FATIGUE CRACK PROPAGATION IN TRIP STEELS

A. Plumtree and V. P. Swaminathan*

INTRODUCTION

TRIP steels were developed in an effort to combine the high ductility and toughness of metastable austenitic steels with additional strengthening available from prior warm working of the austenite in the lower temperature range of the stable austenite field [1]. The warm working considerably enhances the yield strength of the austenite. It has been shown that the ductility of these steels increases due to transformation of metastable austenite to martensite during deformation at temperatures below M_d (i.e., the temperature below which austenite can be transformed to martensite by plastic deformation) [1, 2]. Another very desirable characteristic of these steels is their high fracture toughness. This is caused by additional energy absorption associated with the strain induced martensitic transformation [3]. In the present investigation, the fatigue crack propagation characteristics of a TRIP steel were studied at room temperature and 100°C to assess the influence of austenite stability. Also, the effects of the prior or static martensite and strain induced or dynamic martensite on the fatigue crack propagation rates over a range of stress intensity values have been studied. A fracture mechanics approach has been used to explain the fatigue crack propagation results.

EXPERIMENTAL PROCEDURE

Material processed in the TRIP condition was available from two heats of similar composition. The composition of these heats is as follows:

Heat 2294 - C-0.27, Mn-0.43, Si-0.09, Cr-11.15, Mo-1.90, Ni-7.96
Heat 2295 - C-0.25, Mn-0.22, Si-0.20, Cr-11.95, Mo-1.94, Ni-7.95

TRIP processing of the solution heat treated plates was carried out by 80% reduction in thickness by warm rolling at 425°C (i.e. above M_d = 215°C). The sheets were approximately 61 cm (rolling direction) x 18 cm x 0.24 cm with an average hardness of 48 R_c.

The martensite content of the as-received TRIP steel was about 1% (vol). Higher initial or static martensite contents in the steel were produced by rolling at room temperature to 10% reduction in thickness. The resultant martensite content was between 11 to 16% (vol). The martensite content was measured using a Magne-gage up to 30% (vol) and a transformer system for martensite contents in excess of 30% (vol).

Fatigue crack propagation tests were carried out on single edge notch (SEN) specimens which were cut parallel to the rolling direction. The notch was cut perpendicular to the rolling direction. An MTS servo-

*Department of Mechanical Engineering, University of Waterloo, Waterloo, Ontario, Canada.

controlled closed-loop hydraulic testing machine was used for the fatigue crack propagation (FCP) tests. These tests were carried out under tension-tension loading with a sinusoidal waveform at a frequency of 10 Hz during the crack initiation stage and at 5 Hz during the crack propagation stage. The ratio of the minimum load to the maximum load was maintained constant at 0.1. An electric induction unit was used to heat the specimens for the tests at 100°C (±2°C). Load and temperature were continuously monitored during the tests using strip chart recorders.

The crack length was measured with a travelling microscope to an accuracy of 0.001 cm and the fatigue crack growth rate (FCGR) was calculated by the successive difference method. The average of the ΔK values at the beginning and at the end of each separate increment in crack length was calculated. The crack propagation rate (da/dN) and the stress intensity factor range (ΔK) were related by the well-known Paris relationship.

$$da/dN = A\ (\Delta K)^m \qquad (1)$$

where A and m are constants.

RESULTS AND DISCUSSION

FCP tests conducted at room temperature showed that the FCGR was lower for the rolled steel than for the as-received TRIP steel. Similar crack growth behaviour was observed at 100°C. However, FCGR for both conditions at 100°C were higher than at room temperature. Measurement of martensite on the fracture surfaces of the fatigue specimens tested at room temperature and 100°C are given in Table 1. The amount of martensite decreased for the same crack length as the test temperature increased. The steel showed a lower resistance to crack growth at 100°C than that at room temperature, indicating that the crack growth rate was controlled by the dynamic martensite formed in the plastic zone.

Comparison with Type 301, 304 and 316 Steels at Room Temperature

Fatigue crack growth behaviour of the present steel was compared with other data available from the literature for stable and unstable austenitic steels, TRIP steels and fully martensitic steels. The room temperature FCGR data of the present TRIP steel and that of the type 301, 304 and 316 are plotted as a function of ΔK on logarithmic coordinates in Figure 1. The types of steels, monotonic tensile properties, slope of the da/dN vs ΔK curves are summarized in Table 2.

