INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE TENSILE AND FRACTURE PROPERTIES OF STRUCTURAL STEELS

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ABSTRACT

The influence of temperature and strain rate on the tensile and fracture properties of the three structural steels has been investigated in the range of temperatures between 77 K and 295 K and strain rates between 10^{-4} and $10^{2}s^{-1}$. For the high rate fracture mechanics tests a special technique has been developed to get valid K_{Id}-values. Additional efforts have been made to augment these results with the corresponding COD values.
Yield strength data are presented as a function of the activation energy $kT\ln A/\varepsilon$ taking into consideration the influence of temperature and strain rate on yield strength with good agreement. Mechanical properties at large plastic strains were found to be determined by the opposite influence of increased strain rate and increased temperatures caused by adiabatic heating.
High loading rates reduce the amount of yielding able to occur before fracture. The transition from brittle to ductile fracture is shifted to higher temperatures, whereas K_{Ic}-values show only little sensitivity to strain rate. Crack opening displacement values COD were found to show corresponding behaviour. An inverse correlation between yield strength at the crack tip and fracture toughness K_{Ic} has been established for the steels investigated.

KEYWORDS

Dynamic fracture toughness; impact loading conditions; inertial effects; specimen instrumentation; fracture mechanism; adiabatic heating;

INTRODUCTION

Since linear elastic fracture mechanics has been developed to provide a quantitative link between laboratory test data and structural performance there has been increasing interest in the evaluation of fracture toughness under dynamic loading conditions. A number of investigations have shown that dynamic fracture toughness data, derived from instrumented Charpy-V tests are affected by uncertainties as far as size limitations and determination of critical fracture loads are concerned. The aim of this work was to establish a testing technique for the evaluation of dynamic fracture characteristics from compact specimens (CT) under impact loading conditions. Thus earlier results concerning the influence of strain rate on tensile strength and fracture toughness data of structural steels should be augmented (Dahl, Krabiell 1978).

EXPERIMENTAL TECHNIQUES

The tensile and fracture toughness tests were performed on a high speed hydraulic testing machine at constant displacement velocities between 3.10^{-3} mm/s and 5.10^{3} mm/s over a range of temperatures between 77 K and 295 K. For the high rate tests a specially designed slack-adapter has been used which impacts the specimen after the piston is accelerated. Variable masses are incorporated in order to influence the kinetic energy available. The results of the high rate tensile tests have been evaluated by a testing apparatus similar to the 'split-Hopkinson' bar. The fracture toughness tests were performed on 1 CT specimens with a thickness of 13 mm, test procedures were as laid down in ASTM E 399-78 A with the only exception of loading rate. Force, clip-gage displacement and strain were recorded on four transient recorders with a capacity of 8 bit x 4000 words and a maximum sample rate of 20 MHz (resp. 5 MHz). Details of the materials investigated have been published elsewhere (Dahl, Krabiell, 1978).

Determination of Dynamic Fracture Characteristics from Impact Loading Tests.

The main problems withs impact loading conditions result from the determination of the actual load required to fracture the specimen. It is well known from instrumented Charpy-V tests that impact loading introduces inertial effects and oscillations which are superimposed on the load-time record, and these complicate the evaluation of fracture characteristics. A typical load-time record of a CT-specimen, fractured at 5 m/s is shown in Fig. 1. Even though a load cell with high natural frequency (20 kHz) has been used, oscillations seem to be determined by the total compliance of machine and specimen rather than by the true mechanical response of the specimen.

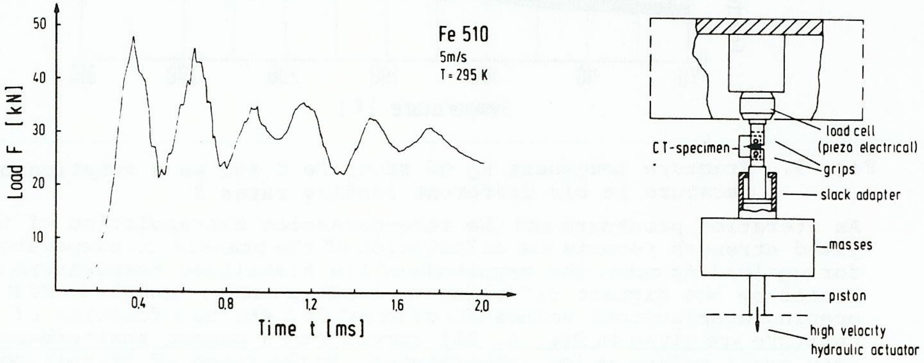

Fig. 1. Load time record of a fracture mechanics test at 5 m/s and schematic view of the testing machine

