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Role of constraint on ductile brittle transition temperature of pipe steel X65

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Abstract

The brittle–ductile transition temperature (DBTT) is not intrinsic to a material but depends on the specimen type and loading mode used for the test. The influence of these parameters is related to the plastic constraint. Here the constraint is evaluated by the effective T stress obtained by the stress different method on the notch tip stress distribution. From Charpy energy values at different temperatures, it is possible to get a material failure master curve (MFMC) where the notch fracture toughness is plotted versus the shift of test temperature with the transition temperature corresponding to the effective T stress value.

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Keywords: Constraint, transition temperature, T stress, Material Failure Master curve

1. Introduction

The ductile-brittle transition temperature (DBTT), nil ductility temperature (NDT), or nil ductility transition temperature (NDTT) of a metal represents the point at which the fracture energy passes below a pre-determined value]. Design against brittle fracture considers different level (generally 3). Level 3 considers that the material exhibits a defect less than an admissible one which can promote fracture. The size of this defect is obtained through Fracture Mechanics. Level 1 and 2 assume that the material exhibits at service temperature, a sufficient ductility to prevent cleavage initiation and sudden fracture with an important elastic energy release. Concretely, this means that reference temperature T_s is higher than transition temperature T_t:

$$T_s \geq RT_t + \Delta T \quad (1)$$

Service temperature is conventionally defined by codes or laws according to the country where the structure or the

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component is built or installed.
where ΔT is the uncertainty on reference temperature. This reference temperature RT_i varies according to codes (RT_{NDT} or RT_{T0}):

$$RT_{NDT} = T_{NDT}$$
$$RT_{T0} = T_{10}+19.4\ °C \quad (2)$$

T_{NDT} is the Nil-Ductility Transition (NDT) temperature determined by some form of drop-weight test T_0 is the fracture toughness transition temperature associated with the level of 100 MPa√m. For Charpy tests, transition temperature is determined at conventional level of 27 joules and called T_{K27} and also at half the jump between brittle and ductile plateau ($T_{K1/2}$), figure 1.

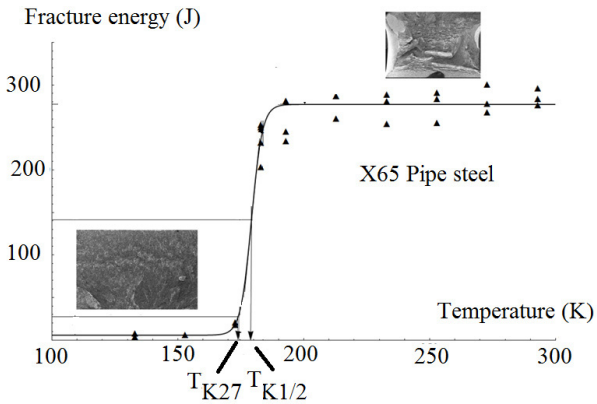

Fig 1: Charpy energy versus temperature curve for API 5L X65 pipe steel and definitions of transition temperature T_{K27} and $T_{K1/2}$.

Material strength, like all mechanical properties, is sensitive to geometric parameters such as size, specimen geometry, thickness, loading mode, etc. Consequently, the brittle–ductile transition temperature (DBTT) is not intrinsic to a material but depends on the specimen type, notch geometry and loading mode used for the test. The influence of these parameters is related to the plastic constraint. This is the consequence of the Poisson effect limitation due to material elasticity near the localized plastic zone. In this paper, transition temperatures have been determined on Charpy V and U, smooth tensile, CT specimens. Constraint is evaluated by critical effective T stress, which is the value of the stress difference distribution at the effective distance provided by the Volumetric Method at critical load. A linear dependence of transition temperatures with constraint is shown. A Material Failure Master curve M of the API X65 pipe steel depending of constraint is given.

2. Material and transition temperature t_t and t_0

The studied material is API X65 pipe steel with ferrite pearlite microstructure. Its typical chemical composition is given in Table 1. Its mechanical properties at room temperature are given in Table 2.

Table 1. Typical chemical composition of pipe steel API 5L X65 (wt %).

	C	Si	Mn	P	S	Mo	Ni	Al	Cu	V	Nb
min.	0.05	0.15	1.00	-	-	-	-	0.01	-	-	-
max.	0.14	0.35	1.50	0.020	0.005	0.25	0.25	0.04	0.080	0.080	0.040

Table 2. Mechanical properties of pipeline steel API 5L X65 at 20°C.