It can be seen that there is no marked difference in the slope of the curves for the TRIP steel in both the as-received and in the 10% rolled conditions. However, the FCGR is about a factor of two lower at $\Delta K = 35\ MPa \cdot m^{1/2}$ for the rolled specimens. This difference is less at higher values of ΔK. The TRIP steel shows better resistance to fatigue crack propagation than other stainless steels of comparable strength. The transformation from austenite to martensite during fracture absorbs energy that would otherwise be available for crack extension. Static results also reflect the beneficial influence of the transformation [3].

Type 301 and 304 stainless steels displayed better crack growth resistance characteristics after warm and cold working than in the annealed condition. For type 301 stainless steel, 65% warm working in the temperature range

450 - 500°C gave lower crack growth rates for ΔK values greater than 45 $MPa \cdot m^{1/2}$ and the slope m of the da/dN vs ΔK line decreased from 8 to 3.45 [4]. These results reflect the effect of prestraining with no induced martensite prior to fatigue testing. The decrease in m and FCGR may be due to the increase in yield strength which was about 5 times that of the annealed material. Data from reference [9] for type 304 stainless steel in the annealed (m = 3.2) and 25% cold worked (m = 2.4) conditions are also plotted in Figure 1. It can be seen that the cold working resulted in a slightly beneficial effect by lowering the slope, m, and decreasing the FCGR in general. Similar effects were observed in the present alloy where the slopes of the lines for the as-received and 10% cold worked conditions were close to 2. There was a slight beneficial effect on the FCGR due to cold working which may be due to the increase in the dislocation density as seen in the type 301 stainless steel.

The number of cycles to produce a fatigue crack of 1 mm increased for the prestrained specimens [5]. These results suggest that prestraining and the presence of static martensite play an important role in the initiation of the fatigue crack yet the present results show they have only a slight effect on crack growth.

Comparison can also be made with fully austenitic and fully martensitic steels [4, 6]. This is illustrated in Figure 2. The slope of the log da/dN - ΔK curve was 9.6 for the fully austenitic material whereas the slope was 2.3 for the fully martensitic condition. Presence of martensite formed prior to testing (static martensite) in the present TRIP steel tended to produce a similar effect by decreasing the slope.

COMPARISON WITH OTHER TRIP STEELS

The room temperature results may be compared with some other TRIP steels which received similar thermomechanical treatments [7, 8]. The FCGR results are illustrated in Figure 3. Since the other two steels were of similar composition it is not surprising that the FCGR for a given ΔK are similar. The present steel showed better crack growth resistance. This difference is most probably due to the differences in composition which is an important factor in determining the stability of the austenite [2]. If the alloy is more unstable, more martensitic transformation will bring about slower crack growth rates. Some contribution may be due to differences in specimen geometry and test equipment. But this effect is expected to be minor [11]. The austenite instability index based on composition [2] for the present TRIP steel was higher than either the corresponding indices for the other TRIP steels.

It can be seen from Table 2 that the slope, m, falls in the range 2 to 4 for all the thermomechanically treated TRIP and martensitic steels. This suggests that the micromechanisms controlling the crack growth behaviour may be similar. As discussed by Schwalbe [10], the cyclic plastic crack opening displacement is directly related to the crack extension per load cycle. The characteristic displacement near the crack tip is controlled by the size of the cyclic plastic zone Δω, which is given by

$$\Delta\omega = \frac{(1-2\nu)^2 \cdot \Delta K^2}{4\pi \cdot \sigma_y^{\ 2}} \qquad (2)$$

where ν = Poisson's ratio

σ_y = yield stress

The crack growth rate is given by

$$da/dN = \frac{\sigma_y^{1.67}}{E} \cdot 1.59 \frac{(1-2\nu)^2 \cdot \Delta K^2}{0.33 \cdot \varepsilon_b \cdot \sigma_y \cdot \pi} \qquad (3)$$

where E = Young's modulus

ε_b = Strain at monotonic fracture

This model could explain the second power relationship between da/dN and ΔK. Since the plastic deformation at the crack tip is a function of ΔK^2, the variations in the slope, m, may be due to the additional factors like crack closure and corrosion effects which are not treated quantitatively in these theories. However, since it is apparent that a slope of 2 is based on a planar crack front, any deviation from this value would correspond to a non-planar crack front where the crack length would vary throughout the thickness of the specimen [12].