Different studies on instrumented Charpy-V tests have shown that specimen instrumentation gives some advantage over the use of conventional load transducers. Similar observations have been made on WOL and CT specimens (Turner 1975, Sunamoto 1975). However, there are some problems arising from specimen instrumentation:

1. strain gages on the specimen have to be calibrated statically,
2. stress-strain relationship must be linear,
3. if the bending moment of the specimen is measured, the dynamic bending moment must be linearly distributed as in static loading,
4. if strain gages have not been calibrated during fatigue loading, static calibration must be below 0.6 K_{Ic}.

According to finite element calculations (Redmer 1980) and similar studies (Sunamoto 1975) strain gages have been placed on the outer faces of the CT specimen opposite the crack tip. Two half bridge arrangements were used with both gages being mounted close together to provide temperature compensation. The amplification was DC. The first test results on instrumented specimens, fractured under impact loading conditions, showed significant differences between the measurement of the load cell and the records of the strain gages mounted on the specimen. The frequency of the oscillations, the specimen was subjected to, was about one magnitude higher than the (natural) frequency of the whole testing device. The amplitude of these oscillations was very small, compared to the large drops of load, indicated by the load cell. However, there were qualitative and quantitative differences between both strain records which might result from non uniform stress distribution. Best results were found by damping with a thin rubber sheet which had been placed inside the slack adapter, reducing the effective impact velocity to 3 m/s. Load-time records of one of these tests are shown in Fig. 2.

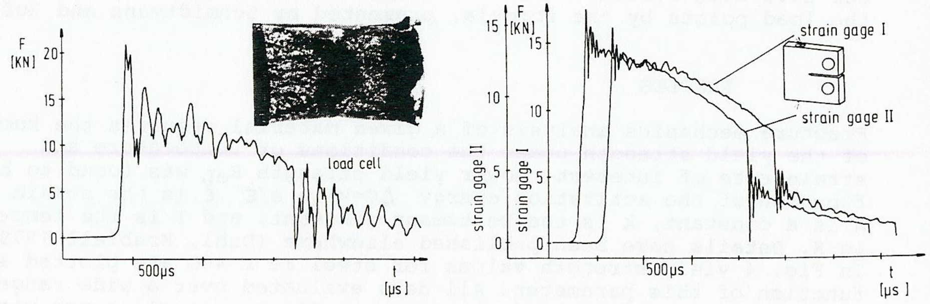

Fig. 2. Load-time records, measured by strain gages and piezoelectric load cell, of an instrumented fracture mechanics test at 3 m/s and corresponding fracture appearance (Fe 510, T = 272 K, $\dot{K} = 4 \cdot 10^{5}$ $MNm^{-3/2}$ s^{-1}).

Both strain gage signals show a linear increase of strain with a well defined maximum indicating the begin of unstable crack extension followed by ductile shear lips on the specimen surface. The 'slow' decrease in the load-time records corresponds to a small amount of ductile fracture. Finally, unstable crack extension is reinitiated and arrested once more. Again the signal of the load cell shows considerable qualitative and quantitative differences. Crack opening displacement has been measured by using a non contact displacement measuring system with maximum frequency response of 20 kHz (± 1 dB) to confirm continual loading of the specimen during impact testing. Fig. 3 shows

