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Recently,[1] it was shown that the strain-induced transformation of austenite to martensite during testing produced unusually good combinations of strength and elongation. The phenomenon, designated by the acronym TRIP, (TRansformation Induced Plasticity) was observed to extend to the 250,000 psi strength level. At these high strength levels, it is important to know if the ductility indicated by uniaxial tensile elongation is also evident under triaxial stress conditions such as those at a crack tip. This is particularly important in materials with complex microstructures where it has been shown[2,3] that elongation and reduction of area measurements may have little bearing on the strain-energy release rate or fracture toughness of a cracked plate. Some evaluations of both plane strain, K_{Ic}, and plane stress, K_c, fracture toughness were thus initiated.

MATERIAL AND TEST PROCEDURES

Preliminary results have been obtained on the three following alloy compositions:

Heat	C	Cr	Ni	Mo	Si	Mn
676-1	0.26	9.0	9.0	4.9	2.0	2.5
676-3	0.26	10.1	8.8	5.5	2.0	1.7
6711-3	0.20	13.5	8.8	2.9	2.0	2.0

The nominal heat treatment was to austenitize at 1200°C for 45 minutes, brine quench, reheat and deform the austenite above M_d (e.g. > 250°C). Subsequent testing at room temperature produced the TRIP phenomenon since M_d was greater than ambient.

For measuring plane stress fracture toughness, 2.75 inch wide single-edge notch (SEN) specimens, about 0.08 inches thick were utilized. Even though the SEN specimen is not commonly used for this purpose, previous data[4,5] on D6aC steel indicated that the SEN specimen did provide reasonable results. For example, in the toughest D6aC steel condition, 8 × 24 in. wide panels of the conventional center-notch configuration produced a K_c value of 237 ksi-in$^{1/2}$ from duplicate tests. From 12 tests of 3-inch wide SEN specimens, the average K_c value was 229 ksi-in$^{1/2}$. These two values are sufficiently close to give confidence in using the SEN specimen for a reasonable measure of K_c. Furthermore, it was desirable to use the SEN specimen because of its relative ease of fabrication and the greater amount of material through which slow crack growth can occur.

For measuring plane strain fracture toughness, a crack-line loaded sample of the type suggested by Mostovoy, et al.[6] was utilized. The half-height (H) of the specimen was 1.1 inches, the width (W) 2.2 inches, crack length (a) 0.5 inches, and thickness (B) 0.5 inches. Stress-intensity calculations were made from the collocation results of Srawley, Gross and Brown[7,8] for both SEN and crack-line loaded configurations. In all cases, specimens were pre-fatigue cracked prior to testing.

FRACTURE TOUGHNESS

Both uniaxial and fracture toughness properties are given in Table I. The general result is that for the thin sheet, the plane stress fracture toughness is about 250 ksi-in$^{1/2}$ for a 230 ksi yield strength material. This is comparable to maraging steel which has a K_c value of 270 ksi-in$^{1/2}$ at the same strength level. The fact that no plastic zone correction was made for the TRIP steel calculations would make this a conservative estimate.

For the thick plate, an obvious determination of plane strain fracture toughness was not possible at room temperature. A typical load-displacement curve at room temperature, as shown in Fig. 1, illustrates the difficulty. A definite slope change occurred at 93 ± 6 ksi-in$^{1/2}$ in all cases. The reduced slope after this point was constant and so plastic deformation does not appear to be the reason for this slope change. Furthermore, in one instance, cracking was audibly detected with coincidence of the first slope change. There was then a second slope change which could partially be due to plastic deformation. As the crack was stable between the first slope change and the deviation from linearity, there is some question as to whether 93 ksi-in$^{1/2}$ represents a realistic value of K_{Ic}. It may be noted in Table I that the deviation from linearity occurs at a reproducible value of 154 ± 1 ksi-in$^{1/2}$. In all of the room temperature tests, the crack was stable to a very high stress intensity factor. In one case the specimen was unloaded and additional fatigue cracking was performed to outline the previous slow-growth region. This procedure indicated that 0.4 inches of slow crack growth had taken place, and that a K value of 256 ksi-in$^{1/2}$ was reached without instability.

