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Mechanical Properties and Corrosion Resistance of TRIP Steels

V. F. Zackay, W. W. Gerberich and S. F. Ravitz

The stress-strain curves of TRIP steels are quantitatively predicted by defining the austenite stability in terms of the composition and processing history and, relating, in turn, the stability to the mechanical properties. The highest known values of plane stress (K_c) fracture toughness for yield strengths above 200,000 psi (140.6 Kg/mm^2) have been achieved for TRIP steels of low austenite stability. The low cycle fatigue life of TRIP steels both at room temperature (in the presence of the martensitic transformation) and at 200°C (in the absence of the transformation) were related to the plastic strain range, ε_{PR}, by the Coffin-Manson law. Either cyclic hardening or softening occurred at room temperature depending primarily upon the ε_{PR} used in cycling. Hardening was observed for ε_{PR} greater than about 3%, while softening occurred below 3%. Although strongly resistant to embrittlement by hydrogen it appears that under certain conditions of dynamic testing the ductility of TRIP steels can be sharply decreased. The susceptibility to embrittlement can be greatly decreased by compositional control. The general corrosion resistance of TRIP steels appears to be comparable to that of the well known austenitic stainless steels.

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Introduction

The qualitative concepts underlying the development of TRIP steels have been described, as well as some of their mechanical properties, in a series of papers appearing over the last several years (1-10). The purpose of the present report is two fold: one, summarize the more recent efforts to predict quantitatively their mechanical properties in terms of compositional and processing history; and two, to depict the present status of current studies on the corrosion resistance of these steels and their mechanical properties in aggressive environments.

Prediction of the Stress-Strain Curve

The stress-strain properties of metastable austenites, including the total elongation and the strain-hardening rate, can be quantitatively predicted (10). This is accomplished, in essence, by defining the austenite stability in terms of the composition and processing variables and, in turn, relating the mechanical properties to the austenite stability. In the analysis a number of key experimental relationships are employed. These are briefly discussed below.

A pivotal factor in the quantitative description of the mechanical properties of TRIP steels is the simple experimental relationship that exists between the volume fraction of martensite produced, V_α, and the conventional strain, ϵ, viz,

$$V_\alpha = m\epsilon^{1/2} \tag{1}$$

where m is a constant for a given set of experimental conditions. The value of m would necessarily be zero at the M_d temperature, while at temperatures well below M_d it has been found to be near 3.5. Although this seems to suggest that V_α may be greater than unity, the experimental fact is that failure intervenes at an elongation limited to values such that this does not occur.

The second experimental relationship needed in the analysis is one which predicts the flow stress of austenite-martensite mixtures. Thomas et al, among others, have shown that the rule of mixtures is a valid description, viz,

$$\sigma = \sigma_\alpha V_\alpha + \sigma_\gamma(1 - V_\alpha) \tag{2}$$

where σ is conventional stress and γ denotes austenite (11). The physical basis for the validity of this description probably arises from the fact that the mixture is composed of materials of different strength levels and, mechanically, is analogous to fibrous composites. The martensite is presumably the stronger of the two components because of interstitial strengthening and intensive substructural work-hardening. Thus, the mixture consists of extremely hard ribbons of martensite in a tough and strong austenite. Utilization of the two experimental relationships described above, i.e., equations (1) and (2), make it possible to predict several elements of the uniaxial stress-strain curve.

The Strain Hardening Rate

Combining equations (1) and (2) gives

$$\sigma = (\sigma_\alpha - \sigma_\gamma)m\epsilon^{1/2} + \sigma_\gamma. \quad (3)$$

In terms of the true stress, σ_T, and the true strain, ε, equation (3) becomes

$$\sigma_T = [\sigma_\alpha - \sigma_\gamma][m(e^\varepsilon - 1)^{1/2}]e^\varepsilon + \sigma_\gamma e^\varepsilon. \quad (4)$$

Differentiating and assuming that $\partial\sigma_\alpha/\partial\varepsilon$ and $\partial\sigma_\gamma/\partial\varepsilon$ are negligible compared with the two-phase contribution leads to

$$d\sigma_T/d\varepsilon = \sigma_\gamma e^\varepsilon + me^\varepsilon\ [\sigma_\alpha - \sigma_\gamma][(1/2)e^\varepsilon(e^\varepsilon - 1)^{-1/2} + (e^\varepsilon - 1)^{1/2}] \quad (5)$$

