:

Fe	Cr	Mo	V	Mn	Si	N	C
bal.	4.85	1.34	0.50	0.22	0.84	0.30	0.21

Two separate processing treatments were used in the present study. One series of specimens was deformed by rolling 50% at three different temperatures (375°C, 410°C and 565°C) above the M_s temperature after austenitizing for 1/2 hour at 1050°C. A second series of specimens was isothermally transformed for 4 hours at the same temperatures. All specimens were double tempered for 2 + 2 hours at 565°C after the above treatments.

The tensile properties were determined with 1 in. gauge length sheet specimens. The fracture toughness was evaluated using 1 in. × 2 in. single edge notch specimens after Sullivan.[5] These were fatigue cracked prior to testing. Microstructural details of the crack path were investigated by bending the notched specimens and observing under a light microscope at high magnification.

The tensile properties of the two series are shown in Fig. 1. It can be seen that there is little variation in yield stress, tensile strength, elongation, and reduction in area within each series. Comparing the two series it can be seen that the material deformed 50% prior to transformations has higher values of yield and ultimate strength but that within a given series the tensile properties were essentially independent of processing temperature. The toughness values vary considerably within each series as is shown in Fig. 2. Figure 2 also shows the agreement between the present work and that of Gerberich et al.[3,4]

The fracture toughness of the material ausformed at 410°C is much higher than that for the other two deformation temperatures. Moreover the material deformed at 410°C fractures by an intermittent series of crack bursts and at ever increasing loads, whereas the other two cases fail in a brittle "catastrophic" manner once the crack is initiated at a relatively low stress. For the isothermal treatments the specimen processed at 410°C has the lowest toughness value. It was also observed that the fracture mode of the specimens isothermally transformed at 375°C and 575°C was very similar to that of the specimen ausformed at 410°C. Raymond et al.[3] attributed this behavior at the intermediate deformation temperature to the existence of two phases in the structure, i.e., low toughness tempered martensite and high toughness lower bainite. He suggested that the crack is arrested whenever it encounters the bainite.

It was felt by the authors that ausforming per se was not the source for the enhancement of toughness at a particular processing temperature since ausforming just raises the general strength level of steels. Rather, it is thought that the existence of lower bainite is responsible for the toughness peak. Examination of the TTT curve[6,7] shows that it is reasonable to expect bainite both when deforming at 410°C and when isothermally transforming at 375°C since ausforming should enhance the nucleation and growth of bainite and cause its appearance at a temperature higher than that when isothermally transforming. It is suggested that the isothermal 375°C treatment results in a two phase structure (tempered martensite and bainite) whereas the material deformed at 375°C is primarily tempered martensite. The material isothermally transformed at 410°C is tempered martensite and is therefore of relatively low toughness. The specimen isothermally reacted at 575°C contains pearlite which accounts for the low strength and high toughness observed.

Studies of the advancing crack tip revealed a marked difference between the material with high toughness (410°C ausformed, and isothermally transformed at 375°C and 575°C) and the material with low toughness (375°C and 575°C ausformed, and isothermally transformed at 410°C). Figure 3 shows a typical comparison between the crack in a material with high toughness and one in a specimen with low toughness. As can be seen the crack in the tough material is very blunt with a relatively large crack opening displacement while the crack in the low toughness material is very sharp. Although not shown here, it was also observed that the crack for the brittle case followed the carbide-matrix interface.

A replication of the fracture surface (Fig. 4) of the material deformed at 410°C shows that alternate regions of cleavage and dimpled rupture occur, as postulated by Gerberich.[4] Presumably the dimpled rupture occurs in the bainite.

This study has emphasized the necessity of considering the micromechanics of fracture, with due consideration to the immediate microstructural environment of the advancing crack tip. A tensile test involves bulk behavior of the material whereas crack propagation involves the microscopic behavior in the vicinity of a crack and its stress field. Since fracture involves the propagation of a local defect, it is not surprising to find that local variations in structure (which will be averaged out in a tensile test) have a direct controlling influence on the fracture toughness. In the particular case studied here, the fracture toughness was enhanced by the presence of a tough second phase whereas the tensile properties were little affected.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1 Variation of tensile properties with ausforming and isothermal transformation temperatures.

Fig. 2 Variation of fracture toughness with processing or transformation temperature.

Fig. 3 Comparison of crack in tough material to that in brittle material. Note difference in magnification.

