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Correlation between Instrumented Notched-bar, Tensile, and K_{Ic} Tests on the Basis of Steel Specimens in Different Conditions

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ABSTRACT The first section deals with the correlation between the yield point derived by tensile testing and the force F_{gy} at which general yield occurs obtained by notched-bar impact testing. A direct relationship between the yield point and F_{gy} in accordance with equation $\sigma_y = QF_{gy}$ is evident when the yield points obtained by testing and the calculated stresses σ_y are plotted as a function of enthalpy ΔG. The cleavage stress σ_f has been determined from the maximum force F_m measured in the instrumented impact test. By multiplying them with Q, these F_m values were converted into stresses σ_m. With the aid of the well-known Hill theory or a numerical elastic/plastic analysis the cleavage stress σ_f can be calculated. The radiation effect is represented geometrically by way of a coordinate transformation consisting of two translations. The translation in the σ-direction represents the increase in the non-thermal fraction of the yield points caused by irradiation. The second translation by ΔT has the effect of causing the values measured on the irradiated and non-irradiated material to coincide.

Notation

$\boldsymbol{b}$	Burger's vector
F_a	Force for crack arrest
F	Impact force
F_{gy}	Force for general yield
F_m	Ultimate force
F_u	Force for unstable crackgrowth
ΔG	Enthalpy of activation
ΔG^*	Transformed abscissa
d ΔG	Irradiation induced shift of the abscissa
k	Boltzmann's constant
K_{Ic}	Critical stress intensity factor (mode I)
K	Plastic stress concentration factor
M_T	Taylor's factor
Q	Proportionality factor
RT–K_{Ic}	Reference temperature at which K_{Ic} equals 1874 N/mm$^{1.5}$
R_{eL}	Lower yield stress
R_{eH}	Upper yield stress
$R_{p0.2}$	0.2 proof stress

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s	Distance (see equation (6))
T	Temperature
T^*	Transformed temperature axis
T_{gy}	Lowest temperature for general yield
ΔT	Irradiation induced shift of temperature axis
σ_y	Flow stress evaluated by the Charpy 'V' notch impact test
σ_G	Athermal part of the yield stress
$\Delta\sigma_G$	Irradiation induced shift of the athermal part of the yield stress
σ^*	Thermally activated part of the yield stress
σ	Stress
σ_m	Stress $F_m Q$
σ_f	Cleavage fracture stress
v_0	Frequency factor
$\dot{\phi}$	Strain rate
$\dot{\phi}_0$	Constant
ρ_m	Density of mobile dislocations

Introduction

Impact energy, fracture appearance, and lateral extension can be measured by means of the Charpy 'V' notch test. When testing the reactor pressure vessel, the load–time curve of the 22 NiMoCr 37 was measured additionally by instrumenting the Charpy 'V' notch test. Figure 1 represents the typical load deflection curves for the Charpy specimen. The forces F_{gy} and F_m were taken from the diagrams type C, D, and E. Diagrams type A and B were not evaluated because corrections had to be made for fractures occurring before 100 μs. It is the intention of this paper to establish a correlation between the results of the instrumented Charpy 'V' notch test and the results of the additional tensile tests as well as those of the K_{Ic} measurements of irradiated and non-irradiated material.

The cleavage fracture stress σ_f is important for the fracture toughness of a ferritic steel. During the Charpy 'V' notch test this cleavage fracture stress is locally reached at some distance behind the notch root, thus forming a nucleus from where brittle fracture will start. It is possible to evaluate the exact number of the fracture stress as a multiple of the yield stress σ_y by means of Hill's theory (**1**) or by means of elastic–plastic calculation (**2**).

$$\sigma_f = K(F_m/F_{gy})\sigma_y \tag{1}$$

K, here, is a constant depending on the quotient F_m/F_{gy}. The instrumented Charpy 'V' notch impact test gives the values F_m and F_{gy} for evaluating K. The determination of the yield stress σ_y is more difficult, as the value cannot be gathered directly from tensile tests because of their low strain rate. However, we know from the slip line theory that at the moment of general yield