At this point it is only necessary to describe m, σ_α and σ_γ for evaluation of the strain-hardening rate from equation (5). Although not discussed here, it was also possible to determine empirical equations of σ_α and σ_γ in terms of composition and processing variables (10). Utilizing these estimates and the value of ε at the end of the Lüders strain, the strain-hardening rate was calculated from equation (5) and compared with experimental data from a series of 9 Cr-8Ni-2Mn-XC steels, as shown in Fig. 1.

Total Elongation

In a manner similar to that described above, total elongation may be predicted. Failure is initiated either because of a high martensite content or because of the lack of strain-hardening due to insufficient martensite production in the necked region. These will be denoted as transformation and necking criteria. It was generally observed that those materials obeying a transformation criterion had between 70 and 100% martensite at the time of fracture. Using this fact in conjunction with equation (1) leads to the elongation (in conventional strain) to be given by

$$\begin{aligned} \epsilon &= 1/m^2 \text{ for } V_\alpha = 1; \\ \epsilon &= 1/2m^2 \text{ for } V_\alpha = 0.7. \end{aligned} \quad (6)$$

When the rate of strain-induced martensite is very low, the necking criterion is obeyed as given by $d\sigma_T/d\varepsilon = \sigma_T$. The values of σ_T occurring in the Lüders band is dependent upon the amount of strain-induced martensite. During the Lüders band formation, if the region in the band contained much less than 40% martensite, necking would ensue rather than the propagation of the Lüders front. Using 40% for V_α in equation (2), describing the true stresses in terms of true strains, and then equating this to equation (5) leads to

$$m = 0.8[e^\varepsilon(e^\varepsilon - 1)^{-1/2} + 2(e^\varepsilon - 1)^{1/2}]^{-1} \quad (7)$$

In Fig. 2 it is seen that these criteria describe the elongations observed for tests covering a wide range of alloy contents and test conditions.

In addition to elongation and strain-hardening rate, it is also possible to predict the Lüders strain which allows the whole stress-strain behavior to be predicted, as indicated in Fig. 3 (10). The low elongation of the 0.52 wt% C alloy was predicted on the basis of no martensite production and subsequent necking. The only serious discrepancy is in

the prediction of the total elongation of the 0.34 wt% C alloy. The low observed value may be attributed to a premature brittle fracture because no necking was observed. As further substantiation of this assumed premature failure, the final strength of the material should have been greater than the 0.25 wt% C alloy but was not. In all other respects the agreement is good.

Fracture Toughness

The crack propagation characteristics may also be predicted in terms of the austenite stability. For example, a theoretical derivation demonstrated that the plane stress fracture toughness, K_c, may be approximately related to the transformation by

$$K_c \propto m^{1/2} \tag{8}$$

for values greater than about 0.5 (12). This relationship was evaluated with six different steels with varying degrees of austenite stability, as shown in Fig. 4. Upon interpolation at values of m = 0.5 and m = 2, K_c values of 235 (832 $Kg/mm^{3/2}$) and 460 ksi-$in^{1/2}$ (1628.4 $Kg/mm^{3/2}$) are obtained for the upper curve. Since $235/460 \approx (0.5/2)^{1/2}$, it would appear that equation (8) is reasonably well founded. Thus a relatively simple method for achieving excellent combinations of strength and toughness might be to make metastable austenites as unstable as possible thereby giving relatively large values of m.

Cyclic Loading of TRIP Steels

The alloy compositions of TRIP steels to be studied under cyclic loading were chosen to have the M_s well below room temperature and the M_d above room temperature after thermo-mechanical processing (13). Both high-strain low cycle experiments on round and well-polished specimens as well as fatigue crack propagation (fcp) tests on SEN specimens at various stress-intensity range (ΔK) levels were carried out. To study the effect of a mixed austenite-martensite matrix, low cycle fatigue tests were also done on the TRIP steel after inducing fresh martensite by a high prestrain. To establish the role played by the martensite transformation, tests were also run at 200°C which was above M_d. The amount of martensite induced was magnetically measured by a permeameter built specifically for this purpose.

