DYNAMIC FRACTURE MECHANICS APPROACH IN REACTOR VESSEL SURVEILLANCE

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ABSTRACT

The introduction of the F.M. approach in nuclear pressure vessel surveillance programmes entails a greater complexity in the execution of the tests.

Instrumented impact tests allow the rapid and simple determination of a large mass of data, which may be analysed in terms of F.M. They are thus suitable for the determination of the caracteristics of a material before and after irradiation.

The test is examined with particularly reference to the dynamic determination of C.O.D. and K_{IC}. The philosophy of the test is described, and the possibility is considered of the correlation of F.M. results on heavy sections of non-irradiated material with those obtained dynamically on small specimens of irradiated materials.

The results presented refer to 100 mm plate of Mn, Mo pressure vessel steel.

1. INTRODUCTION

Present design against brittle fracture of steel nuclear pressure vessels requires a precise knowledge of tensile strength and notch ductility of unirradiated and irradiated metallic components. In this way vessel reliability may be assured both at the reactor start up and during the vessel life, mechanical properties of steel being markedly affected by neutron irradiation. Radiation embrittlement is generally evaluated in terms of increase in ductile-brittle fracture transition temperature and of reduction in fracture resistance: both changes are measured by checking the absorbed energy in dynamic fracture tests. The Charpy V impact test, combined with the DWT (drop weight test), allows a sufficiently precise evaluation of NDT temperature and a meaningful evaluation of radiation effects: all the nuclear vessel surveillance programs presently under operation are consequently based on tensile and Charpy V impact tests (1). Criticism of the theoretical interpretation of Charpy-V impact data (2) has led to extensive studies and sophisticated modifications of the testing machine in order to achieve greater significance of testing data and to pursue a more quantitative approach to fracture analysis. The evaluation of the critical stress intensity factor (K_{IC}) at different temperatures together with recent observation (3) that the irradiation-induced shift along the temperature axis of the K_{IC}/T and E/T curves is of the same order in the same irradiation conditions, have also given further significance to surveillance programmes based on Charpy-V impact data, whenever the K_{IC}/T reference curve for non-irradiated steel is known.

Nevertheless in many cases the reference curve for the non-irradiated material cannot be obtained because, since the reactor has been operating several years, the original vessel plate coupons are no longer available; moreover the determination of a complete K_{IC}/T curve in the temperature range above 0°C requires the use of particular test equipment and very thick CT specimens to guarantee plain strain fracture conditions. whenever original material is still available.

The aim of the present paper is to discuss the possibility of obtaining significant dynamic K_{IC} and COD values from Charpy impact test on irradiated materials, limiting any special instrumentation to the testing machine and avoiding complicated handling of the irradiated test specimens.

2. TEST METHOD

The instrumentd Charpy pendulum has been adopted recently in normal laboratory practice to determine, through impact tests, the yield and fracture load and the time to fracture of notched specimens (4) (5) (6). During the test, the load -time recording required for the determination of the true bending and fracture stress of the specimen may be affected by spurious oscillations which may represent a high proportion of the load to fracture, and careful corrections are thus required to avoid misleading data (2).

The correct value of the fracture stress may only be determined knowing the time to fracture of the specimen, through the formula (1), since during the initial impact no simple relationship links the load on the tup or on the anvil to the bending stress on the test specimen (Fig. 1).

2.1. K_{Id} Measurement

The fracture force F_{fd} and the stress intensity factor K_{IC} may be determined, knowing the time to fracture t_f and the delay time to fracture, t_o (part of the time between the instant of impact of the tup on the specimen and the instant of the impact of the specimen on the anvil) from the following relationship:

$$F_{fd} = V_o \quad S_e \; (t_f - t_o) \tag{1}$$

$$K_{Id} = y \cdot \frac{F_{fd}}{B \quad W} \tag{2}$$

The meaning of symbols and the theoretical derivation of the above relationship are summarized in the appendixs.