Yield stress R_e (MPa)	Ultimate strength R_m(MPa)	Elongation at failure A %	Charpy Energy K_{CV} (J)	Fracture Toughness K_{Jc} (MP√am)	Hardness HV

465.5	558.6	10.94	285.2	280	205

Tensile tests at very low temperature exhibit brittle fracture, and ductile failure at high temperature. When the test temperature reaches the transition temperature, failure occurs with plasticity at ultimate stress. Plasticity is a thermally activated process, and the yield stress decreases exponentially with temperature:

$$R_e = R_e^{\mu} + AExp(-BT) \quad (3)$$

where R_e^{μ} is a threshold, A and B are constants, and T is the temperature in Kelvin. Tensile tests have been performed on standard specimens in a temperature range [120–293 K] with a strain rate of about $10^{-3}s^{-1}$. Stress–strain diagrams have been recorded and the (static) yield stress and ultimate strength determined. Values of yield stress R_e, and ultimate strength R_m are reported in Figure 3 and the tensile transition temperature (T_t) defined as previously is determined (T_t= 123K), figure 2. Fracture toughness tests have been performed according to standard with CT specimens in the temperature range [128 – 293 K]. Fracture toughness K_{IC} evolution versus temperature for brittle and quasi-brittle fracture can be modelled through plasticity-temperature relationship since the fracture process needs a preliminary yielding. Plasticity is a thermally activated phenomenon which follows Arrhenius law. Fracture toughness versus temperature from brittle plateau to transition foot is therefore given by exponential law. For API X65, T_0 is equal to 156K, Capelle et al. (2013).

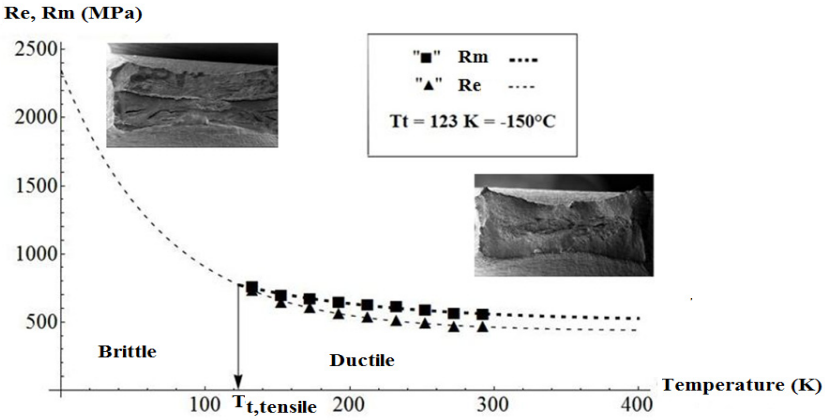

Fig 2. Evolution of static yield stress and ultimate strength versus temperature for API 5L X65 pipeline steel.

3. Effective T stress as a measure of constraint

The stress difference, Chao and Zhang (1997), ($(\sigma_{xx} - \sigma_{yy}) = \sigma_{yy} (\nu_{ap}-1)$) where ν_{ap} is the apparent Poisson ratio indicates how lateral contraction is hampered. This stress difference is now widely used to signify the plastic constraint. In the case of a singular stress distribution at crack tip, the stress difference is identical to the T stress, Larsson and Carlsson (1973). Several methods have been proposed in the literature to determine the T stress for a cracked specimen, Chao and Zhang (1997), Ayatollahi et al. (1998) and Wang (2003). Here, the difference in stress method (SDM) proposed by Yang and Ravi-Chandar (1999) is used and evaluated from the notch stress distribution calculated by Finite Element method. For a tensile smooth specimen, the strain difference is rather used as the constraint and the u parameter has the same dimension as T.

$$u = E(\varepsilon_{xx}-\varepsilon_{yy}) \quad (4)$$

In case of a distribution reflecting a stress concentration, the stress difference $(\sigma_{xx} - \sigma_{yy})$ is not constant along a ligament but increases slowly after a given distance. It is therefore evaluated for a conventional distance X_{ef} given by the volumetric method, Pluvinage (2001), and related to the size of the fracture process zone. In this case, this stress difference $(\sigma_{xx} - \sigma_{yy})$ is called T_{ef} and when it is computed for the critical load, $T_{ef,c.}$ The volumetric method is

a local failure criterion used for fractures emanating from a notch. It is assumed in this method that the fracture process requires a physical volume. This volume is assumed to be quasi-cylindrical and centered at the notch tip. The radius of the cylinder is called the 'effective distance'. By calculating the averaged opening stress in this volume, one gets the effective stress. This local failure criterion is therefore based on two parameters, namely, the effective distance X_{ef} and the effective stress σ_{ef}. The distance corresponding to the minimum of the relative stress gradient is conventionally regarded as the relevant effective distance.

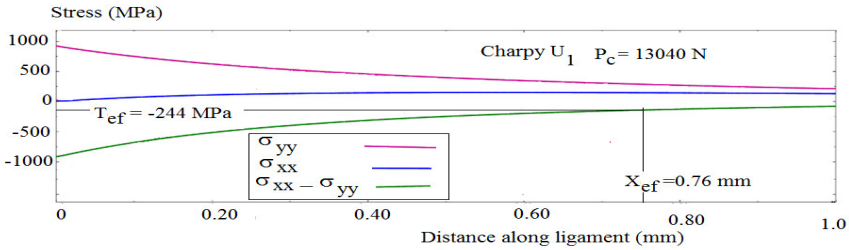

Fig 3. Stress distribution at notch of Charpy specimens U1. Determination of Tef,c on stress difference distribution.