It was found that the low cycle fatigue life of TRIP steels both at room temperature (in the presence of martensitic transformation) and at 200°C (in the absence of the transformation) was related to the plastic strain range, ε_{PR}, by the Coffin-Manson law. Either cyclic hardening or softening occurred at room temperature, depending primarily upon the ε_{PR} used in cycling. Hardening was observed for values greater than approximately 3% ε_{PR}. For 200°C low cycle fatigue tests, only cyclic softening was observed in all the cases.

A simple theoretical model of fcp based on fracture mechanics was developed. To a first approximation, the experimental results were in agreement with the model and showed the correlation between the ΔK and fcp rates as $da/dn \propto (\Delta K)^4$. The fatigue fracture appearance of TRIP steels comprised of fatigue striations, quasi-cleavage, and elongated dimples reflecting the extremely complex structure of TRIP steels.

A TRIP steel given a prior deformation of 80% at 250°C showed better fcp properties than a number of conventional steels having similar strength levels and it compared favorably with maraging steels in the low ΔK range.

The Influence of Aggressive Environments

Hydrogen Embrittlement

Hydrogen embrittlement of TRIP steels appears to be a dynamic phenomenon - exhibiting the most severe embrittlement at the slowest strain rates, as Koppanaal has observed (8,14). Single-edge-notch specimens, either electrolytically charged with hydrogen or subjected to 3 atmospheres of gaseous hydrogen, were held at loads corresponding to 80% of K_c for over 6 hours without significant slow crack growth. At slow strain rates and in 3 atompsheres of hydrogen, however, slow crack growth began at loads corresponding to 60% of K_c. Tensile tests (at slow strain rates) run in 3 atmospheres of hydrogen revealed a loss of elongation of 95% and a loss of reduction of area of 57% relative to the same test run in air. The fact that TRIP steels are embrittled only under dynamic conditions can be rationalized in terms of the large diffusivity of hydrogen in martensite relative to austenite. There must be a continual new supply of martensite at the tip of a crack in order for the hydrogen to continue to diffuse inwardly. The continued new supply of martensite is provided only under dynamic conditions.

At higher strain rates a significant temperature rise is observed due to adiabatic heating. Since a temperature rise accelerates the diffusion of hydrogen, an increase in the severity of the hydrogen embrittlement would be expected, other conditions remaining the same. However, this effect is overshadowed by the fact that at the higher strain rates there is much less time for diffusion. Hence hydrogen embrittlement is actually less severe at higher strain rates, as evidenced by the increase of both elongation and reduction of area.

Another effect of the temperature rise is that the austenite is slightly more stable; i.e., slightly less strain-induced martensite per unit strain will form at the higher strain rates. Thus elongation by the TRIP process is decreased for tests conducted in air at higher strain rates. Reduction of area, which is relatively independent of the strain-induced phase, on the other hand, increases slightly at the higher strain rates owing to a temperature rise.

Corrosion Fatigue

Preliminary tests conducted in both air and water atmospheres indicated that there is no evidence of corrosion fatigue at high cyclic rates but at very slow rates there may be about an order of magnitude increase in fatigue crack growth rates in the water environments, as shown in Figs. 5 and 6. At the higher cyclic rate there is no corrosion fatigue presumably because there is insufficient time for the hydrogen to diffuse to the crack tip (15). Lowering the carbon level (to about 0.20%) and increasing the austenite stability by the addition of substitutional solute elements appears to be helpful in increasing in increasing the resistance of TRIP steels to deliterious environmental effects. Decreasing the carbon level increases the resistance of the

first-formed untempered strain induced martensite to hydrogen embrittlement and increasing the austenite stability results in a lower volume fraction of the embrittling phase. The latter effect has been observed by Webster for the metastable form of AFC77 steel (16).