It is apparent that, for the evaluation of F_{fd} the precise knowledge of the t_f and t_o is required and that both values can be only measured directly on the specimen during the test.

Several methods have been suggested, but their use is limited in the post-irradiation oondition since they require complicated handling of the specimen. These methods involve the measurement of specimen strain, either through post yield strain gauges attached in several positions directly on the specimen, or by measuring the temperature increase due to adiabatio plastic strain during fracture (7). In other cases the use of resistive paints has also been suggested (8).

One of the Authors observed, in the course of an extensive experimental programme that the fracture diagrams for geometrically identical specimens follow exactly the same behaviour, and that from any abrupt change in the time-load diagram it is possible to determine the time to fracture of the specimen (8).

Fig. 2 shows some load-time diagrams obtained with identically fatigue precracked Charpy specimens fractured in the temperature range from -190°C to room temperature. From any abrupt change in the specimen rigidity, the correct value of the time required to fracture the specimen can be deduced.

2.2. COD Measurement

To obtain the COD values at the tip of a fatigue crack it is necessary to consider the notch profile during loading (Fig. 3), assuming that plastic deformation occurs without crack extension and that the notch faces open as a hinge about a centre of rotation due to the three point bending.

The crack opening displacement δ can be related to the surface displacement, δ_s, and to the specimen deformation, d_p, through the following equations (9):

$$\frac{\delta_s}{\delta} = \frac{a}{b/n} + 1 \tag{3}$$

and

$$\frac{d_p}{\delta} = \frac{W}{a+b/n} \left(\frac{a}{b/n} + 1\right) \tag{4}$$

The symbols are defined in the appendix and in Fig. 3; n is a numerical constant depending on the specimen deformation d_p.

Knowing the ratio $\frac{d_p}{\delta}$ as a function of d_p (see Fig. 3.), the critical crack opening displacement δ_{cd} (dynamic) may be obtained from

$$\delta_{cd} = \frac{\delta}{d_p} d_f \qquad (5)$$

where

$$d_f = \frac{v_o + v_f}{2} (t_f - t_o) - \frac{F_{fd}}{S_m}$$

is the total pendulum displacement after the contact with the specimen, less the machine deformation.

3. EXPERIMENTAL WORK

Charpy V test specimens were obtained at different depths and in different orientations from 100 mm thick Mn-Mo pressure vessel steel plate: surface, 1/4 and 1/2 thickness either in WR or RW direction. One half of the specimens were fatigue precracked and the total crack length (notch + fatigue crack) was 5 mm, while the standard notch is only 2mm depth. Impact tests were performed using an instrumented Charpy pendulum and the recorded load-time diagrams were used to calculate the data quoted in Table 1.

Some of the results referring to 1/4 thickness WR specimens are given as a reference: Fig. 4 shows the absorbed impact energy and percent crystallinity of Charpy V notch and fatigue precracked Charpy V specimens tested at different temperatures; Fig. 5 summarizes the data obtained from the load-time diagrams (F_{fd}, F_{yd}, F_{md}, F_{ca}, t_f) on the same specimens, while in Fig. 6 are plotted K_{Id}, σ_{yd} and δ_{cd} values versus test temperature. In the last figure are also shown, for comparison, the behaviour of these parameters obtained in static conditions (10)for similar materials.

4. DISCUSSION OF THE RESULTS

The fracture mechanics approach to the NDT temperature suggests that the nominal critical stress σ_c allowing the propagation of a fracture in a structure containing a surface crack of depth "a" may be obtained from the Irwin equation (11).

$$\sigma_c = \frac{K_{IC}}{1.1\sqrt{\frac{\pi a}{Q}}} \qquad (7)$$

where Q is a geometrical factor.

In a dynamic test the NDT is reached when the critical stress σ_c is equal to the dynamic yield stress σ_{yd} and the equation (7) changes to

$$\frac{K_{Id}}{\sigma_{yd}} = 1.1 \sqrt{\frac{\pi a}{Q}} \qquad (8)$$

In the case of DTT specimens the value of the right hand side of equation (8) is between $0.4 \div 0.6 \sqrt{\text{inch}}$ (12).