$$\sigma_y = QF_{gy} \tag{2}$$

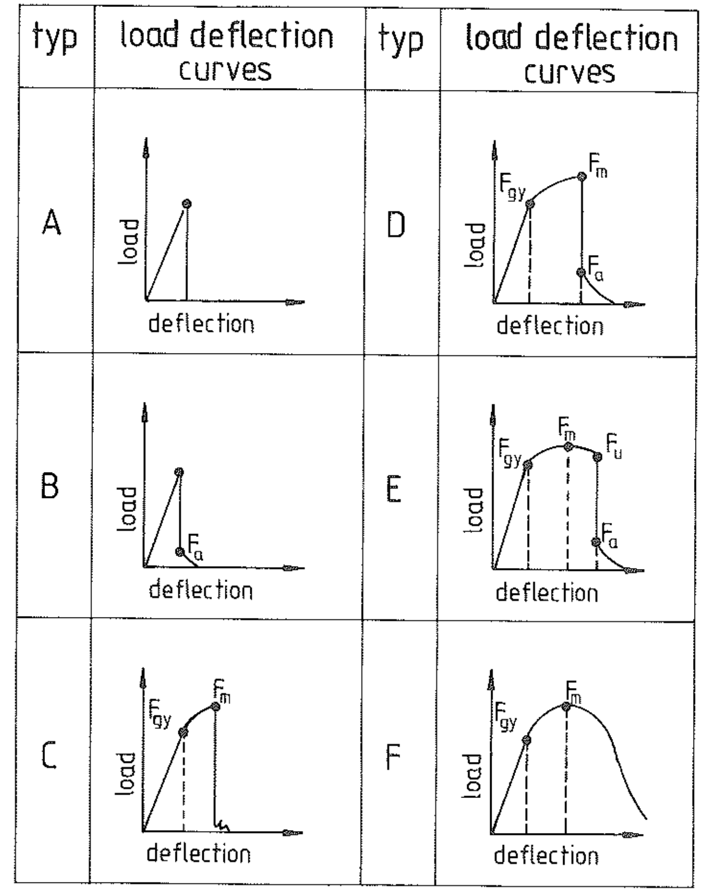

Fig 1 Schematical presentation of load deflection curves for the instrumented Charpy 'V' notch impact test

σ_y can be evaluated from the measured F_{gy} values. Thus σ_f can be determined by means of equation (1).

Determination of the Q value

In principle the Q value could be determined by forming the quotient $Q = \sigma_y/F_{gy}$ at variance the text following equation (8) at a constant temperature, under the condition that the strain rates in tensile test (σ_y) equal the strain rates in Charpy 'V' notch test (F_{gy}). The yield stress was determined at a strain rate of

$$\dot{\phi} = 4 \times 10^{-4}\ s^{-1} \quad \text{(tensile test)} \tag{3}$$

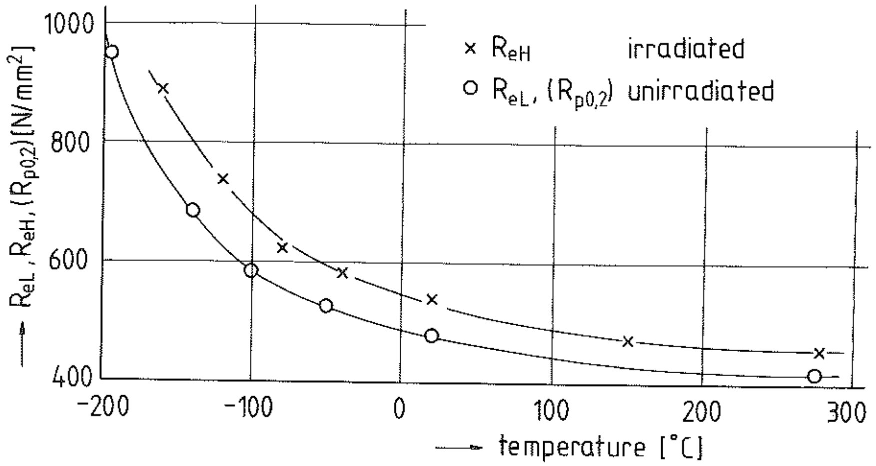

Fig 2 **Yield stress of 22 MiMoCr 37 steel in irradiated (1.05 × 10^{19} n/cm^2) and non-irradiated condition**

In the case of the Charpy 'V' notch test the strain rates are higher by a factor of approximately 10^7 **(3)(4)**. If we consider the condition in the notch root as conclusive for the beginning of the general yield we can say

$$\dot{\phi} = 3 \times 10^{+3}\ \mathrm{s}^{-1} \quad \text{(Charpy 'V' notch impact test)} \tag{4}$$