General Corrosion Resistance

The microstructure of TRIP steels is complex consisting of severely deformed precipitation hardened austenite. Complex carbides precipitate in the deformed grain boundaries during processing, on slip bands and, presumably, on the dislocation networks (5,10). Because the prior deformation is done at a temperature too low to permit long range diffusion it may be assumed that the matrix abounds in depleted carbon and substitutional solute zones near the precipitated particles. Since these and other chemical and structural inhomogenieties might conceivably alter the corrosion resistance a number of tests were made on a series of TRIP steels of widely varying compositions.

The corrosion resistance was evaluated by a standard potentiodynamic procedure in which the anodic polarization current of the metal in a suitable electrolyte is measured as a function of the applied potential (17,18). Measurements on specimens cut from 0.080-inch (2.05 mm) sheet were made at room temperature (22°C) in an electrolyte of 2-normal sulfuric acid solution freshly prepared from reagent-grade sulfuric acid and triple-distilled water; the solution was purged with hydrogen prior to and during the measurements. The potential was swept in the noble direction at a rate of 1.3 volts per hour after the corrosion potential had reached a steady state. The results of the tests are summarized in Table 1.

The corrosion test results are shown in the columns headed "current density" in Table 1. The critical current density (i_{cr}) is a measure of the ease with which the steel can become and remain passive - the lower the value of i_{cr} the less strong are the oxidizing conditions required to make the metal passive and the less likely is the metal to become depassivated by changes in its environment. The passive current density (i_p) is a measure of the corrosion resistance of the metal in the passive state; for steels, the corrosion rate in mils per year is approximately one-half the value of i_p in micro-amperes per square cm.

Because of slight differences in the test procedure, the corrosion data for series III may not be strictly comparable with those for series I and II. However, for alloy A, which was tested by both procedures, the two values of i_p are the same and the two values of i_{cr} agree with each other in order of magnitude, so it appears that the data for the two procedures are at least qualitatively comparable.

For the electrolyte used and the ranges of alloy composition studied, the following observations may be made: (1) chromium has an extremely strong effect on i_{cr} and a strong effect on i_p; (2) molybdenum has a strong effect on i_{cr} and a slight effect on i_p; (3) nickel has relatively little effect on either i_{cr} or i_p; and (4) manganese tends to increase i_{cr} somewhat but has little effect on i_p.

In spite of the severe chemical and structural inhomogenieties of the TRIP steels studied in this investigation the corrosion-resistant properties, as measured by anodic polarization tests, approach those of type 304 stainless steel, and several of them (alloys F, G, L, N, and O in Table 1) had corrosion-resistant properties approaching those of type

Table 1. Compositions, Mechanical Properties, and Anodic-Polarization Current Densities

Alloy	Percent Cr	Ni	Mo	Mn	C	Current density, μa per sq cm Passive[a]	Critical	Strength, kpsi(Kg/mm^2) Yield	Tensile	Elong., pct. in 1 inch(25.4mm)	Red. in area, pct
Series I											
A[b,c]	13	8	-	-	.26	12	1,000	164(115.3)	253(177.9)	28	32
B[b,c]	13	11	-	-	.26	11	750	187(131.5)	187(131.5)	8	51
C[b,c]	13	10	1	-	.26	12	100	194(136.4)	194(136.4)	11	51
D[b]	13	9	2	-	.25	12	35	200(140.6)	209(146.9)	46	41
E[b]	13	8	1	-	.24	12	75	190(136.6)	264(185.6)	27	35
F	13	8	3	-	.25	8	15	187(131.5)	231(162.9)	38	38
G	13	7	4	-	.25	10	15	185(130.0)	249(170.5)	34	42
H[b]	13	6	3	2	.25	9	30	185(130.0)	231(162.4)	40	33
I[b]	13	6	3	4	.25	10	35	186(130.7)	188(132.1)	46	42
Series II[d]											
304	19	9	-	2	.08	5	80	-	-	-	-
316	18	14	3	1	.04	5	15	-	-	-	-
Series III											
J[b]	8	8	-	-	.26	100	200,000	196(137.8)	271(190.5)	17	-
K[b,e]	11	8	-	-	.24	40	30,000	198(139.2)	242(170.1)	35	-
A	13	8	-	-	.26	12	3,000	164(115.3)	253(177.9)	28	-
L	16	8	-	-	.28	9	10	-	-	-	-
M[f]	9	8	4	1	.26	10	50	-	-	-	-
N	11	8	4	-	.26	10	20	223(156.8)	241(169.4)	31	-
O[f]	13	8	4	1	.24	6	6	-	-	-	-

(a) Divide by 2 to obtain approximate corrosion rate in mils per year.
(b) Slightly magnetic.
(c) No TRIP effect
(d) Commercial stainless steels containing also up to 1 pct Si, .045 pct P, .03 pct S.
(e) Quenched in liquid nitrogen after austenitization.
(f) Also contains 2 pct Si.