The test specimens fractured close to the NDT temperature do not generally satisfy the plain strain conditions given by the equation,

$$B, \quad a \geqslant 2,5 \left(\frac{K_{Ic}}{\sigma_Y}\right)^2 \qquad (9)$$

The T_2 and T_5 quoted in Tab. 1 refer to the temperatures at which equation (9) is still satisfied with Charpy-V notch specimens (a=2mm) and fatigue precracked Charpy specimens (a=5mm). These values are indicated also in Fig. 6 and show the limits of validity, according to ASTM conditions, of the K_{Id} vs. temperature curves. It is in fact known that the coefficient 2.5 in equation (9) is sometimes conservative and that 1.5 would still be sufficient to fix the plain stress-plain strain transition. A remarkable difference (ranging from 104° to 142°C) has been observed in the NDT temperature measured with Charpy-V notch and fatigue precracked Charpy specimens; a part of the increase, about 50°C, (T_5-T_2 in Fig. 6) is due to the crack depth, (see eq. 9) while the residual part could depend on the sharpness of the crack tip.

It is evident from Fig. 4 and Table 1 that the use of fatigue precracked Charpy specimens does not affect the transition temperature measured from the increase of impact energy or from the percent crystallinity in the fracture surface. Nevertheless, when the instrumented pendulum is used (see Fig. 5) and NDT is evaluated as the temperature at which the fracture and yield load are equal, a remarkable difference can be observed.

A less important difference was observed in T_{ca} values, that is in the crack propagation conditions. T_{ca} values are, practically identical to the transition temperatures measured at 50% crystallinity. It is thus evident that standard Charpy tests may only be used to obtain some indication of the crack arrest temperature for a given thickness.

More information about the crack start and propagation in dynamic conditions may be obtained only from instrumented tests. The values of K_{Id} quoted in Fig. 6 are independent, in the temperature range of validity of the tests, of the specimen size and can be considered a metallurgical property of the material. K_{Id} is, moreover, an important parameter for the qualification of the base metal because whenever the fracture starts from the weld metal or HAZ of a vessel and propagates through the base metal, the resistance to propagation will depend on the dynamic fracture toughness. Moroever in pressure vessel steels, because of their high strain rate sensitivity, it could be useful to know K_{Id} even if the fracture can initiate in static conditions. In fact, some results (13) on plain carbon steels exist which, if confirmed, should show an identity between the values of K_{Id} and K_{IT} (trough) (that is the minimum value of K_{IC} in the whole range of possible load application speeds). This indication seems to reduce the necessity for knowledge of static K_{IC} values in the strain rate sensitive base materials in order to obtain information about crack initiation. In order to compare the K_{IC} and K_{Id} behaviour and to evaluate the temperature shift between static and dynamic conditions it is necessary to know the range of validity, according to ASTM suggestion, of specimen of identical thickness.

On this bases if one precise value for "a" or B is fixed, the ratio $\frac{K_I}{\sigma_y}$ is known for either static or dynamic test. This ratio defines, in the diagrams of Fig. 6, a precise temperature. The static dynamic temperature shift may be defined for this thickness in an unequivocal way. The same thinking may be applied when the irradiation induced shift must be evaluated.

In Fig. 6, as an example ΔT_{10} shows the static-dynamic shift for 10 mm thick plates.

5. CONCLUSIONS

Instrumented impact tests have been carried out to characterize a steel for nuclear pressure vessels through dynamic K_{IC} measurements using fatigue precracked standard Charpy specimens. Absorbed energy vs temperature diagrams were compared with more completed ones obtained from the load-time recording on the tup and on the machine anvil. The behaviour of the specimen-pendulum system was also analyzed with particular care for the K_{Id} determination.

