DYNAMIC FRACTURE MECHANICS TESTING OF THE HSLA STEEL

Z. Radakovic[1], G. B. Lenkey [2], A. Sedmak[1]

ABSTRACT

The high strength low alloyed steel (HSLA) has been tested using instrumented Charpy pendulum in order to assess its impact fracture resistance. Testing was performed at different temperatures (-70°C; -30°C; +20°C), using different energy levels (300 J and 62.5 J) on standard three-point bending specimens with different crack lengths (a/W=0.35÷0.65), having the parallel and perpendicular orientation to rolling. The applied magnetic emission (ME) technique was used to determine initiation of crack propagation. The ME signal was recorded by digital oscilloscope and used to determine initiation of brittle fracture, whereas for ductile fracture the signal was integrated (MF). The representative dynamic fracture property, J_{Id}, is determined from data obtained from measurements that are handled by a spreadsheet procedure.

INTRODUCTION

Reliable operation of structures requires precise judgement of cracks or crack-like defects behaviour. Usually the dynamic loading is more critical for a structure than the static one, thus the determination of dynamic fracture mechanics properties of materials is often necessary. One of the most widely used technique for this purpose is the instrumented impact testing. Recently the magnetic emission (ME) technique was used to determine initiation of crack propagation and applied for the instrumented impact testing of certain types of steels, including railroad steels and reactor pressure vessel steel /1,2/.

Certain temperature dependence for ferritic steel material is known to exhibit lower shelf values of fracture toughness in case of cleavage at lower temperatures; and upper shelf values for ductile type of fracture. An intermediate region between the former two is observed as a mixed mode of fracture. Various types of fracture can as well be evident from force-time records of instrumented impact tests. The main object of this research was to test HSLA steel behaviour by applying dynamic forces under different temperature and speed at impact, from a fracture mechanics point of view. To achieve this the steel was tested at different temperatures (-70°C; -30°C; +20°C), using different energy levels (300 J and 62.5 J) on standard three-point bending specimens with different crack lengths (a/W= 0.35÷0.65), having parallel and perpendicular orientation to rolling. In this paper some results and conclusions of an extensive investigation are presented.

1) Faculty of Mechanical Engineering, 27. Marta 80, 11000 Belgrade, Yugoslavia
2) BAY ZOLTÁN Institute for Logistics and Production Systems, 3519 MISKOLC, IGLÓI U. 2. and University of Miskolc, H-3515 Miskolc-Egyetemvaros, Hungary

EXPERIMENTS

The chosen material was hot rolled steel (0.075% C) micro alloyed with Nb and Ti, produced by SARTID 1913 - Smederevo, with yield stress R_e=411 MPa. It is delivered in the shape of hot rolled plates, thickness 12 mm. Exactly 200 standard V-notched Charpy specimens were produced, with notch tip radius r=0.25-0.3 mm, 100 were machined in the rolling direction and 100 perpendicular to rolling direction. Subsequently, the specimens were pre-cracked using a high frequency fatigue regime with the RUMUL device. Fatigue cracks spread from notch tip in the direction of material thickness, thus forming ligaments of different sizes. In order to avoid plastic deformation, pre-cracking was performed in several fatigue steps, i.e. by using the gradual step change of dynamic load and source frequency (from the initial value of 300 Hz to as low as 160 Hz). Different crack lengths were produced in order to investigate its effect on dynamic fracture mechanics properties.

All experiments were performed at the Department of Mechanical Engineering, University of Miskolc. The instrumented impact testing system with computer aided data-acquisition was based on real time force measurements by strain gauges glued on both sides of the hammer tup /3/. The magnetic emission probes were located close to the notch root of the specimen. The instrumentation of an impact pendulum enabled measurement of the force and magnetic signals as a time function, while computer aided data-acquisition maintained constant monitoring and recording. Monitoring and recording of data started by triggering an external optical device. The impact velocity was determined by measuring the time interval between two pulses, which were produced when the hammer passed through the optical trigger device. Strain gauges and emission probes were connected to voltage sources and amplifiers, and their signals were recorded on the TEKTRONIX TDS 420A digital oscilloscope. The data was then transferred to the PC, where all evaluations were handled by spreadsheet programs, since at least 15,000 sampled data was recorded for each specimen alone.

