EFFECT OF STRAIN AGEING ON THE FRACTURE TOUGHNESS AND TENSILE PROPERTIES OF Si-KILLED C-Mn STEELS

R.Moskovic*, B.D.Leigh* and R.H.Priest**

The effect of static strain ageing on the tensile and fracture toughness properties of a Carbon-Manganese steel has been investigated. A uniform 2% pre-strain has been applied to tensile specimens and its equivalent has been achieved at the crack tip of notched specimens by loading them elastically to 60 MPa√m. Analyses of the data showed that strain ageing brought about a significant increase in the yield stress and a change in the shape of the fracture toughness curve.

INTRODUCTION

Below the creep regime under monotonic loading, two types of failure can be observed in ferritic steels: brittle, usually by a cleavage mechanism, and ductile involving nucleation of voids at second phase particles, their growth and coalescence. The transition from brittle to ductile mode is dependent on the tensile properties of the steel. C-Mn ferritic steels deoxidised by silicon are susceptible to strain ageing. This phenomenon (1) is associated with the interaction of interstitials, principally nitrogen and to a lesser extent carbon, with the strain fields of dislocations. This interaction leads to the formation of interstitial concentrations around dislocations. Formation of interstitial atmospheres at dislocations involves diffusion of the solute. As both carbon and nitrogen diffuse very rapidly in iron, the strain ageing can occur at ambient temperatures.

The practical significance of strain ageing is that it leads to both higher yield strength and lower ductility. These in turn can change the fracture toughness response of the material when compared with the non-strain aged

---

*Magnox Electric, Berkeley, Gloucestershire GL13 9PB

** Nuclear Electric, Barnwood, Gloucester GL4 7RS

condition. The resistance of materials to fracture is conventionally measured on notched specimens which are loaded in bending. The fracture toughness of notched specimens is controlled by local tensile properties at the crack tip. The crack tip conditions can be uniquely characterised by the linear stress intensity factor, K, or the J-integral. It is relatively easy to measure J experimentally (2) although the J values measured are calculated from the energy absorbed by the deformation of the whole specimen.

The purpose of the current investigation was to carry out a controlled experimental programme which assessed the effect of strain ageing on fracture toughness properties. In principle, strain ageing in a test specimen can be effected by following one of two sequences: 1) cold work→age→machine specimen→test; 2) machine specimen→elastically pre-load→age→test. The former uses strain ageing to change the bulk properties of the whole specimen and its effect can be viewed as being equivalent to changing the properties of the specimen by for example heat treatment or some other process. The latter uses elastic pre-loading of pre-cracked specimens to bring about strain ageing locally at the crack tip without affecting the bulk properties of the material. The deformation of fully yielded specimens will be more constrained when the whole specimen is strain aged compared with strain ageing applied at the crack tip. The second sequence only has been used in the current investigation.

MATERIAL AND EXPERIMENTAL PROCEDURE.

The material used in this investigation was a ferritic-pearlitic cross rolled plate steel. The chemical content of the main alloying elements in the steel was (wt%): 0.14C, 1.31Mn, 0.11Si, 0.029S and 0.012P. Stress relief (SR) heat treatment of 6 hours at 600 °C followed by cooling at 10 °C/hour to 250 °C and then air cool represents the baseline condition. In addition, SR and pre-strain (SRP), and SRP and aged (SRPA) conditions were investigated.

Two types of tests, tensile and fracture toughness, were performed. The gauge length and diameter of the tensile specimens were 28 and 5.6mm, respectively. The axis of the tensile specimens was parallel to a rolling direction. For the tests on SRP and SRPA materials, specimens were subjected to a pre-strain of 2% at ambient temperature. Tensile tests were carried out at a strain rate of $6 \times 10^{-5} sec^{-1}$. Standard 25mm thick and 50mm wide compact tension specimens with crack length to width ratio of 0.5 were used for fracture toughness testing. Specimens were pre-strained by loading them elastically to 60MPa√m at ambient temperature. This pre-load was equivalent to a pre-strain of 2% at the crack tip. For both pre-strain and the toughness test, compact tension specimens were loaded under displacement control at a rate of 2mm/min. The crack plane of the compact tension specimens was normal to the tensile specimen axis and the crack line normal to the plate surface.

Those specimens subject to ageing were annealed after pre-straining for one hour at 250 °C and air cooled.

RESULTS

Tensile Tests

All specimens except those in the pre-strained condition exhibited a yield point. The yield/0.2% proof stress, $R_{p0.2}$, and the tensile strength, R_m, values for the three conditions are plotted as a function of temperature in Figure 1. As expected the $R_{p0.2}$ values measured for the SRP were higher than for the SR condition, due to work hardening. Comparison of the $R_{p0.2}$ and R_m values for the SR and SRPA conditions shows a substantial increase in the $R_{p0.2}$ but only a small change in R_m as a result of static strain ageing. Both $R_{p0.2}$ and R_m can be seen to decrease with increasing test temperature. The ratio of R_m values at 20°C and 250°C was approximately 0.86. This is consistent with a significant increase in the flow stress as a result of dynamic strain ageing at 250°C. In a material free of strain ageing, this ratio would be greater than 1.