These observations indicate the plane stress fracture toughness to be very high in this 0.5 inch thick material.

Effect of Strain Rate

Strain rate effects have been observed in the uniaxial behavior of TRIP steel.[9] There also appears to be an effect on the resistance to crack propagation. For three orders of magnitude of testing speed, data are shown in Table I. Although the data are limited, there appears to be a definite decrease in toughness with increasing crosshead rate. It is significant that in the three faster tests, the fracture mode changed from a flat mode to a shear mode at instability. The slowest test, however, tore completely in a flat mode with no fast fracture instability. This is perhaps due to a gradual change from an adiabatic (fastest) to an isothermal (slowest) situation. If the heat transfer away from the crack tip was not rapid enough at the faster strain rates, it could possibly suppress the transformation. However, in all cases, a magnetic phase, presumably martensite, was detected on the fracture surface of all specimens. Thus, the exact reason for the strain rate sensitivity remains unclear.

Effect of Test Temperature

The thick plate was evaluated at -196°C and was found to fracture in a flat mode. From Table I, it is seen that K_{Ic} (139 ksi-in$^{1/2}$) was very high for the 230 ksi yield strength of this 0.5 inch thick plate. However, following a conservative criterion, this measurement of toughness may not represent a completely plane strain condition since the plastic zone approaches one-third the thickness of the plate. Clearly, thicker plates must be used to evaluate the K_{Ic} of these steels. Macroscopic views of specimens fractured at room temperature and -196°C are seen in Fig. 2. Even though flat fracture is evident at -196°C, delamination allowed internal shear lips to develop. A considerable amount of slow crack growth occurred prior to fracture instability and the plane stress value might even be high at -196°C. The other curious feature of the low-temperature tests was that no initial slope change was detected in the load-displacement curves as had been the case for the room temperature tests (Fig. 1). It is difficult to conceive of $K_{Ic-196^\circ C}$ being greater than $K_{Ic\ R.T.}$ unless, perhaps, the amount and effect of the transformation product plays a key role. This anomaly requires further investigation over a wider range of temperature and specimen thickness before definite conclusions can be drawn.

FRACTURE APPEARANCE

It was indicated above that slow crack growth occurred in a flat mode. This should not be confused with the small flat triangle that is normally associated with the transition from plane strain to plane stress. In the present case, as illustrated in Fig. 3, the crack slowly grew to a substantial length (~ 0.5 inches) in a completely flat mode and then rapidly fractured in shear. The sharpness of this slow growth mode is illustrated in the side view of Fig. 3(b). It is normal to associate such a flat fracture mode with brittle fracture but the high toughness values in Table I discounts this possibility. Moreover, a fracture surface replica taken from a similar flat area indicates in Fig. 4(a) that the fracture mode is ductile rupture. Similar dimples or microvoids were observed on the thick samples tested at room temperature. For the tests at -196°C, fractographs indicated two fracture modes. In Fig. 4(b), dimple rupture was evident. In Fig. 4(c), river line markings indicative of cleavage occurred almost as often as the dimpled rupture mode. A tentative explanation of the fractographic observations is that the strain-induced martensite is fracturing by microvoid coalescence at room temperature but by cleavage at -196°C. The dimpled rupture observed at -196°C could be associated with the untransformed austenitic phase.

In summary, both the plane stress and plane strain fracture toughness of TRIP steels appear to be high. Thus it would appear that the high ductility observed under uniaxial conditions is also manifested under triaxial conditions. Anomalous strain rate and temperature effects need further investigation as well as larger specimen configurations to more quantitatively define K_c and K_{Ic}.