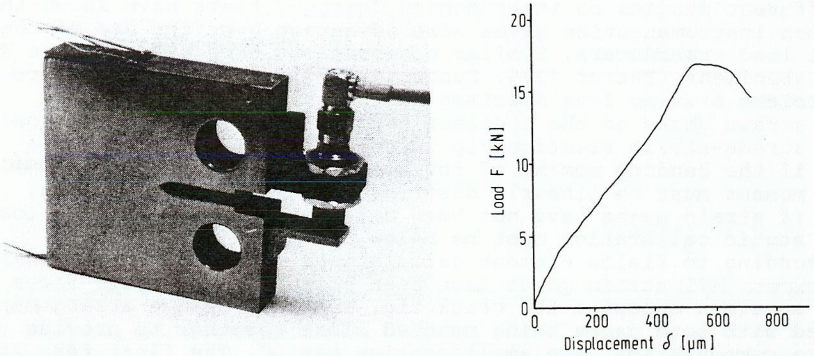

Fig. 3. Instrumented CT specimen and load-displacement graph of a fracture mechanics test under impact loading conditions

an instrumented CT specimen and a load-displacement graph, plotted by the transient recorder. According to strain measurement on the specimen, displacement records did not show any oscillation during impact loading as being indicated by the load cell. Dynamic fracture toughness data K_{Id} have been calculated from the two independent measurements of strain indicating with good agreement the first drop of load under the condition of slightly reduced impact velocity. Before each test strain gages have been calibrated with a static load not exceeding the last fatigue load ($K_f \doteq 0.6\ K_c$). Load-strain relationship was found to be linear in the position outlined above ($a/W = 0.56$) in the range of plastic zones corresponding to LEFM.Crack opening displacement values COD have been evaluated from the displacement, measured in front of the load points by the formula, presented by Schmidtmann and Ruf(1974).

RESULTS

Fracture mechanics analysis of a given material requires the knowledge of the yield strength under the conditions of temperature and strain rate of interest. Lower yield strength R_{eL} was found to be a function of the activation energy $\Delta G = kT\ln A/\dot{\varepsilon}$. $\dot{\varepsilon}$ is the strain rate, A is a constant, k is the Boltzmann constant, and T is the temperature in K. Details have been published elsewhere (Dahl, Krabiell 1979). In Fig. 4 yield strength values for steel Fe E 460 are plotted as a function of this parameter. All data evaluated over a wide range of different temperatures and strain rates fit one single curve with a small scatterband. Fracture toughness K_c is presented as a function of temperature for the steel Fe E 460 in Fig. 5. The curves shown represent different loading rates $\dot{K}$, i.e. rates of increase in stress intensity with time. Above the ASTM geometry transition temperature K_{max} values were calculated. At low temperatures the K_{Ic} values seem to be independent of loading rate and all data fit a common scatterband. With increasing temperatures the tendency for yielding to occur before fracture is markedly reduced at higher loading rates and fracture toughness values decrease. The calculation of the transition temperature according to the ASTM geometry criterion requires the knowledge of the yield strength of the material at the particular temperature and strain rate. Strain rates for the fracture toughness tests were calculated for a small element located on the crack tip elastic-plastic boundary from the formula presented by Shoemaker, 1969.

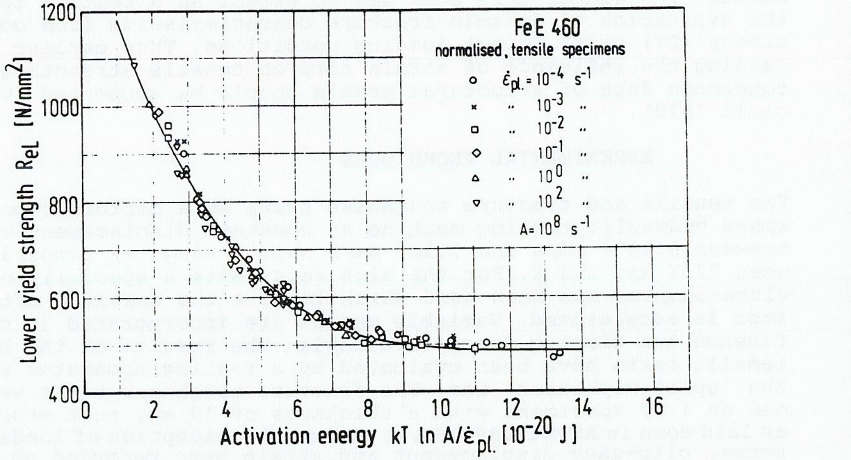

Fig. 4. Lower yield point R_{eL} of steel Fe E 460 as a function of activation energy $kT\ln A/\dot{\varepsilon}$