The two testing methods, therefore, cannot be directly compared. A new possibility is given to us by the introduction of a new variable, the activation enthalpy ΔG. Every dependency on the strain rate leads consequently to a dependency on temperature. We use the equation

$$\Delta G = kT \ln (\dot{\phi}_0/\dot{\phi}) \tag{5}$$

$\dot{\phi}_0$ is a structure dependent constant, defined by equation

$$\dot{\phi}_0 = \rho_m b s v_0/M_T \tag{6}$$

ρ_m, here, is the density of the mobile dislocations; b is the Burger's vector, s the product of the number of places where thermal activation may occur per unit length of dislocation and the area swept by the dislocation at a successful activation **(5)** and v_0 a factor of the order of magnitude of the Debeye frequency. The symbol k in equation (5) represents the Boltzmann constant. M_T is the Taylor factor which considers the orientations of the active slip planes. Dahl *et al.* found the value of $\dot{\phi}_0 = 10^{10}\ \mathrm{s}^{-1}$ for 20 MnMoNi 55 steel in quenched and tempered state **(6)**.

Taking this value and the ϕ values representative for the tensile test and the Charpy 'V' notch test we get

$$\Delta G = 4.26 \times 10^{-22}\ \mathrm{T\ J\ K^{-1}} \tag{7}$$

for the tensile test and

$$\Delta G = 2.07 \times 10^{-22}\ \mathrm{T\ J\ K^{-1}} \tag{8}$$

for the Charpy 'V' notch impact test.

The yield stress σ_y as measured in the tensile test and the F_{gy} values measured in the course of the Charpy 'V' notch test can be presented as a function of ΔG by means of equations (7) and (8). If one determines the quotient $Q = \sigma_y/F_{gy}$ at variance with equation (2) for all ΔG values one derives a Q as a function of ΔG, which according to the slip line theory is constant. In our case a Q value was calculated as far as possible for every Charpy 'V' notch test. For this reason we calculated first the ΔG value belonging to the Charpy 'V' notch test, by introducing the impact temperature into equation (8). In order to determine the yield point belonging to this ΔG value by means of Fig. 2 the temperature at which the tensile test ought to have been effected was calculated according to equation (7). The yield point value $\sigma_y(T)$ belonging to this temperature was taken from Fig. 2. The quotient Q belonging to one ΔG value was calculated as a function of the temperature (at which the Charpy 'V' notch test was effected). The average Q value was used for transforming the forces F into stress σ (for non-irradiated material $Q = 0{,}049\ \mathrm{mm}^{-2}$ and for the irradiated material $Q = 0.051\ \mathrm{mm}^{-2}$).

Introduction of the activation enthalpy as abscissa

$\sigma_y = QF_{gy}$ and $\sigma_m = QF_m$ was calculated by means of the average Q values for all Charpy 'V' notch tests resulting in diagrams type C, D, and E. They were plotted in Figs 3 and 4 together with the yield point values as a function of the activation enthalpy calculated according to equations (7) and (8). The σ_y values evaluated from the Charpy 'V' notch test and those measured during the tensile test fit into one line. The extrapolated intersection of this line with $\sigma_m(\Delta G)$ is marked by an asterisk. σ_f was calculated by means of equations (1) and (2) at this point. The corresponding values have been shown in Table 1. The K value of 2.22 was taken from elastic–plastic calculations with consideration for the form of the yield point. The K value 2.18, found by means of Hill's theory, delivers σ_f values which are about 2 percent lower.

Description of the irradiation influence

Irradiation induces an increase of the athermal part σ_G of the yield stress (Fig. 2). Assuming that the thermally activated part may be practically neglected at more than 200°C, the athermal part appears to be the yield stress above this temperature. Determination of the thermally activated part of the yield stress σ^* was made by calculating the difference between the yield stress σ_y and the athermal part. σ^* is plotted as a function of temperature in Fig. 5, which shows that the increase of σ_G does not completely explain the effect of irradiation. It is obvious that the thermally activated part of the yield stress is