316. These favorable corrosion properties were associated with yield strengths of approximately 200,000 psi (140.6 Kg/mm^2) and elongations of 30 to 40 percent. Particularly notable in their attractive combination of mechanical properties and corrosion resistance were steels D and N. Steel N, with a yield strength of 223,000 psi (156.8 Kg/mm^2) and an elongation of 31 percent, had a corrosion resistance comparable to that of type 316 while that of steel D with similar mechanical properties was comparable to type 304. Further studies on TRIP steels are needed, however, to delineate more accurately the effects of composition, to determine the effects of elements such as sulfur and phosphorus in the concentrations present in commercial steels, and to determine the effect of strain-induced martensite on corrosion resistance.

Summary

During the past four years sufficient experimental evidence has been gathered to suggest that ultra high strength steels exhibiting a strain induced transformation can possess excellent combinations of strength, ductility, fracture toughness and corrosion resistance. By the control of the austenite stability it is now possible to produce TRIP steels of predictable and diverse mechanical properties. In the particular case of fracture toughness it has been possible to produce steels with the highest known values of K_c (at high strength levels) simply by composition and process control.

It is now known that TRIP steels, although more resistant to hydrogen embrittlement than conventional ultra high strength steels of the tempered martensitic type, can nevertheless be embrittled when tested dynamically in hydrogen atmospheres. The susceptability to embrittlement can however be decreased by reducing the carbon content of the steels and increasing the stability of the austenite. The general corrosion resistance, especially that of the 12 Cr series, appears to be comparable to the type 300 series of stainless steels. Perhaps the most intriguing aspect of this development is the realization that with the great latitude in composition and processing that is possible in steels exhibiting the strain-induced phenomenon whole families of steels with new and unusual combinations of mechanical and chemical properties can be developed.

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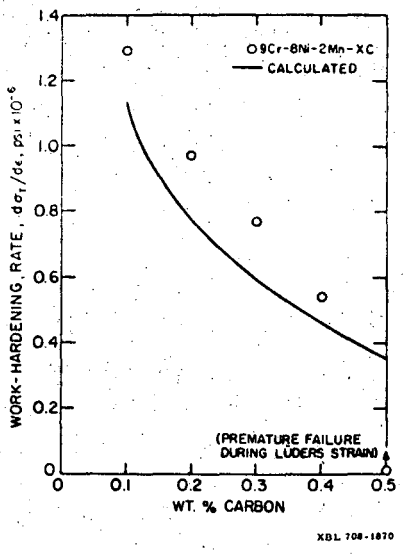

Fig. 1

Prediction of strain-hardening rate for metastable austenites with varying carbon contents.

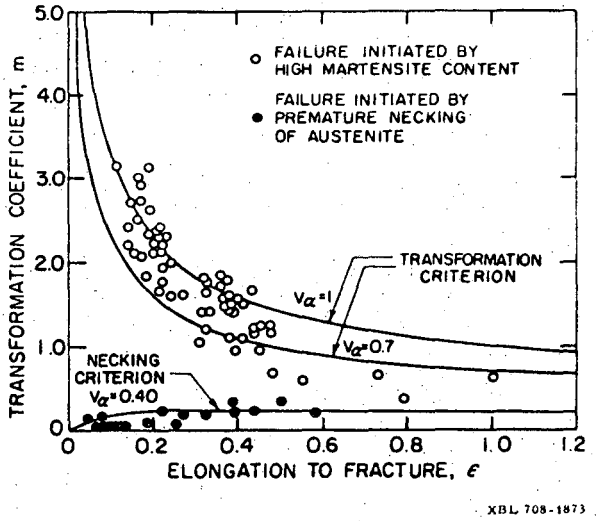

Fig. 2

Effect of transformation coefficient on elongation.