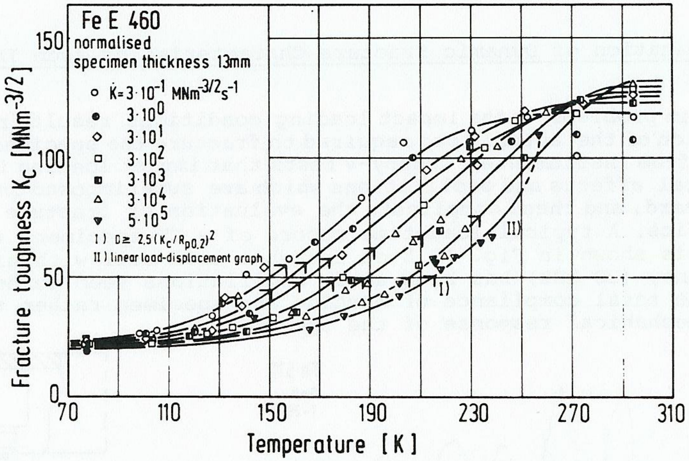

Fig. 5. Fracture toughness K_c of steel Fe E 460 as a function of temperature at six different loading rates $\dot{K}$

An iteration procedure and the rate-parameter extrapolation of the yield strength permits the calculation of the transition temperature for any loading rate. The magnitude of the transition temperature shift, caused by the highest difference in loading rates, amounts to 80 K.Crack opening displacement values COD of steel FE E 460 as a function of temperature are given in Fig. 6. All curves show a common scatterband of very small values at low temperatures. In the range of transition temperatures the increase of COD values and strain rate sensitivity is similar to the trends shown in fracture toughness K_{Ic}.

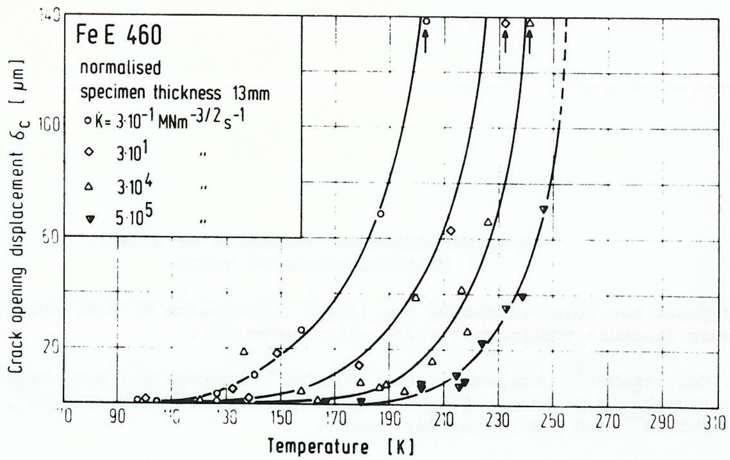

Fig. 6. Crack opening displacement COD of steel Fe E 460 as a function of temperature at four different loading rates

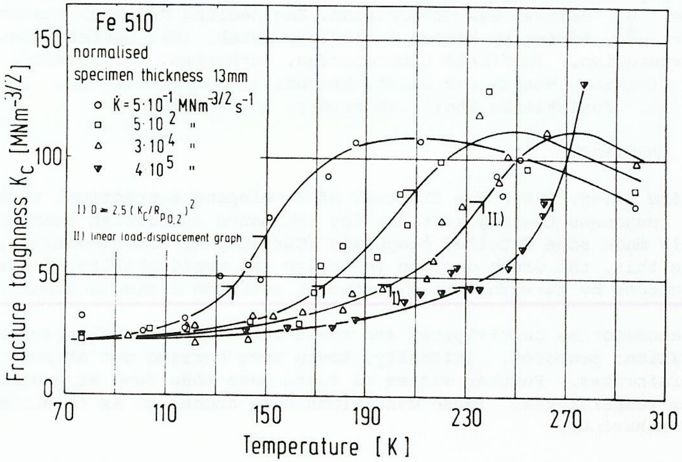

Fig. 7. Fracture toughness K_C of steel Fe 510 as a function of temperature at four different loading rates K