Comparison with Type 301 Stainless Steel and 16-13 Steel at 100°C

Results for the TRIP steel tested at 100°C are compared with those for a type 301 stainless steel at 85°C and 16-13 stainless steel at 90°C. The plots are shown in Figure 4. For the TRIP steel there was only a slight increase in the slope m at 100°C and the curves were shifted upwards resulting in inferior crack growth characteristics at 100°C when compared to those at room temperature. The prestrained specimens showed a lower FCGR. Type 301 steel displayed similar behaviour at 85°C. The FCGR was higher than that at 20°C for the warm worked material with no significant change in the slope of the log da/dN - ΔK curves. The FCGR of the 16-13 alloy increased with increasing test temperature. Moreover, this alloy displayed higher crack growth rates than the other two steels.

The stability of the austenite decreases with decrease in test temperature below M_d and more martensite forms in the plastic zone. This effect obviously resulted in lower crack growth rates. The dynamic martensite which formed in the plastic zone tended to lower the value of the preexponential term A in the Paris equation (equation (1)) since the slope was not greatly affected by temperature change. This phase transformation effects a large degree of work hardening (i.e. the work hardening coefficient increases) and this in turn results in a lower plastic strain range for a given total strain range, leading to better accommodation of the applied strains within the plastic zone [6].

Fractography

The complex nature of the mixed austenite-martensite microstructure was reflected in the microscopic fracture mode of the TRIP steel. Using the scanning electron microscope, striations were found only in isolated areas. At low ΔK values, the fracture surface exhibited mostly flat and featureless areas and at high ΔK values the fracture area was dominated by tear dimples as shown in Figure 5. In reference [4] it was reported that type 301 and 16-13 steels tended to show secondary cracks even at low and moderate ΔK values. But the present TRIP steel did not show any

secondary crack at 25°C and 100°C over a range of ΔK values from 35 $MPa \cdot m^{1/2}$ to 100 $MPa \cdot m^{1/2}$.

The crack front advanced in a planar manner due to the large amount of prestrain caused by the TRIP processing and to the formation of martensite in the plastic zone ahead of the propagating crack.

CONCLUSIONS

1. Fatigue crack growth rates of a TRIP steel were found to be slower than those of other commercial stainless steels for values of $\Delta K >$ 40 $MPa \cdot m^{1/2}$.

2. The FCGR increased with temperature. For the same crack length, the volume fraction of strain induced martensite decreased with increasing test temperature.

3. Cold rolling the TRIP steel resulted in better crack growth resistance at 25°C and 100°C when compared to that of the as-received steel at the same temperatures.

4. The presence of prior or static martensite was found to be beneficial during the initiation stages of the fatigue crack whereas martensite formed during cycling (i.e. dynamic martensite) was beneficial during the propagation stage.

ACKNOWLEDGEMENTS

The authors are grateful to the National Research Council of Canada and Defence Research Board of Canada for financial support.

REFERENCES

1. ZACKAY, V. F., PARKER, E. R., FAHR, D. and BUSCH, R., Trans. ASM, 60, 1967, 252.
2. GERBERICH, W. W., THOMAS, G., PARKER, E. R. and ZACKAY, V. F., Proc. Second Int. Conf. on the Strength of Metals and Alloys, Asilomar, Calif., September 1970.
3. ANTALOVICH, S. D. and SINGH, B., Met. Trans. 2, August 1971, 2135.
4. PINEAU, A.G. and PELLOUX, R. M., Met. Trans., 5, May 1974, 1103.
5. SWAMINATHAN, V. P. and PLUMTREE, A., Proc. Second Int. Conf. on Mech. Behaviour of Materials, Boston, 1976, 578.
6. BATHIAS, C. and PELLOUX, R. M., Met. Trans. 4, May 1973, 1265.
7. CHANANI, G. R., Ph.D. Thesis, Univ. of Calif., Berkeley, 1970.
8. WEISS, V., SHRODER, K., LAL, D. and SENGUPTA, M., AMMRC CTR 73-50, Syracuse University.
9. SHUHINIAN, P., WATSON, H. E. and SMITH, H. H., J. of Materials, 7, No. 4, December 1972, 527.
10. SCHWALBE, K-H, Eng. Frac. Mech., 6, 1974, 325.
11. KNOTT, J. F., Metals Sci., 9, 1975, 485.
12. PICKARD, A. C., RITCHIE, R. O. and KNOTT, J. F., Metals Tech., 2, June 1975, 253.