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Table I. Strength and toughness of TRIP steel

Heat No.	Treatment	Thickness (in.)	Test condition	Yield strength ksi	Ultimate strength ksi	Elongation %	Apparent K_{Ic} ksi-in$^{1/2}$	K_c ksi-in$^{1/2}$
676-1	80% at 450°C	0.083	RT-0.002 in/sec [a]	225	245	26	-	252
676-3	80% at 250°C	0.082	RT-0.0002 in/sec	—	—	—	Specimen Tore	
676-3	80% at 250°C	0.081	RT-0.002 in/sec	234	234	31	-	289
676-3	80% at 250°C	0.082	RT-0.02 in/sec	236	236	32	-	250
676-3	80% at 250°C	0.083	RT-0.2 in/sec				-	199
6711-3	75% at 450°C	0.49	RT-0.0005 in/sec	173	186	38	99[b] 153[c]	> 213[d]
6711-3	75% at 450°C	0.48	RT-0.0005 in/sec	176	185	36	96[b] 153[c]	No failure
6711-3	75% at 450°C	0.48	-196°C - 0.0005 in/sec	230	258	29	139.2[e]	> 144[d]
6711-3	75% at 450°C	0.49	-196°C - 0.0005 in/sec				139.3[e]	> 144[d]
6711-3	75% at 250°C +5% at -196°C	0.475	RT-0.0005 in/sec				92.4[b] Loading pin broke	
6711-3	75% at 250°C +5% at -196°C	0.475	RT-0.0005 in/sec				87.3[b] 155[c]	> 256[d]

a. Crosshead rates only apply to fracture tests; tensile data run at 0.0005 in/sec.

b. From first deviation of linearity (see Fig. 1).

c. From second deviation of linearity in same specimen (see Fig. 1).

d. Lower bound since no slow crack growth or plastic zone incorporated.

e. From pop-in.

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FIGURE CAPTIONS

Fig. 1 Room-temperature load-deflection curve for 0.5 inch thick specimen.

Fig. 2 Macroscopic views of fractured specimens (0.5 in. thick) tested at room and liquid nitrogen temperature.

Fig. 3 Macroscopic views of fracture specimen (0.07 in. thick) tested at room temperature.

Fig. 4 Electron fractographs taken from (a) plane stress, R.T. test and (b) (c) plane strain, -196°C test.