The K_C-values of the steels Fe 510 and 20 MnMoNi 5 5 are shown in Figs. 7 and 8. Similar trends as for the steel mentioned previously are observed. The lower shelf of the curves tends to a constant value independent of temperature and strain rate. The transition from brittle to ductile fracture is shifted to higher temperatures with increasing strain rates. The lower strength structural steel Fe 510 seems to be the most sensitive to changes in strain rate of the three steels investigated. The shift of transition temperature is 94 K from static loading to impact loading conditions compared with 69 K for the 20 MnMoNi 5 5. The opposite sensitivity of yield strength and fracture toughness suggests an inverse relationship between these two material properties. Fig. 9 shows fracture toughness data of the three steels investigated as a function of yield strength which has been evaluated under identical conditions of strain rate and temperature with the help of the rate parameter. All data fit a relatively broad scatterband. The results of the high strain rate tests tend to the upper bound of the band. This might be due to adiabatic heating which has been observed in the tensile tests. However, the knowledge of the temperature and strain rate dependence of the yield strength and the K_{IC}-values under static loading conditions make it possible, to give a conservative prediction of fracture toughness for a given material under dynamic loading conditions.

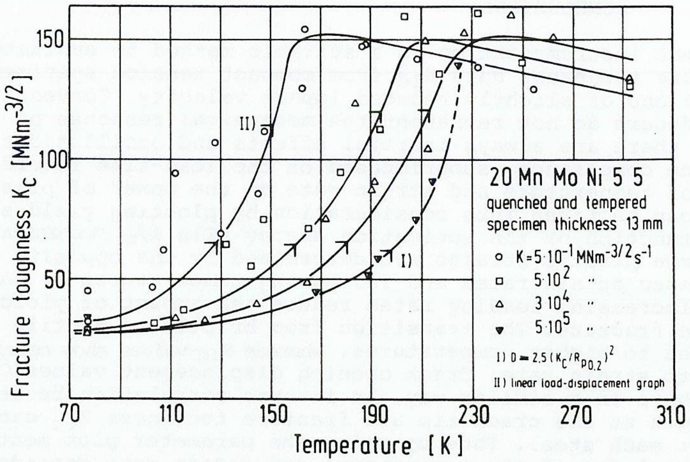

Fig. 8. Fracture toughness K_C of steel 20 MnMoNi 5 5 as a function of temperature at four different loading rates $\dot{K}$

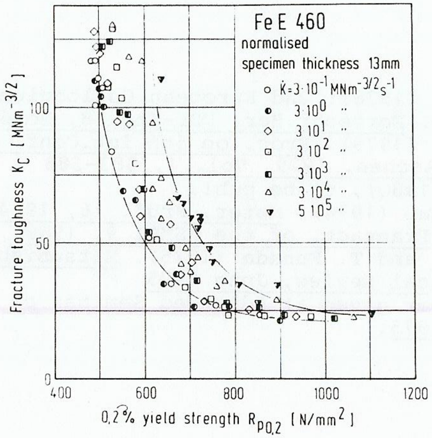

Fig. 9. Fracture toughness K_C of steel Fe E 460 as a function of yield strength $R_{p0.2}$ at six different loading rates $\dot{K}$

CONCLUSIONS

Specimen instrumentation is a suitable method to evaluate dynamic fracture toughness data K_{Id} from compact tension specimens under the conditions of slightly reduced impact velocity. Conventional load transducers do not represent the mechanical response of the specimen since there are always inertial effects and oscillations due to the machine compliance, superimposed on the load-time record. The influence of temperature and strain rate on the onset of plastic deformation can be taken into consideration by plotting yield strength data as a function of the activation energy $kT\ln A/\dot{\varepsilon}$. Mechanical properties at large plastic strains are determined by the opposite influence of increased strain rates and increasing temperatures by adiabatic heating. Increasing loading rates reduce the amount of yielding to occur before fracture. The transition from brittle to ductile fracture is shifted to higher temperatures, whereas K_{Ic}-values show nearly no sensitivity to strain rate. Crack opening displacement values COD were found to behave in a similar way. An inverse correlation between yield strength at the crack tip and fracture toughness K_{Ic} can be established for each steel. Thus, by using the parameter plot mentioned above, the knowledge of the temperature and strain rate dependence of yield strength, enables the dynamic fracture toughness data to be evaluated for a given steel.

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