Table 1 Martensite Content on Fatigue Fracture Surface for 3 Different Crack Lengths

Specimen No.	Test Temperature °C	% Martensite (vol.) at Crack Length of:		
		1.9 cm	2.45 cm	3 cm
M_1	25	8	14.8	23
R_6	25	14.2	21.0	31
M_8	100	3.8	5.8	9
R_3	100	10.8	13.1	16.2

M_1, M_8 - As-received

R_3, R_6 - 10% Cold Rolled

Table 2 Summary of Tensile and Fatigue Data for the Present TRIP Steels and Other Steels from Literature

S No.	Type of Steel	0.2% Yield (MPa)	UTS (MPa)	FCGR Test Temperature(°C)	*Specimen Type	Specimen Thickness (mm)	Slope of log da/dN -ΔK curve	Reference
1a	TRIP as-received	1413	1689	25	SEN	2.2	1.74	present work
1b	- " -	1413	1689	100	"	"	2.1	
1c	TRIP - 10% Cold Worked	1438	1798	25	"	"	1.97	
1d	- " -	1438	1798	100	"	"	2.3	
2a	301 Annealed	221	1448	20	CT	7	8	4
2b	301 Warm Worked (65% at 500°C)	1058	1300	20	CT	7	3.45	4
3a	304-Annealed	255	586	25	SEN Cantilever	15.2	3.2	9
3b	304-25% Cold Worked	510	765	"	"	"	2.4	9
4	316-Alloy	303	563	"	"	"	3.2	9
5a	Fe-31.5 Ni (Austenite)	195	530	20	CT	7	9.6	4
5b	Fe-31.5 Ni (Martensite)	552	690	20	"	"	2.3	4
6	Maraging-Annealed	965	1000	25	DCB	9.5	2.5	6
7	16-13 Alloy	138	758	20	CT	7	9.1	4
8	9 Cr-7 Ni TRIP Steel	1585	1724	25	SEN	1.9	4	7
9	8.8 Cr-8.6 Ni TRIP Steel	1379	1413	23	CT	6.4	3	8

*SEN = Single Edge Notch
CT = Compact Tension
DCB = Double Cantilever Bend

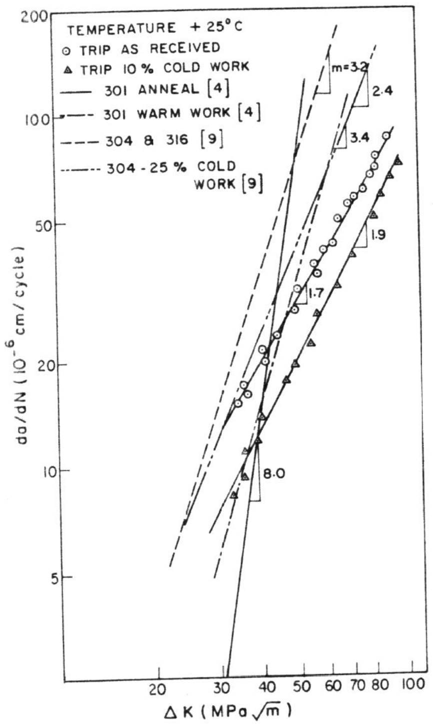

Figure 1 Fatigue Crack Growth Rates at Room Temperature as a Function of ΔK for TRIP Steels and Type 301, 304 and 316 Steels [4, 9]