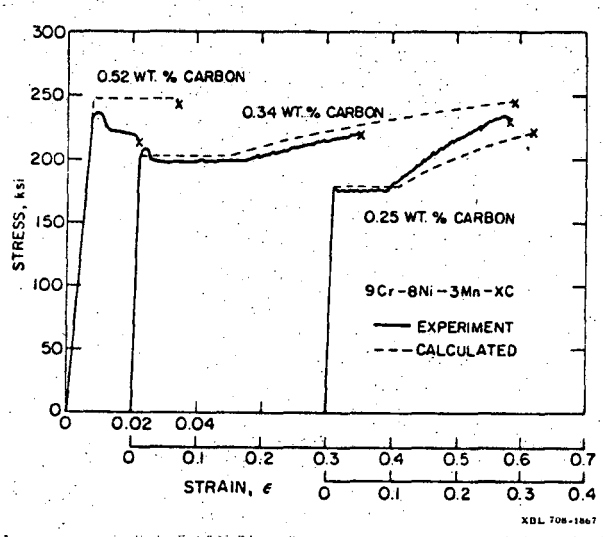

Fig. 3

Prediction of stress-strain behavior for three alloys of different austenite stability.

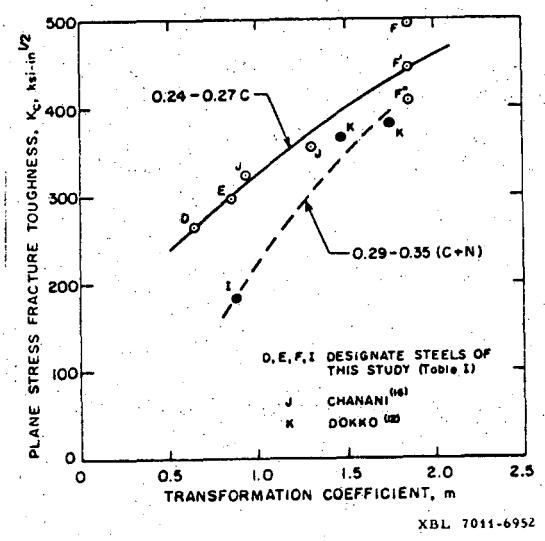

Fig. 4

Influence of austenite stability on the plane stress fracture toughness of high strength, metastable austenites for several levels of carbon content.

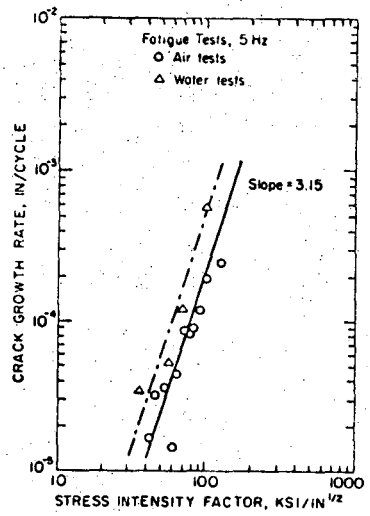

Fig. 5

The crack growth rate for a TRIP steel in air and water atmospheres at a rate of 5 cycles per second.

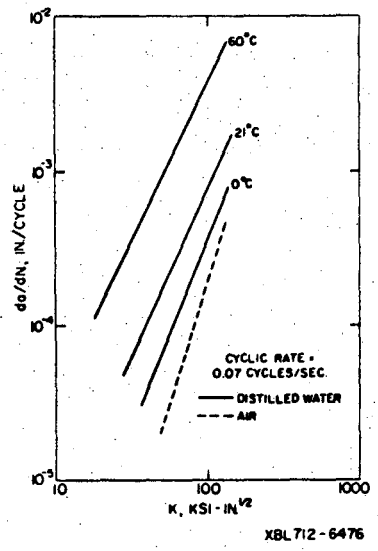

Fig. 6

The crack growth rate for a TRIP steel in air and water atmospheres at a rate of 0.07 cycles per second for several temperatures.

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