The magnetic emission probe (ME), located on the instrumented pendulum, recorded the change in the external magnetic field surrounding the propagating crack. The calibrated strain gauge acted as a force (load) transducer, also located on the tup, and was used for indirect measurement of impact load. Photocell sensors were used for measuring the triggering time. The instrumented pendulum was connected to the signal amplifier and voltage supply, and both were tied to the four-chanelled digital oscilloscope (Tektronix TDS 420 A) with the T-trigger, 200 Hz frequency capacity, and 100 MS/s recording capability. The following time dependent variables were recorded: force, ME and pulse (trigger). The positioning of Charpy hammer was defined by a choice of two impact speeds: V_1=5.5 m/s and V_2=2.5 m/s producing two different energy levels, 300 J and 62 J, respectively.

The applied magnetic emission technique enabled precise definition of the onset of crack growth in the ferromagnetic material, as the point of noticeable change of MF-t slope (MF is integrated ME signal), /2/. Taking this point into account one can define the related absorbed energy, U, which is used to calculate the critical J-integral data from the well-known relation: $J=2U/[B/(W-a)]$. For the brittle fracture behaviour K_{Id} should be evaluated according to the ASTM standard /4/ if the ``$3\tau$`` condition is fulfilled /5/ or by using procedure described in /6/.

RESULTS AND DISCUSSION

Analysis of the force-time, ME-time and MF-time curves shows various material fracture behaviour, from brittle to ductile. Over 100 specimens were tested, and as an example of one ductile and one brittle material behaviour these diagrams are shown in Figs. 1 and 2, respectively. Shape of the force-time, ME-time and MF-time curves follow closely different material behaviour (brittle at -70°C, ductile at 20°C). Namely, as one can see in Fig. 1a, there was an increase of force from the point of stable crack initiation, i.e. stable crack propagation preceded unstable event. The point of stable crack initiation was determined from the slope change (Fig. 1 – 0.79 ms). In the case of brittle behaviour, Fig. 2, one can notice an abrupt decrease of force after the maximum value, which is also the point of unstable crack initiation. It is also clear that ``3τ`` condition is not fulfilled.

Figures 3 and 4 show results obtained from calculating J_{cm}^{d} in function of pre-crack lengths for U (parallel-to-roll) and P (perpendicular-to-roll) specimens at impact speed V=5.5 m/s and V=2.5 m/s and test temperature t=20°C. The average value of J_{cm}^{d} for the higher impact speed is 180 kJ/m^2 (scatter is 50 kJ/m^2), Fig. 3, indicating higher crack growth resistance of material, since the corresponding value for lower impact speed is 90 kJ/m^2 (scatter is approximately the same), Fig. 4. From these two diagrams one can also conclude that the scatter of J_{cm}^{d} values produced by different crack length does not differ significantly from the usual scatter of the similar static tests.

In Figs. 5 and 6 fracture toughness versus temperature is shown, where the fracture toughness is calculated for all three types of fracture modes (brittle, mixed, ductile), for both U and P specimens, respectively. In the case of brittle fracture (-70°C) the fracture toughness is calculated either by ASTM E399 standard procedure (values denoted as K_{Id}) or by procedure /6/ (values denoted as K_{Jc}), depending on ``3τ`` criterion. In the case of ductile fracture (20°C) the fracture toughness is calculated using J_{cm}^{d} values and denoted as K_{Ji}, whereas the mixed fracture is treated in both ways, as for brittle and as for ductile fracture. Results shown in Fig. 5 and 6 clearly indicate temperature influence on fracture toughness values, proving pronounced difference in HSLA steel behaviour at lower temperatures (-70°C and -30°C) and room temperature (20°C).