Some general conclusions are:

a) When the transition temperature was measured on the basis of percent crystallinity of the fracture surface and not with reference to a fixed absorbed energy value the results were practically identical either in V notched or fatigue precracked specimens and no significant difference was also observed between WR and RW specimens. The 50% crystallinity temperature was observed to be close to the crack arrest temperature in both types of specimen.

Consequently the standard Charpy impact data could be considered for the measurement of T_{ca}, provided that the limitations due to the small specimen sizes are taken into account.

b) Further improvement could be obtained by the NDT measurements to define the transition between brittle and ductile initiation conditions. In this case also if the specimen sizes and notch severity are inadequate some improvement was obtained by using fatigue precracked specimens.

c) Size and geometrical limitations can be overcome only through the fracture mechanics analysis of load-time diagrams of precracked Charpy specimens when the ASTM (eq 9) conditions are satisfied and the K_{Id} is determined. These values are of more practical meaning in base material characterization as this material is generally involved in crack propagation which is a dynamic phenomenon. Static K_{IC} determination is, in fact, more significant in weld metal or HAZ characterization.
In strain rate sensitive steels the marked temperature shift allows valid K_{Id} data to be obtained with smaller specimens in the same temperature range.

The K_{Id} test method described offers a simple procedure for the rapid evaluation, using not particularly sophisticated instrumentation, either for non irradiated or irradiated materials at different temperatures. It is foreseen that Charpy specimen from sorveillance programmes already in progress may also be used and that more extensive data can be obtained.

REFERENCES

(1) ASTM Book of Standards part 30. Surveillance tests on structural materials in nuclear reactors. Rec. Practice E 185-66.

(2) Venzi S., Priest A.H., May M.J., . Influence of inertial load in instrumented impact tests. ASTM STP 466 p. 165 (1969).

(3) Mager T.R., Yanichko S.E., . Use of fracture mechanics in reactor vessel surveillance . Westinghouse Electric. Co., Report WCAP-7538 (July 1970).

(4) Fearnehough G.D., and Hoy C.J., . Mechanism of deformation and fracture in Charpy test as revealed by dynamic recording of im pact loads. J.I.S.I. Vol. 202, (1964), p. 912.

(5) Turner R.A., . Measurement of fracture toughness by instrumented impact test. ASTM STP 466, (1969) p. 93.

(6) Wullaert R.A., . Applications of the instrumented Charpy impact test. ASTM STP 466, (1969) p. 148.

(7) Priest A.H., and May M.J., . Fracture toughness testing in impact. BISRA open report MG/C/46/69. (1969).

(8) Venzi S., . Problemi connessi con la prova di resilienza strumen tata . CSM rapporto interno 1043/R . (1971).

(9) Elliott D., and May M.J., . The effect of position of measurement on crack opening displacement. BISRA open report MG/C/47/69. (1969).

(10) Wessel E.T., . Linear elastic fracture mechanics for thick walled, welded steel pressure vessels. Material property considerations . Proceedings of the symposium on fracture toughness concepts for weldable structural steel . Risley. April 1969.

(11) Irwin G.R., Krafft F.J., . Integration of metallurgical and frac ture mechanics concepts of transition temperature factors rela ting to fracture-safe design for structural steel . NRL report 6900 (1969); Welding Res. Concil Bull. 141 (1969).

(12) Loss F.J., and Pellini W.S., . Coupling of fracture-mechanics and transition temperature approaches to fracture-safe design . Proceedings of the symposium on fracture toughness concepts for weldable structural steel . Risley(April 1969).

(13) Turner C.E., Radon J.C., . Fracture toughness measurements on low strength structural steels .
Proceedings of the second international conference on fracture. Brighton(April 1969).

APPENDIX 1 – Fracture force determination

The pendulum is considered to be a system of mass M and stiffness S_m, while the test specimen has a stiffness S_p and mass nil; the following equation can represent the equilibrium of the forces acting.

$$M \frac{d^2 x}{dt^2} + S_e x = 0 \qquad (A.1)$$

where x is the displacement of the tup after the impact, t the time and S_e is the equivalent rigidity of the system.