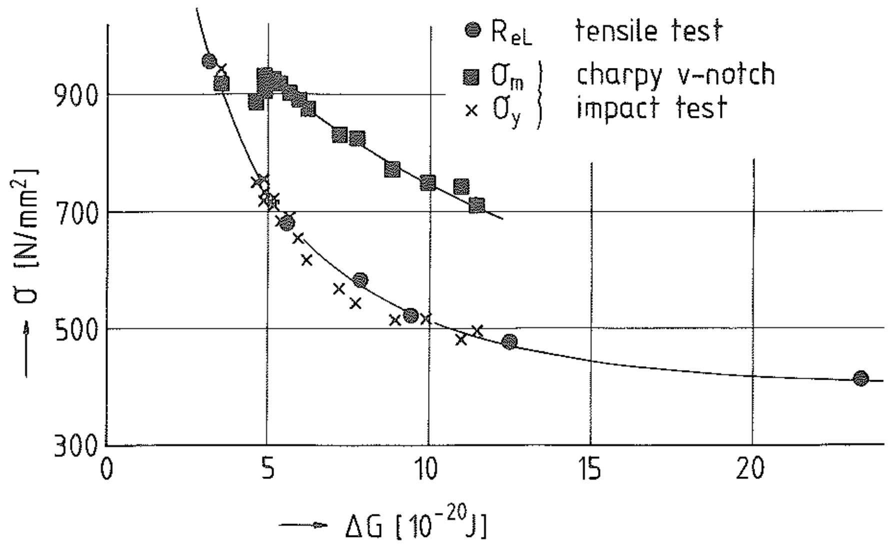

Fig 3 Yield stress, σ_y and σ_m of the non-irradiated 22 NiMoCr 37 as a function of activation enthalpy

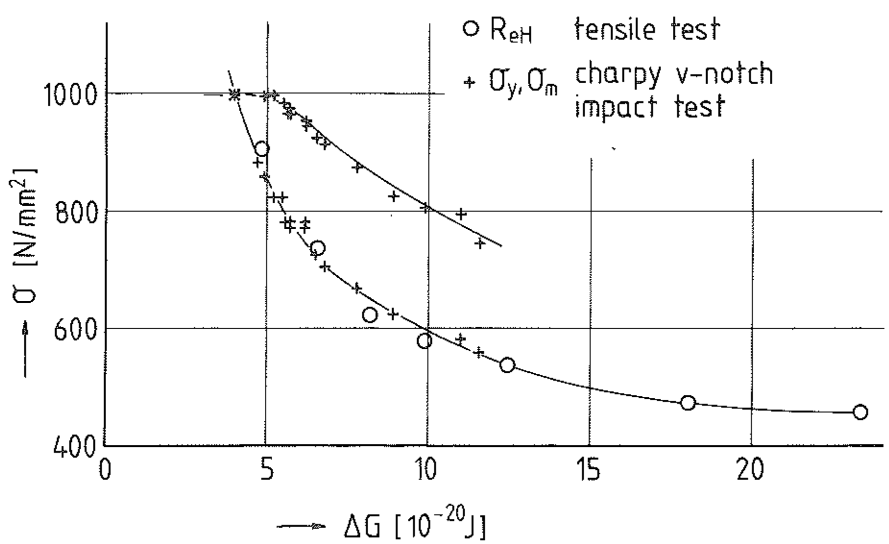

Fig 4 Yield stress, σ_y and σ_m of the irradiated (1.05×10^{19} n/cm²) condition as a function of enthalpy

Table 1 Listing of cleavage stresses for nuclear reactor pressure vessel steel

Author	σ_f*(N/mm²)*
Kotilainen (7)	1736, 1891
Curry (8)	2500, 1650
Ritchie *et al.* (9)	2000
Present results based on elastic–plastic analysis (2) condition	
Non-irradiated	2020
Irradiated 1.05×10^{19} n/cm²	2210

changed as well. In order to simplify matters, the effect of irradiation on the thermally activated part of the yield stress was empirically described by means of a transformation of the coordinates $T^* = T - \Delta T$. Figure 5 shows the results of this translation, with the translation $\Delta T = 24$ K marked with an arrow. Figure 5 shows that the irradiation induced increase of the yield point may be described by two translations. The advantage of interchanging the temperature against the activation enthalpy ΔG as abscissa lies in the fact that, now, the F_{gy} values which were evaluated from the Charpy 'V' notch test can be introduced into a diagram alongside of the values found in tensile tests. Thus we arrived at Figs 3 and 4. Figure 6 shows how a translation of the abscissa for d $\Delta G = 0.4 \times 10^{-20}$ J, and of the ordinate for σ_G, can reduce the values of irradiated material, shown in Fig. 4, to those of non-irradiated material, shown in Fig. 3. The thermal part of the yield point (and formally of