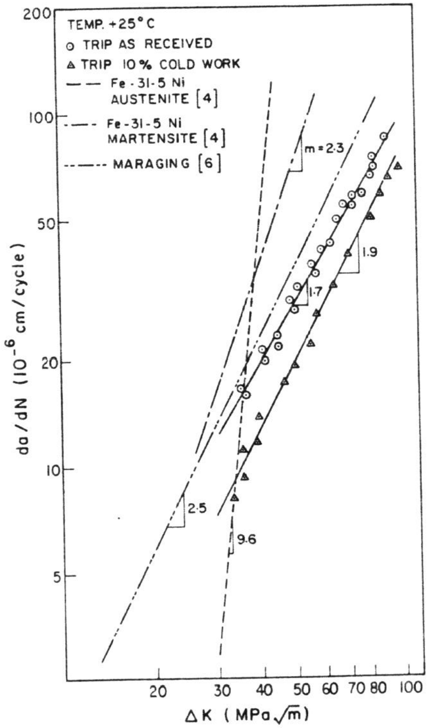

Figure 2 Comparison of Data From Present Work with Results for Stable Austenitic and Martensitic Steels [4, 6]

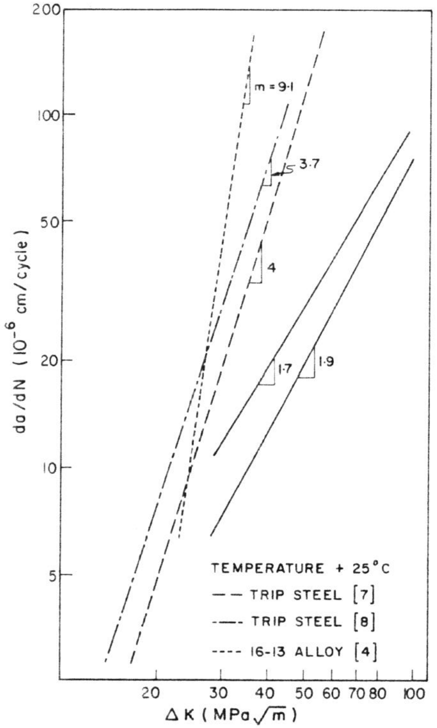

Figure 3 Room Temperature Results for Present TRIP Steels and other TRIP Steels from the Literature [7, 8]

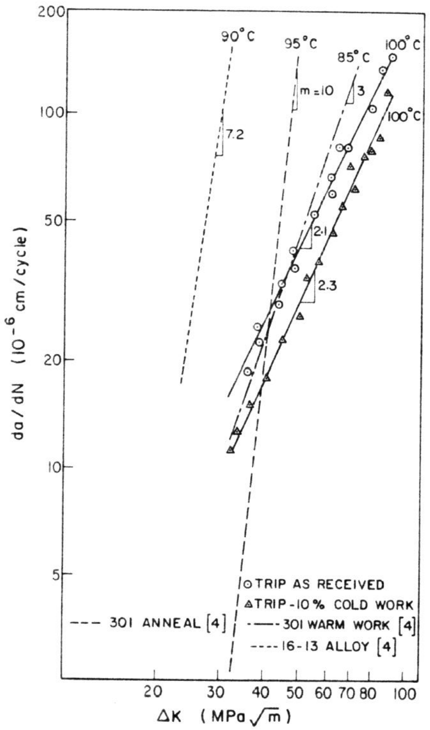

Figure 4 Fatigue Crack Growth Rates for As-Received and 10% Cold Worked TRIP Steel at 100° C, Annealed 301 at 95° C, Warm Worked 301 at 85° C, and for 16-13 Alloy at 90° C, [4]

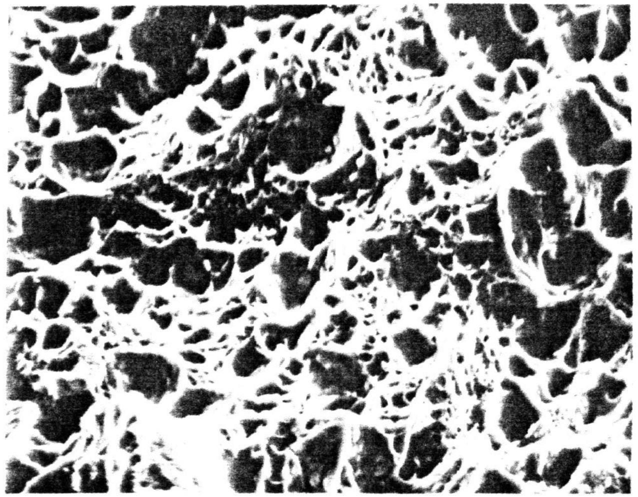

Figure 5 Fatigue Fracture Surface Room Temperature Test X 2550