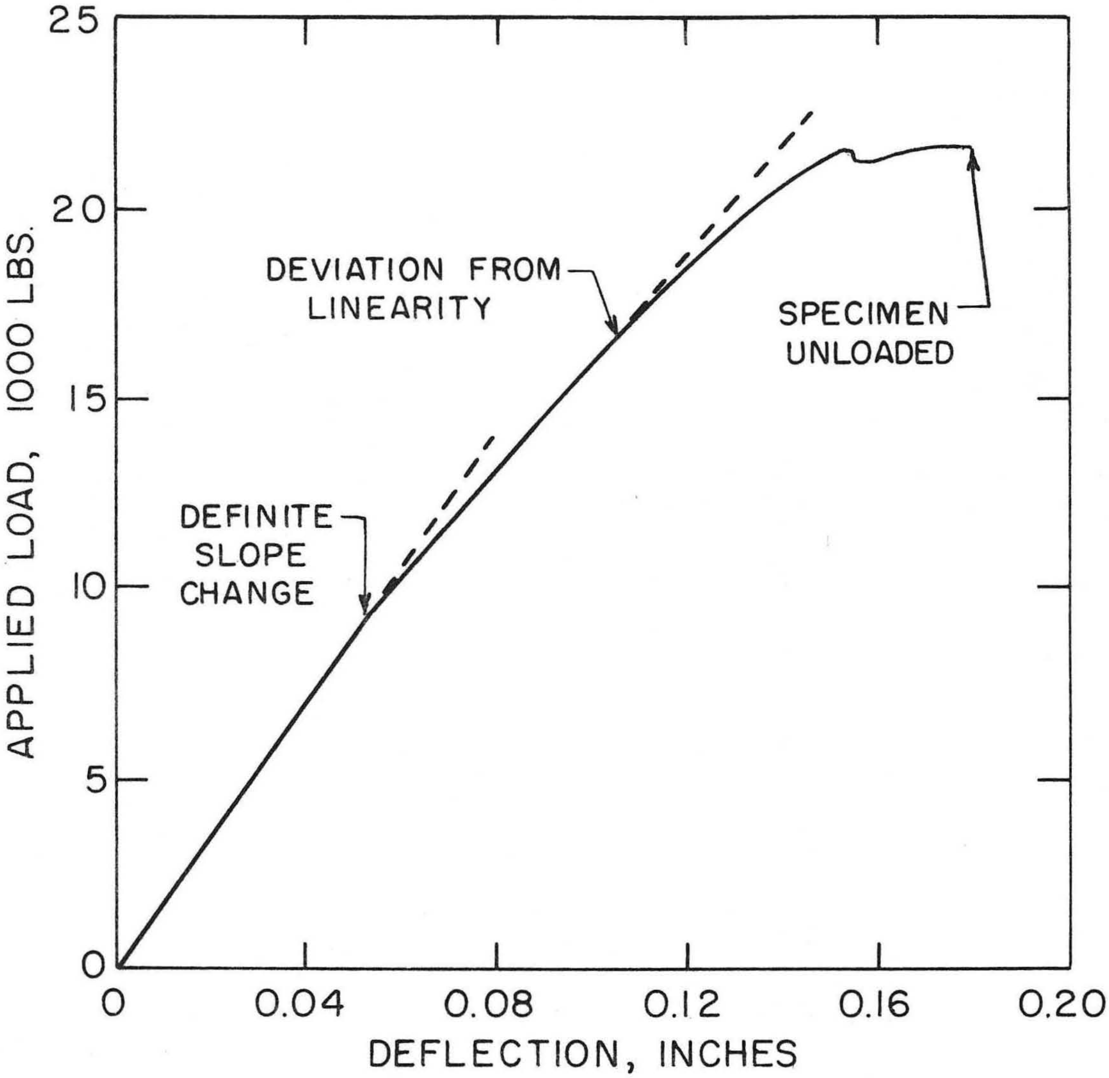
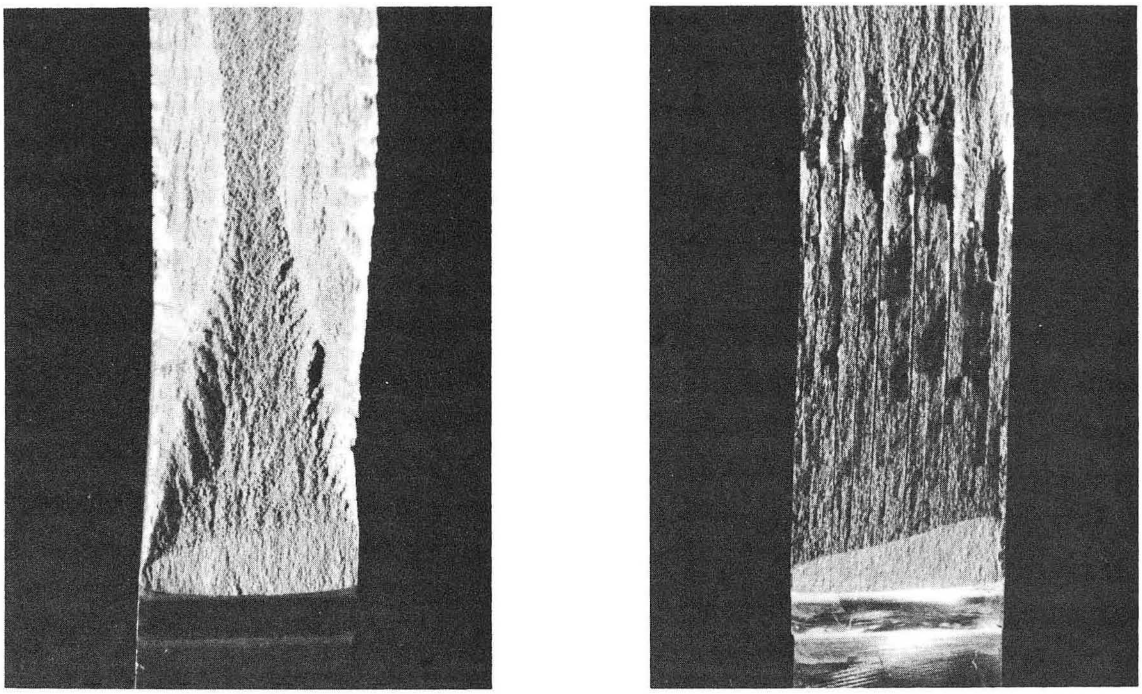