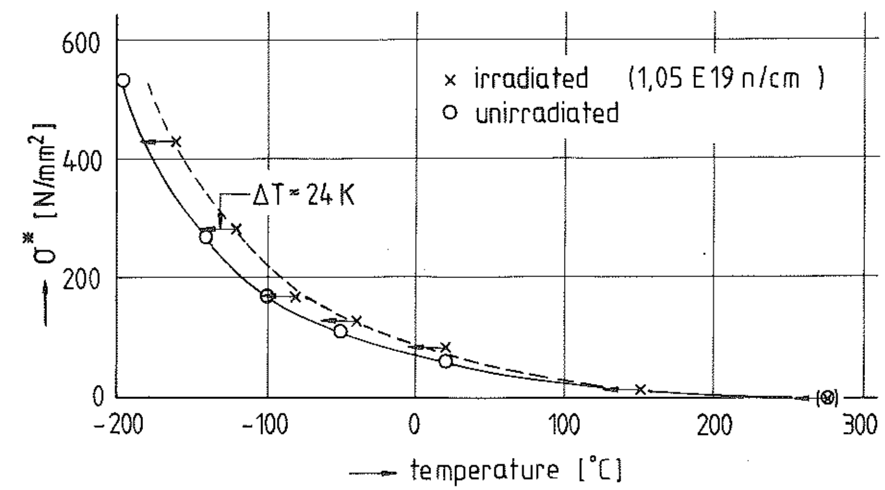

Fig 5 Thermal part of the yield stress of non-irradiated and irradiated 22 NiMoCr 37 steel as a function of temperature

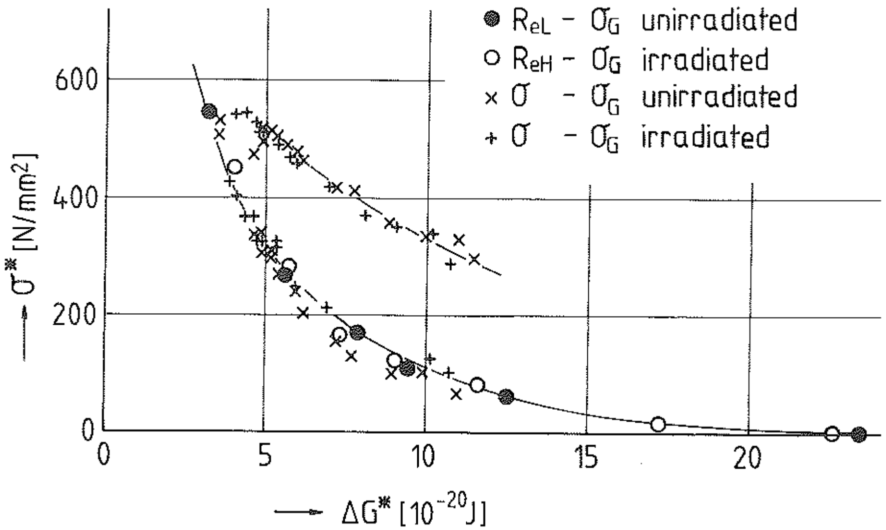

Fig 6 **Geometrical presentation of the irradiation induced translation σ_G and ΔT for 22 NiMoCr 37 steel in σ^*–ΔG^* coordinates**

the σ_m value) delivers the ordinate $\sigma^* = \sigma - \sigma_G$. The abscissa is the difference $\Delta G^* = \Delta G - \mathrm{d}\,\Delta G$. The same process of translation can be used to describe the values of irradiated material measured in a Charpy 'V' notch test and those measured in a tensile test.

Statements concerning the irradiation influence

The cleavage fracture stress has been calculated by means of equation (1) for $T = T_{gy}$. With $K = 2.22$ (a value typical for a stress–strain curve with pronounced upper and lower yield point) (2) we find a cleavage fracture stress of 2020 N/mm² for the non-irradiated, and 2210 N/mm² for the irradiated steel. The irradiation induced increase of the cleavage fracture stress is described by the same translation as the irradiation induced increase of the yield stress. This can be seen specifically in Fig. 6. The $\sigma_y(T = T_{gy})$ values found by extrapolation for irradiated and non-irradiated material and according to equation (1) the σ_f values fall together at one point after application of the characteristic translation for irradiation. The following presents a procedure for investigation of the effect of irradiation, based on the assumptions:

(a) each K_{Ic} value belongs to a cleavage fracture;
(b) irradiation effect can be described by translation which is the same for yield point and cleavage fracture stress;
(c) the embrittlement causes parallel motion of all K_{Ic} values at a certain temperature.