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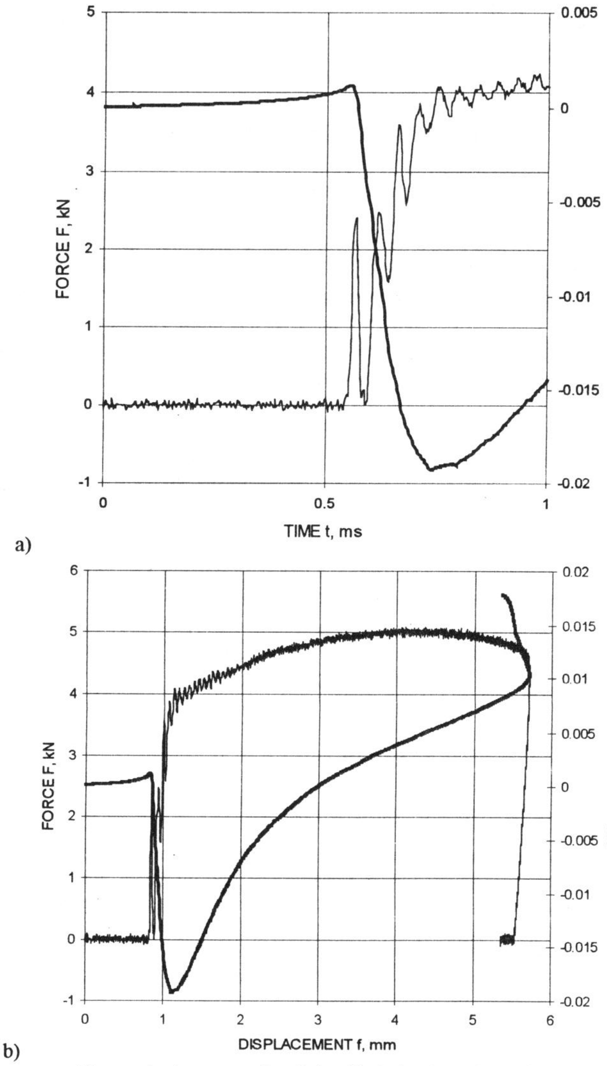

Figure 1. An example of ductile behaviour (t=20°C)

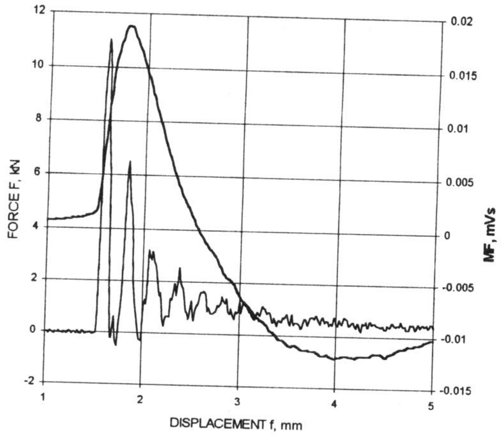

Figure 2. An example of brittle behaviour (t=-70°C)

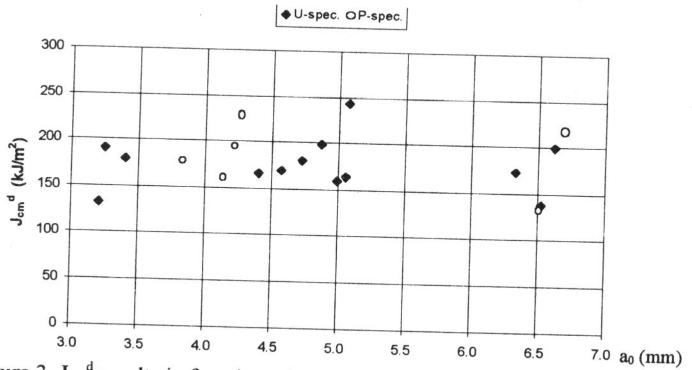

Figure 3. J_{cm}^{d} results in function of pre-crack lengths for V=5.5 m/s and t=20°C