Fig. 4 Replication of fracture surface of material deformed at 410°C showing alternate regions of cleavage and dimpled rupture. Magnification: ×10,000

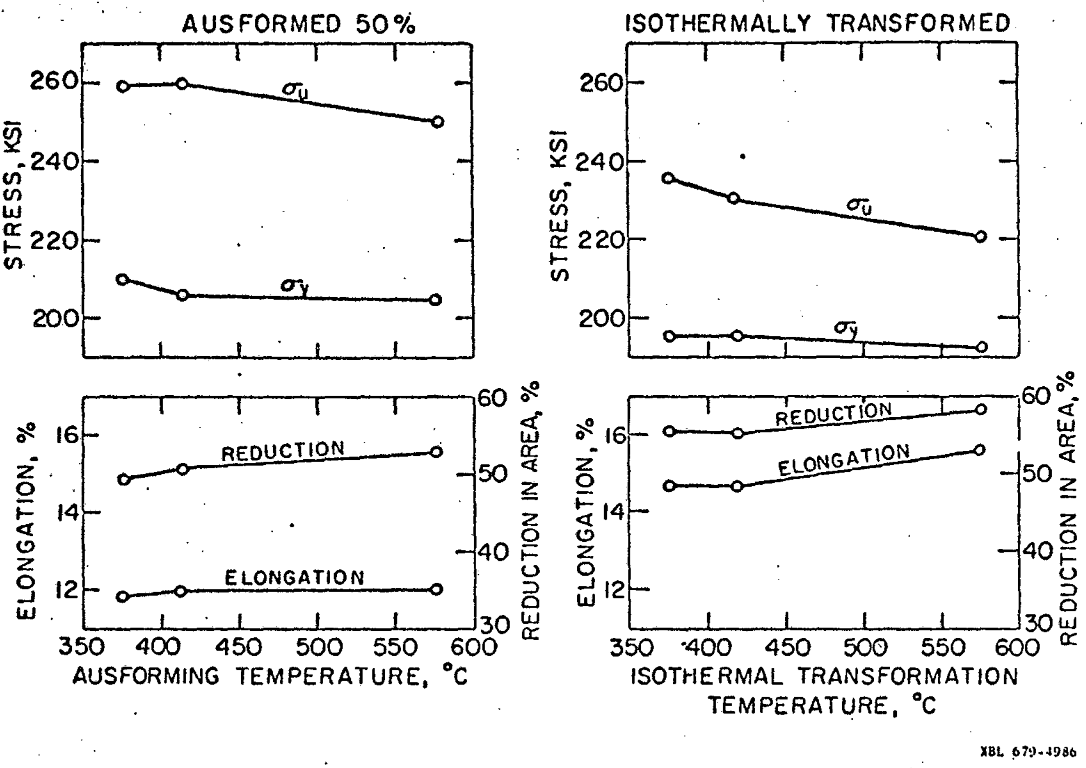
AUSFORMED 50%
ISOTHERMALLY TRANSFORMED
STRESS, KSI
260
240
220
200
σ_u
σ_y
ELONGATION, %
16
14
12
REDUCTION IN AREA, %
60
50
40
30
REDUCTION
ELONGATION
350
400
450
500
550
600
AUSFORMING TEMPERATURE, °C
ISOTHERMAL TRANSFORMATION TEMPERATURE, °C
XBL 679-4986