FIGURE 1 ROOM-TEMPERATURE LOAD-DEFLECTION CURVE FOR 0.5 INCH THICK WOL SPECIMEN.

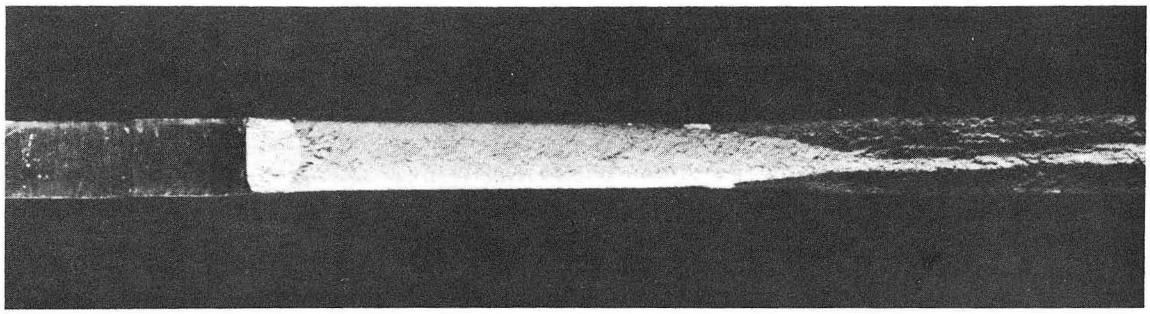


(a) R.T. 2×

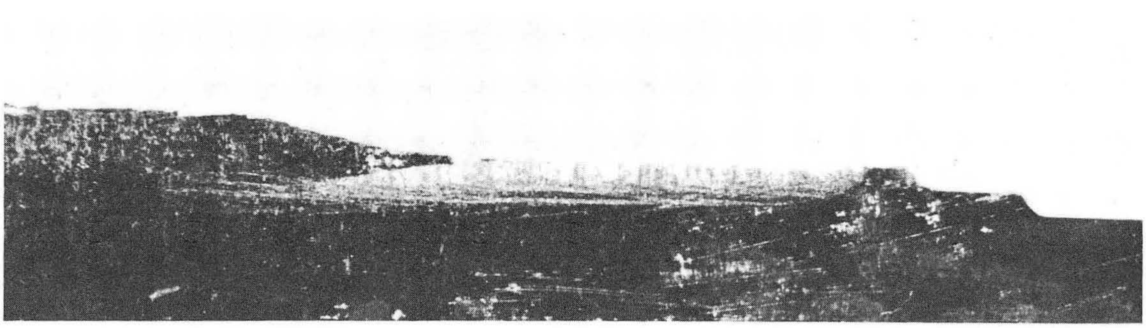
(b) -196°C 2×

XBB 684-2331

Fig. 2