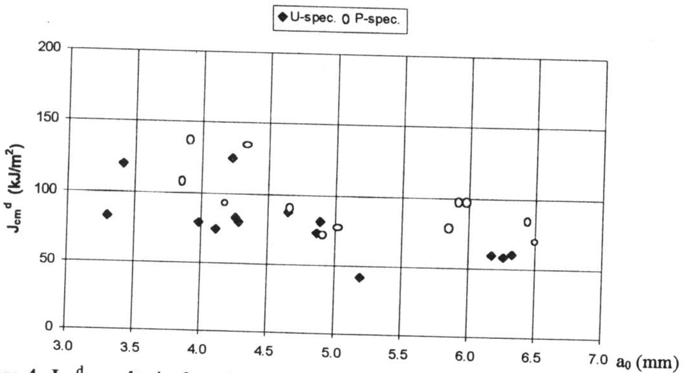

Figure 4. J_{cm}^{d} results in function of pre-crack lengths for V=2.59 m/s and t=20°C

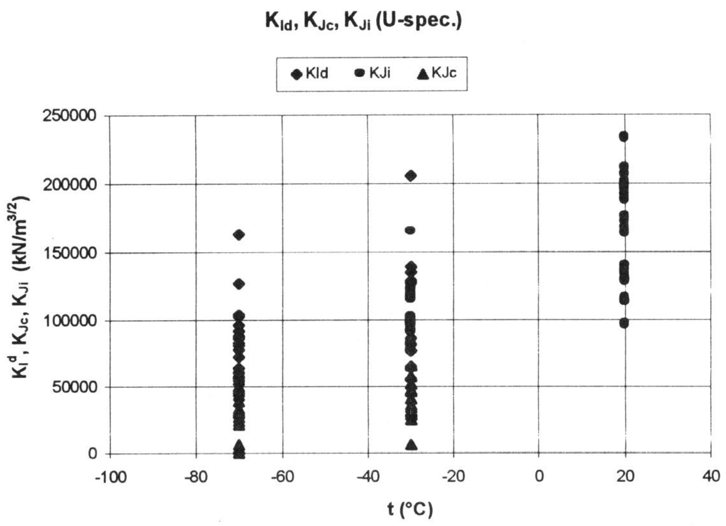

Figure 5.- Fracture toughness versus temperature

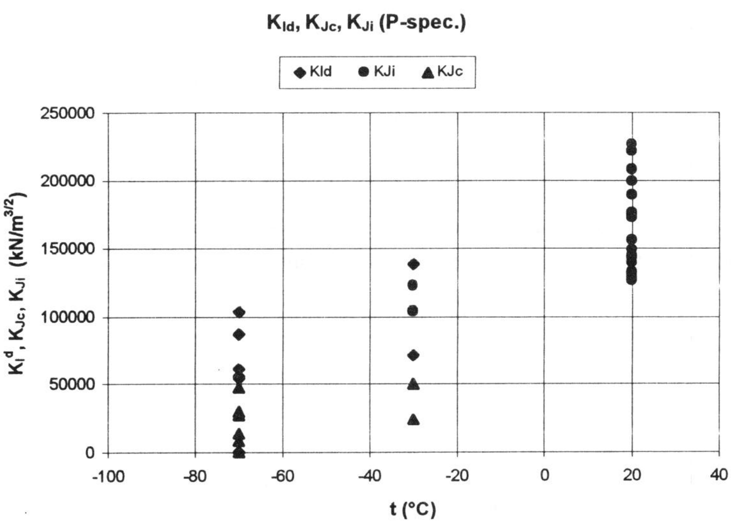

Figure 6.- Fracture toughness versus temperature