Fracture Toughness Tests

The fracture toughness tests were terminated either by cleavage instability or by interrupting the tests when a prescribed value of J was exceeded. The pre-strain on its own had very little effect on the cleavage fracture toughness of specimens which were pre-loaded at ambient temperature, unloaded, immediately chilled and tested at a lower temperature. This observation is consistent with pre-straining causing no significant warm prestressing effects. Figure 2 compares the fracture toughness data obtained on the SRPA specimens with the data for the SR condition. The rate of increase of cleavage fracture toughness with temperature is faster and the values are higher for the SR than for the SRPA condition. To rationalise the variability of cleavage fracture toughness with temperature an assessment was made of the pre-cleavage ductile crack growth as a function of temperature. The data are displayed in Figure 3. The transition from crack initiation by cleavage to a ductile mechanism occurred at a lower temperature for the SR than the SRPA condition. Furthermore, cleavage instability after a prior ductile crack growth can be observed over a wider range of temperatures for the SR than for the SRPA condition and the data for the former enclose all the pre-cleavage ductile crack growth values for the latter.

STATISTICAL ANALYSIS OF FRACTURE TOUGHNESS DATA .

Statistically, the outcomes of a fracture toughness test are observed values of K, Δa and the cause of failure, which is either a cleavage or ductile mechanism. The observed values of both cleavage fracture toughness and pre-cleavage ductile crack growth are random variables and form a joint probability distribution. The magnitudes of both are dependent on test temperature. In addition, the cleavage fracture toughness is dependent on prior ductile crack growth and their relationship is prescribed by a crack growth resistance curve. This, for the purpose of evaluating cleavage fracture toughness, can be considered in terms of a relationship between K and Δa.

The distributions of cleavage fracture toughness and pre-cleavage ductile crack growth, Δa_c, can be described using loglinear regression models which are characterised by two parameters; location and scale. The data can be classified as ductile or cleavage. Ductile tests are those which have not experienced cleavage instability and have been stopped by unloading the specimens after different amounts of ductile crack growth. The possibility of fracture by cleavage instability can not be ruled out in these tests if they had been continued to higher amount of tearing. Statistically, this can be accommodated by treating all the ductile data as censored values. This is equivalent to assuming that if the tests were continued, cleavage instability would intervene at a finite value of fracture toughness. The appropriate statistical methods for this data are discussed in References (3,4). The results of the statistical analyses are summarised below:

a) Estimation of the probability, P_a, that $\Delta a_c = 0.2$mm.

SR condition $\quad P_a = 1/(1+\exp(2.322+0.0474T))$ (1)

SRPA condition $\quad P_a = 1/(1+\exp(35.16+1.73T))$ (2)

b) Estimation of the relationship for pre-cleavage ductile crack growth, Δa_c.

SR condition $\quad \Delta a_c = 1.91\exp(0.0368T+0.933\ln(-\ln(1-p)))$ (3)

SRPA condition $\quad \Delta a_c = 12.95\exp(0.0368T+0.933\ln(-\ln(1-p)))$ (4)

c) Estimation of the relationship for cleavage fracture toughness, K_c.

SR condition $\quad K_c = 476\exp(0.022T+0.01T\ln\Delta a_c+0.409\ln\Delta a_c+0.2134U_p)$ (5)

SRPA condition $\quad K_c = 113\exp(0.0074T+1.05\sqrt{\Delta a_c}+0.112\ln(-\ln(1-p)))$ (6)

Where T is the test temperature, p is a random variable between 0 and 1 and U_p is the standard normal deviate. The relationships for P_a have been modelled by logistic distribution. The random error has been modelled by a Weibull distribution in equations (3),(4) and (6) and lognormal distribution in equation (5).

Equations (3),(4) and (5),(6) can be re-arranged and expressed as the marginal, $f_{c,a}(\Delta a_c)$, and conditional probability densities, $f_{c,K}(K_c \mid \Delta a_c)$, of Δa_c and K_c, respectively. However, in order to estimate the probability of cleavage and the cleavage fracture toughness values for use in the structural integrity assessments, it is necessary to consider the joint failure probability distribution of K_c and Δa_c, $F_{c,j}(K_c,\Delta a_c)$. This is given by:

$$F_{c,j}(K,\Delta a) = P_a \int_0^K f_{c,K}(K_c \mid 0)\,dK_c + (1-P_a)\int_0^{\Delta a}\int_0^K f_{c,K}(K_c \mid \Delta a_c) f_{c,a}(\Delta a_c)\,dK_c\,da_c \quad (7)$$

Equation (7) can be used to estimate the values of K_c associated with the 0.05, 0.5 and 0.95 quantiles of $F_{c,j}$. Fracture toughness values for these quantiles are conventionally used in structural integrity assessments as the lower bound, best and upper bound property estimates. The estimates of the median values of cleavage fracture toughness obtained from Equation (7) for the SR and SRPA conditions are compared in Figure 4. This shows that the shapes of the fracture toughness curves are different. Over the temperature range from -100°C to approximately -25°C both the slope and the values of cleavage fracture toughness are lower for the SRPA than SR condition. The brittle to ductile transition begins at a lower and is completed at a higher temperature for the SR compared with the SRPA condition.