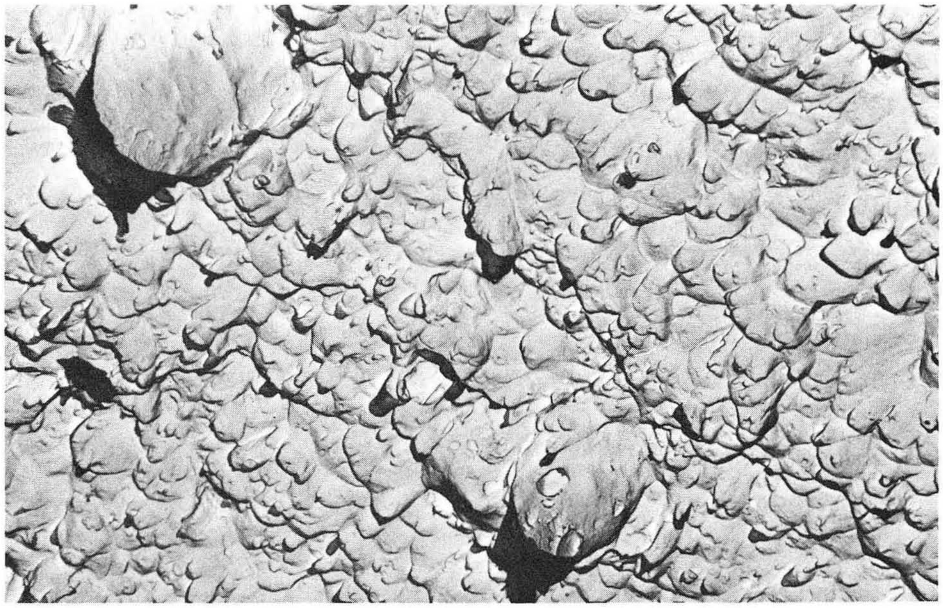
(a) Top View 3×



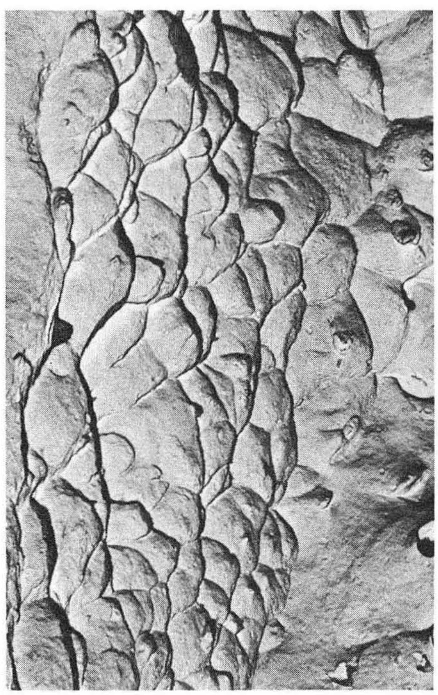
(b) Side View 3×

XBB 684-2332

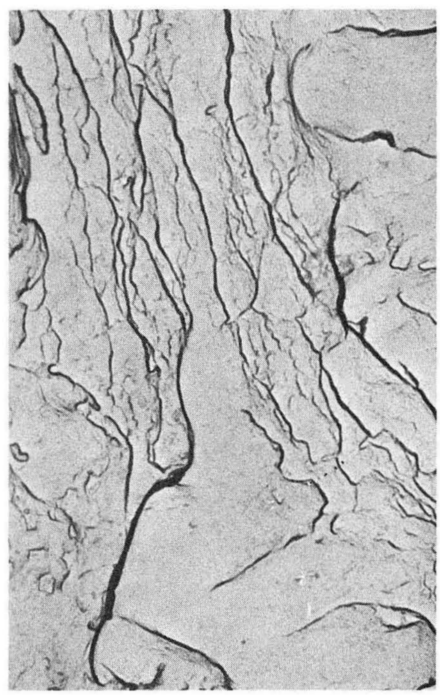
Fig. 3



(a) 3000×



(b) 3000×



(c) 10,000×

XBB 684-2330

Fig. 4