The force F acting on the test specimen is identical to that operating on the machine, while the displacement x is equal to the sum of the deformation of the machine d_m and of the specimen d_p

$$x = d_m + d_p \qquad (A.2)$$

and

$$\frac{F}{S_e} = \frac{F}{S_m} + \frac{F}{S_p}$$

$$Se = \frac{S_m \cdot S_p}{S_m + S_p} \qquad (A.3)$$

The speed of specimen deformation, V_p, may be obtained by

$$V_p = \frac{Se}{S_p} \frac{dx}{dt} \qquad (A.4)$$

and in the case of brittle specimens equation (A.4) becomes

$$V_p = \frac{S_e}{S_p} \quad Vo \qquad (A.5)$$

where V_o is the pendulum speed at impact.

Knowing the equivalent rigidity S_e and the pendulum speed V_o the three-point bending load may be obtained (see Fig. 3) from the equation:

$$F = V_o \, S_e \, (t - t_o) \qquad (A.6)$$

where t_o is a part of the time between the instant of impact of the tup on the specimen and the instant of impact of the specimen on the anvil, to be determined experimentally.

APPENDIX 2 - Symbols -

a	= crack length	σ_c	= critical stress
b	= (W-a) depth of ligament	σ_y	= yield stress
B	= specimen thickness	σ_{yd}	= dynamic σ_y
Cr	= cristallinity percent	t	= time
Crf	= $\frac{Ffd - Fca}{Fmd}$ x 100 = drop in load percent (proportional to Cr)	t_f	= time to fracture
		t_o n	= initial time
		T	= temperature
δ	= COD, crack opening displacement	T_{ca}	= crack arrest temperature
δ_{cd}	= dynamic critical δ	T_p	= transition temperature (propagation of fracture before or after the maximum load)
δ_s	= surface δ		
d_f	= specimen deformation to fracture		
		$T_{0.2}$	= transition temperature at δ = 0.2 mm
d_m	= machine deformation		
d_p	= specimen deformation	T_2	= plain strain-plain stress temperature transition for 2 mm crack depth
E	= Charpy V absorbed energy		
F	= load		
F_{ca}	= crack arrest load	$T_{3.5}$	= transition temperature at 3.5 Kg/m
F_f	= fracture load		
F_{fm}	= dynamic F_f	T_5	= plain strain-plain stress temperature transition for 5 mm crack depth.
F_m	= maximum load		
F_{md}	= dynamic F_m		
F_y	= yield load	T_{10}	= plain strain-plain stress temperature transition for 10 mm thick specimen
F_{yd}	= dynamic F_y		
K_{Ic}	= plane strain critical stress intensity factor		
		T_{50}	= transition temperature at 50% Cr
K_{Id}	= dynamic K_{Id}		
M	= pendulum mass	V_f	= final pendulum speed
n	= rotational constant	V_o	= initial pendulum speed
NDT	= Nil ductility temperature	V_p	= specimen speed of deformation
Q	= flow shape parameter		
Rw	= longitudinal direction (test specimen)	W	= specimen depth
		WR	= transverse direction (test specimen)
S_e	= equivalent stiffness		
S_m	= machine stiffness	x	= tup dislocation after impact
S_p	= specimen stiffness	y	= geometrical factor (depending on $\frac{a}{W}$)