Fig. 1

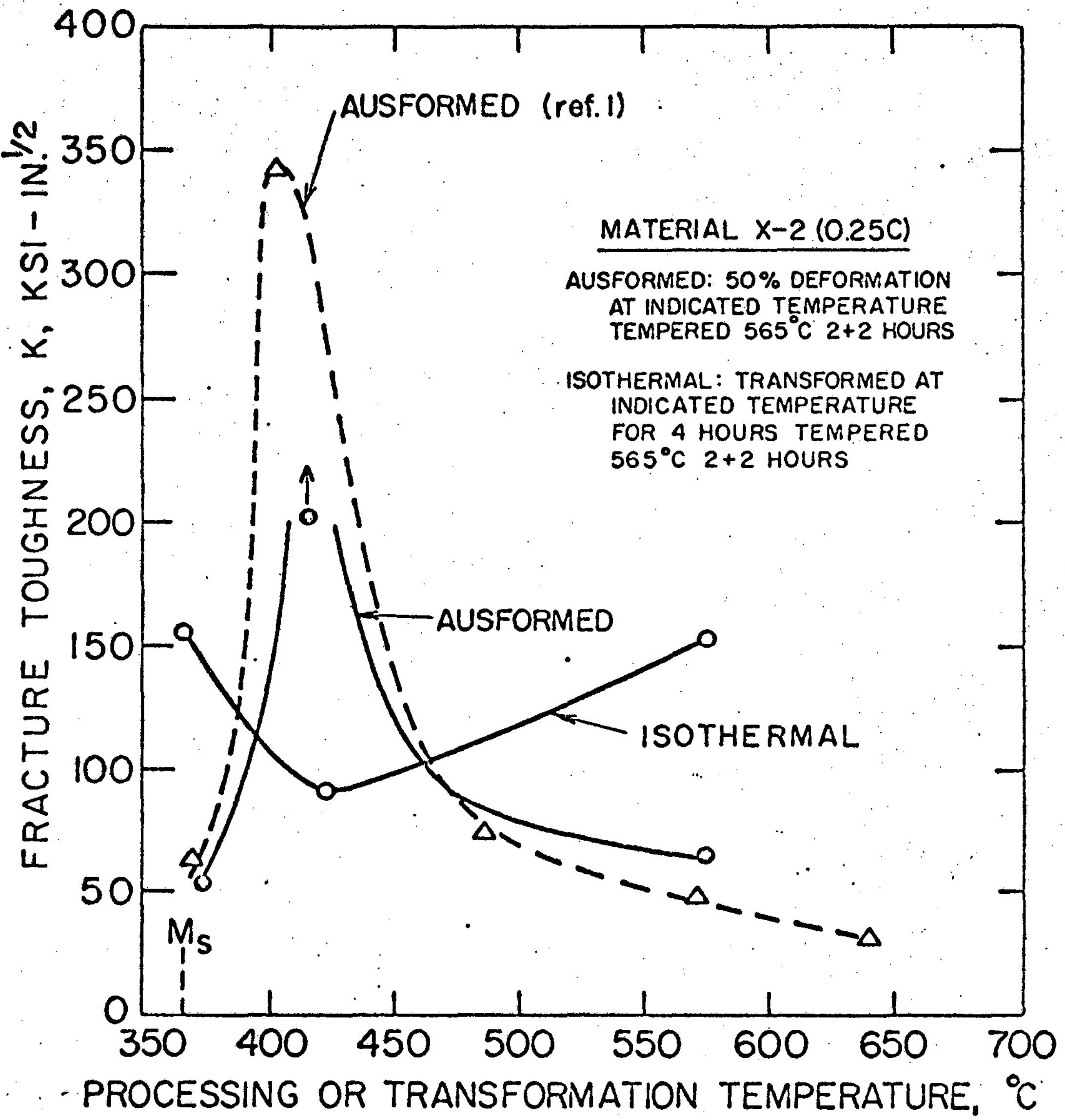

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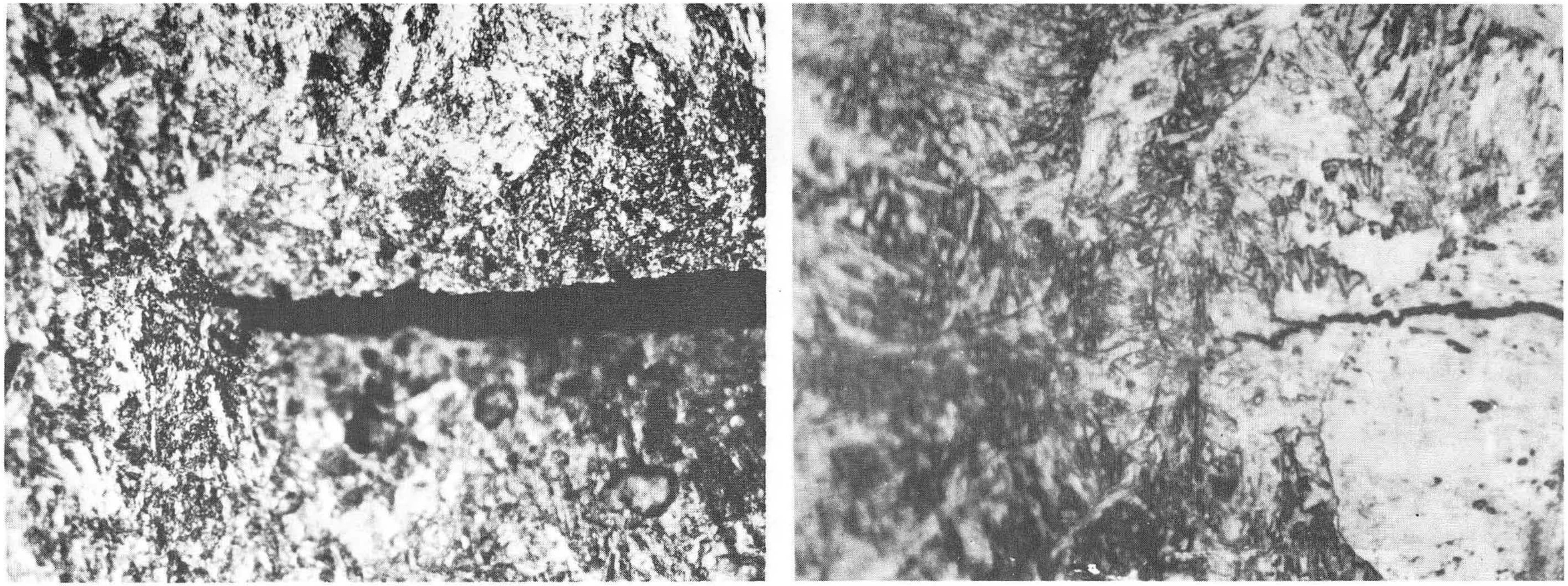
Fig. 2



XBB 670-5721

AUSFORMED AT 410°C 400X AUSFORMED AT 575°C 1600X

CRACKS IN AUSFORMED X-2

Fig. 3

XBB 679-5111-A

Fig. 4