CONCLUDING COMMENTS

To understand the brittle to ductile behaviour transition of the strain aged material, it is necessary to consider some of the physical processes at the crack tip associated with crack initiation and how these physical processes are influenced by the tensile strength properties for the SRPA condition. Slip initiated transgranular cleavage fracture is initiated when the local fracture stress at the crack tip exceeds the critical fracture stress over a characteristic distance, typically two grain diameters. The local tensile stress is dependent on the yield stress of the material and any plastic constraint which is caused by work hardening. This also rules the resistance of the material to the initiation of fracture by ductile mechanism. Plastic deformation at the crack tip starts initially on the most favourably oriented crystallographic plane. With increasing plastic strain, as a result of work hardening, it becomes more favourable for the deformation to continue on another slip plane. With successive increases in strain, hardening will cause the deformation to occur in different locations. Alternatively, when significant work hardening does not occur, plastic deformation continues on the plane on which it started. The high strains generated as a result of this process bring about nucleation of voids around second phase particles or inclusions, their growth and coalescence.

Strain ageing reduces the material's propensity to work harden. This suppresses the initiation of cracking by cleavage and promotes a ductile mechanism as a result of two effects: reduction of plastic constraint and localisation of plastic deformation at the crack tip. Thus, the fracture toughness curves for SRPA condition are upright due to a sharp transition from the lower shelf cleavage to the upper shelf ductile fracture.

REFERENCES

(1) Cottrell, A.H., "Dislocations and Plastic Flow in Crystals", Oxford University Press, 1953.

(2) ESIS Procedure for Fracture Toughness Testing.

(3) Moskovic, R., and Crowder, M.J., Int. J. of Fracture, Vol.73, pp201-212, 1995.

(4) Moskovic, R., Eng. Fracture Mechanics, Vol. 50, pp175-202, 1995.

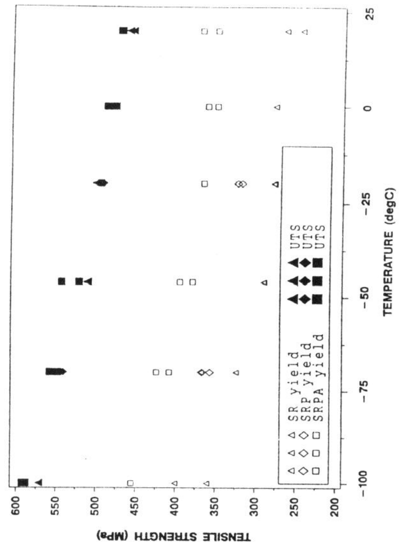

Figure 1 Tensile properties as a function of temperature.

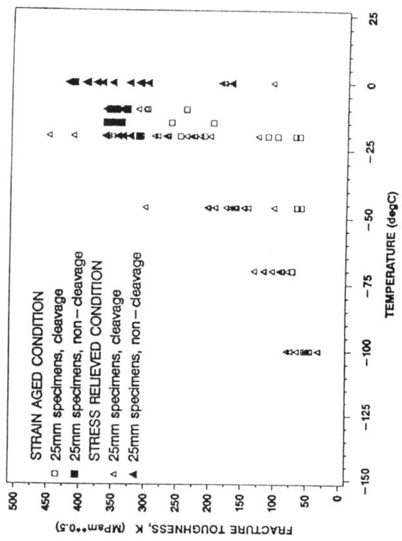

Figure 2 Fracture toughness, K, as a function of temperature

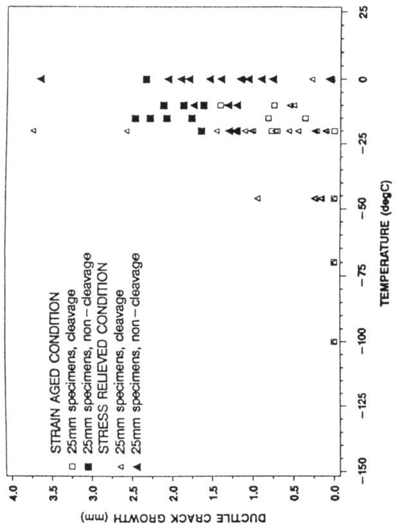

Figure 3 Ductile crack growth as a function of temperature.

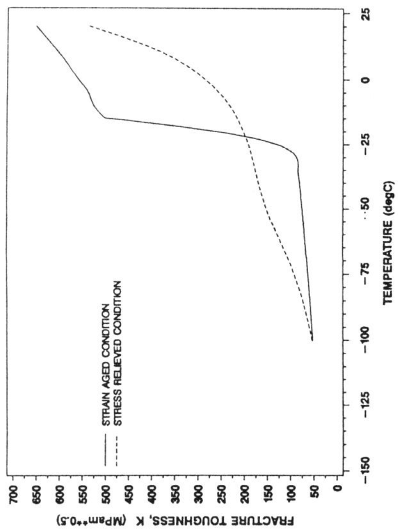

Figure 4 Best estimates of cleavage fracture toughness for SR and SRPA