Test specimen	Transition Temperatures (°C)	Temperature shift (°C)	½ thickness		1/4 thickness		Surface	
			WR	RW	WR	RW	WR	RW
precracked Charpy V	T_2		– 146	– 150	– 132	– 130	– 156	– 168
	T_5		– 91	– 97	– 68	– 68	– 103	– 122
	NDT		+ 7	+ 10	+ 32	– 5	0	– 10
	$T_{0.2}$		+ 20	+ 48	+ 47	+ 34	+ 40	+ 32
	T_{50}		+ 15	+ 26	+ 19	+ 19	– 6	+ 2
	T_{ca}		+ 30	+ 45	+ 45	+ 45	+ 25	+ 20
		(T_5-T_2)	55	53	64	62	53	46
		ΔT_{10} dynamic less static data	114	104	133	141	98	92
Charpy V	NDT		– 105	– 104	– 92	– 130	– 104	– 152
	T_p		– 4	– 50	– 40	– 38	– 74	– 40
	T_{ca}		+ 32	+ 60	+ 24	– 17	+ 57	+ 26
	$T_{3.5}$		+ 15	– 7	– 8	– 43	+ 4	– 12
	T_{50}		+ 29	+ 35	+ 14	– 8	+ 18	+ 20
Charpy V and precracked Charpy V		Δ NDT (*	112	114	124	125	104	142
		ΔT_{50} (*	– 14	– 9	5	27	– 24	– 18
		ΔT_{ca} (*	– 2	– 15	21	62	– 32	– 1
		*precracked Charpy less Charpy V data						

T a b l e 1 – Transition temperatures and temperature shift in Mn Mo steel specimens (100 mm thick plate).

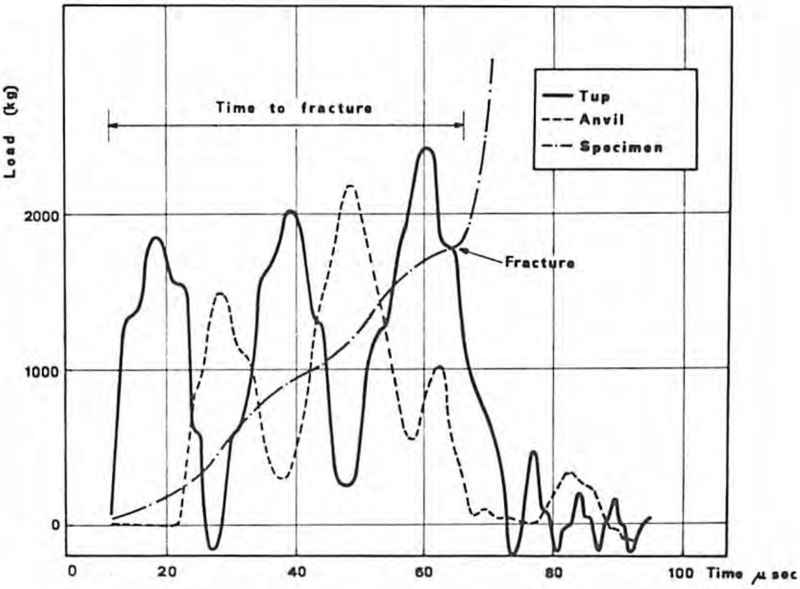

Fig. 1 - Load-time diagram for tup, anvil and specimen.

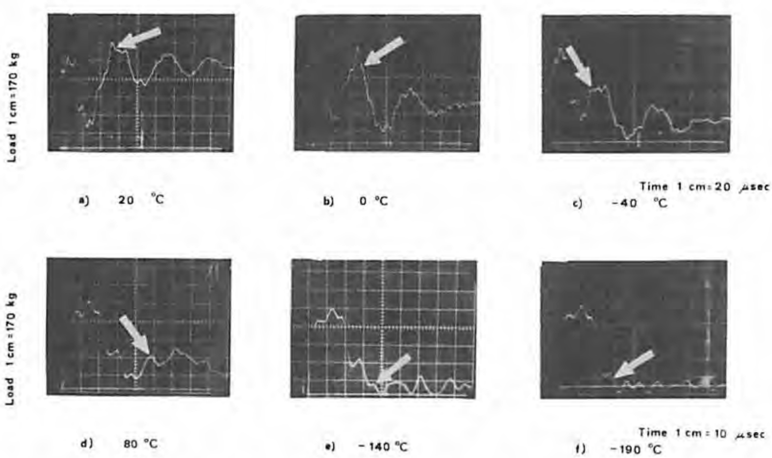

Fig. 2 - Time to fracture obtained through comparison of fracture diagrams for specimens with identical crack depth tested at different temperature. Time to fracture is defined by the desappearing of characteristic picks. In picture a) arrow shows the instant of specimen yielding.