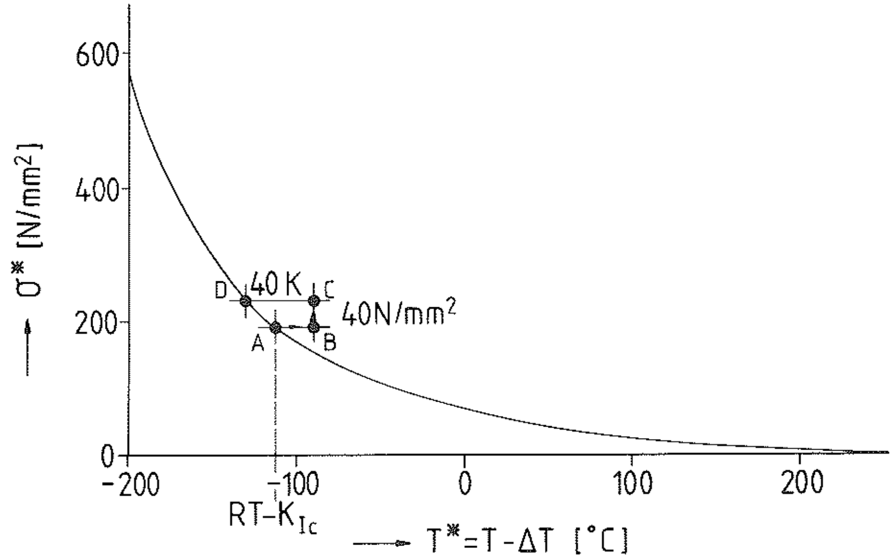

Fig 7 **Graphic presentation of irradiation induced increase of RT–K_{Ic} for 22 NiMoCr 37 steel using σ^*–T^* coordinates**

The most simple starting point for evaluation of the shifting of the $K_{Ic}(T)$ lines is to equate these to the shifting of the $\sigma_y(T)$ lines. This shifting can be graphically found from the two translations. We need the yield point as a function for the state of non-irradiation (Fig. 2). The temperature RT–K_{Ic} is marked on the abscissa in order to obtain a defined starting point (Fig. 7). The σ^* value belonging to this temperature is marked A. Starting from A the first translation is made for 24 K (Fig. 7), and we obtain B. Starting from this point the $\Delta\sigma_G$ value (40 N/mm²) corresponding to the irradiation is marked, and we obtain C. The step from A to C represents the irradiation induced translation of the yield point at RT–K_{Ic}. When comparing yield point values of equal magnitude for irradiated and non-irradiated material, we find that they are practically separated by space because of the corresponding temperature difference of 40°C (Fig. 7). This separation CD corresponds with the shift of the $K_{Ic}(T)$ line.

Comparison of the cleavage stress with values from literature

$\sigma_f = \sigma_y K$ is supposed to take the value of the cleavage fracture stress in the case of temperature T_{gy}, where $\sigma_m = \sigma_y$. We found a value of about 2000 N/mm² for the cleavage fracture stress in the case of the basic material. Table 1 gives a list of own values and of values found in literature.

Summary

Yield stress values can be attached to F_{gy} values which have been measured by means of the Charpy 'V' notch test at more than T_{gy}. A plotting of these two values as a function of the activation enthalpy shows, these values equal the values found during a tensile test.

When plotting the values measured during a tensile test or found at a Charpy 'V' notch test depending not on temperature but on the activation enthalpy, this diagram contains the strain rate dependency of the measured values as well as the temperature dependency. Such plotting delivers dynamical yield point values.

The irradiation induced increase of the yield stress values can be described by means of a transformation of the coordinates. This transformation consists of two translations in the σ^*–T system. Applying this transformation on the yield stress value of the unirradiated material belonging to the RT–K_{Ic} temperature, we arrive at a good approximation for the irradiation induced increase of the RT–K_{Ic} temperature.

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