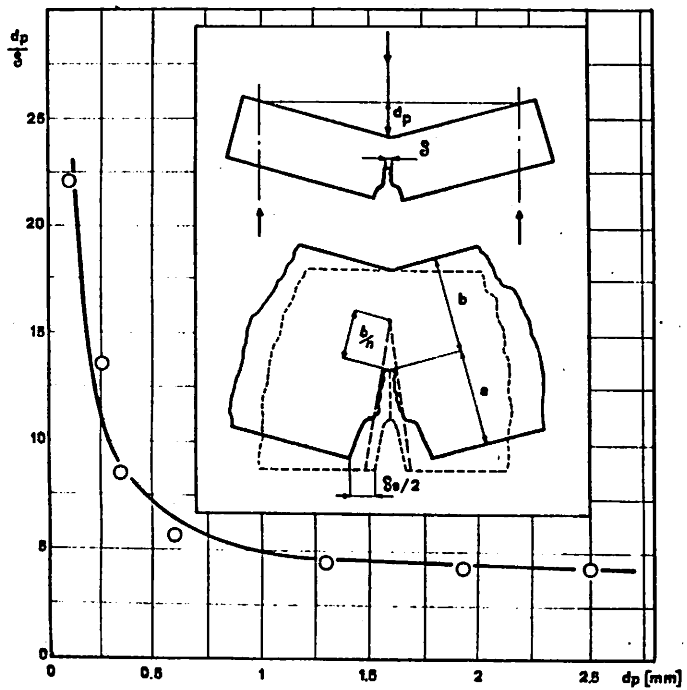

Fig. 3 - Behaviour of the specimen deformation-crack opening displacement ratio at different specimen deformation.

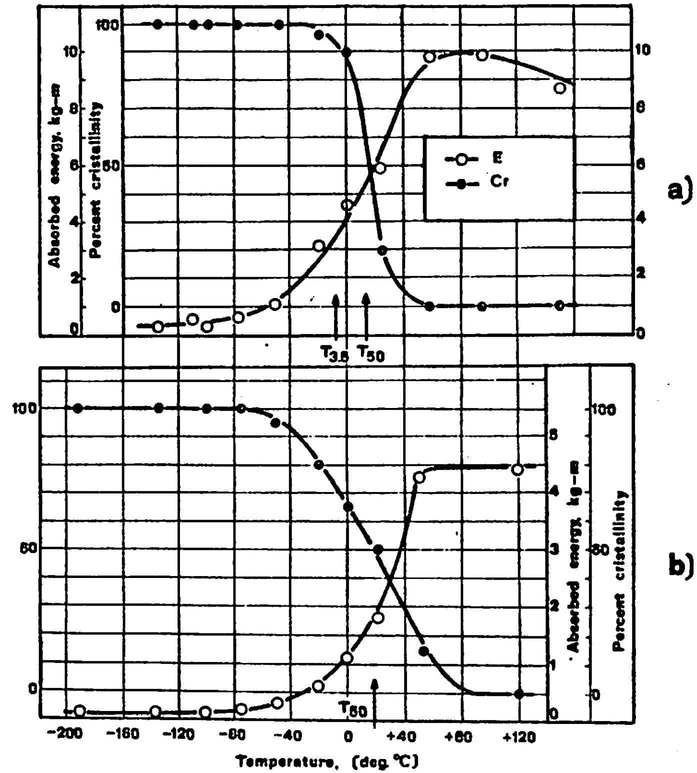

Fig. 4 - Impact energy and percent cristallinity for Charpy V notched and fatigue precracked specimens tested at different temperature (1/4 thickness WR direction).

a) Charpy specimens;
b) fatigue precracked Charpy specimens.

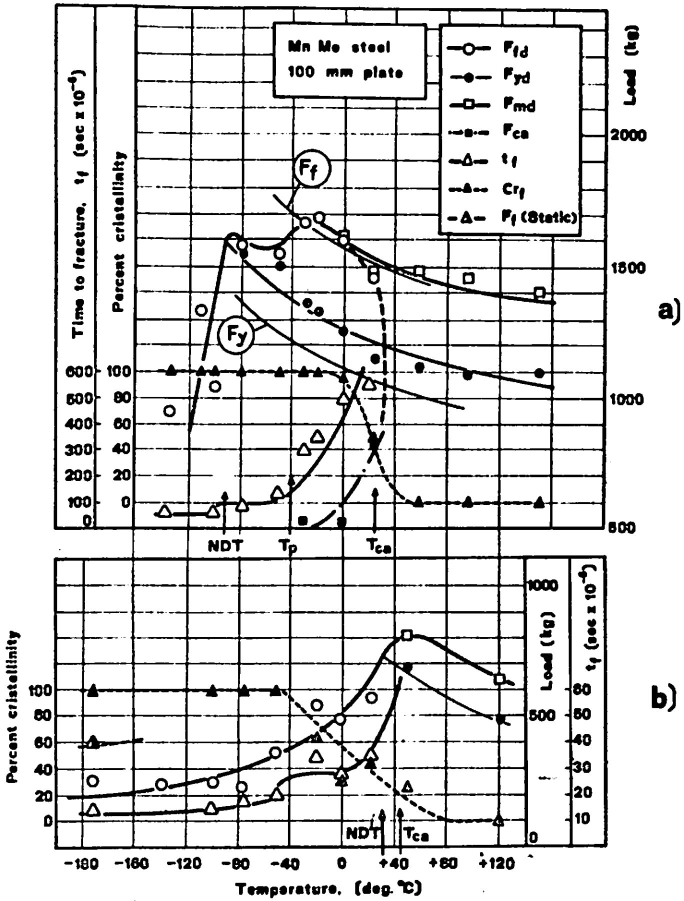

Fig. 5 - Load-time diagrams (1/4 thickness WR direction).

a) Charpy specimens;
b) fatigue precracked Charpy specimens.

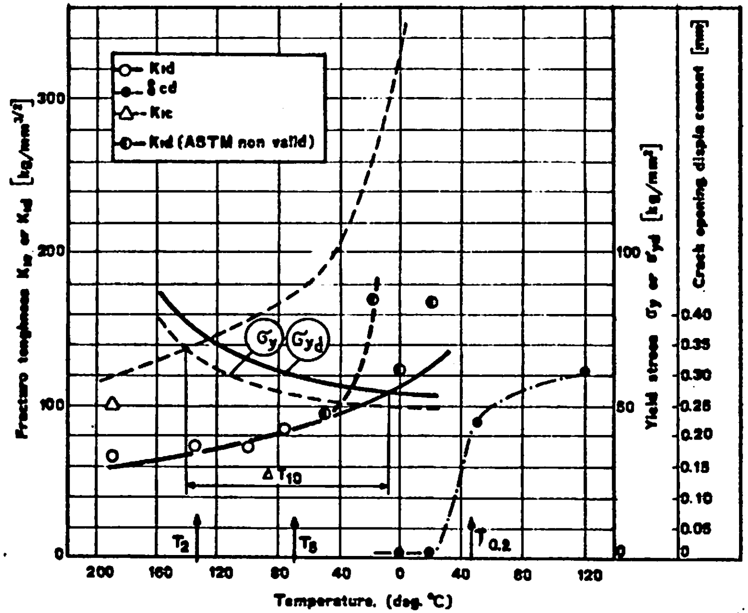

Fig. 6 - K_{Id}, σ_{yd}, δ_{od} vs temperature diagrams. K_{IC} and static σ_y are reported from reference (10) as a comparison. (1/4 thickness WR direction).