The value of the relative stress gradient is given by

$$\chi(r) = \frac{1}{\sigma_{yy}(r)} \frac{\partial \sigma_{yy}(r)}{\partial r} \tag{5}$$

where χ is the stress gradient and σ_{yy} the maximum principal or opening stress. Figure 3 represents the stress distribution in the case of Charpy specimens U (specimen with u notch of 1 mm radius). The maximum stress is related to a stress concentration factor k_t =1.95. Transition temperatures have been determined for Tensile, Ct and Charpy specimens together with effective T stress T_{ef}. The most widely used, the Charpy V specimens (V notch, notch radius ρ = 0.25 mm, notch depth a = 2 mm) and other specimens like Charpy U_1 (U notch, notch radius ρ = 1 mm, notch depth a = 5 mm) and Charpy $U_{0.5}$ (U notch, notch radius ρ = 0.5 mm, notch depth a = 5 mm) are used. Data are reported in Table 3.

Table 3. Transition temperature and effective T stress for different specimens made of X65.

Notch	T_{ef}(MPa)	T_t(K)
U_1	-244.2	150
U_{05}	-228.1	187
V	-230.8	179
CT	-330	156
Tensile	-510	123

4. Influence of constraint on transition temperature

Transition temperatures for the Charpy specimens (U_1, U_{05} and V) are corrected to take into account the strain rate effect and are reported in Figure 4. Data are fitted according to linear interpolation. The relationship between the transition temperature and effective T stress is given by:

$$T_t = 0.14 T_{ef} + 197 \tag{6}$$

This equation represents the material transition temperature master curve T_t = f (T_{ef}), which is the key to determining the appropriate reference transition temperature by comparison with the structure transition temperature. Values of T_{ef} are close for the Charpy V, U_1 and U_{05} specimens' values of the transition temperature relative to the same specimen types. They are higher than the CT specimen, which exhibits a lower plastic constraint

than the 3PB specimen. The CT specimens loaded by both bending and tension have a transition temperature intermediate to those of the tensile and Charpy specimens.

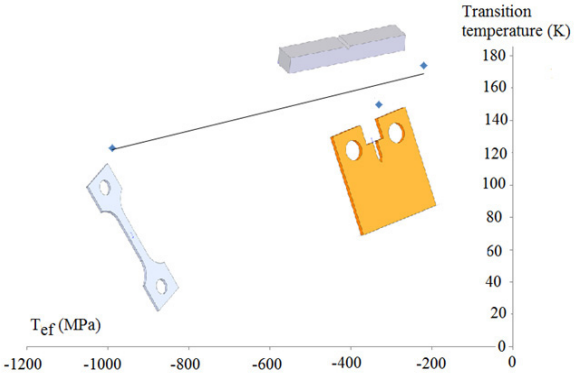

Fig 4. Material master curve $T_t = f(T_{ef})$ for pipe steel API 5L X65.

A linear relation was found by Wallin (2010) between the transition temperature T_0 specific to the material failure master curve (MFMC) K_c = f(temperature) and the T stress.

$$T_0 = T_{0.Tstress=0} + \beta T_{stress} \tag{7}$$

5. Material failure master curve from Charpy specimen

The notch fracture toughness determined on notched specimens like the Charpy is obtained from the fracture energy U_c:

$$J_{\rho,c} = \frac{\eta U_c}{Bb} \tag{8}$$

where B is the thickness and b the ligament size. eta (η) is a parameter for the proportionality between the specific fracture energy per ligament area and the notch fracture toughness. It depends on the notch radius and relative notch depth a/W. Akourri et al. (2000) have tabulated the values of eta for different notch radii and relative notch depths. The fracture energy of the different studied Charpy specimens: Charpy V specimens (V notch, notch radius ρ = 0.25 mm, notch depth a = 2 mm), Charpy U_1 (U notch, notch radius ρ = 1 mm, notch depth a = 5 mm), Charpy $U_{0.5}$ (U notch, notch radius ρ = 0.5 mm, notch depth a = 5 mm), is transformed into the notch fracture toughness $K_{\rho,c}$. All data are fitted to the following equation:

$$J_{\rho,c} = A_{K,\rho} + B_{K,\rho} \tanh\left[\frac{(\Delta T^{*}-)}{C_{K,\rho}}\right] \tag{9}$$

with

$$\Delta T^{*} = T - T_{t.Tef,c=0} - 0.14\, T_{ef,c} \tag{10}$$

ΔT* represents the shift of the test temperature with transition temperature function of constraint Tef,c. $T_{t.Tef,c=0}$ is the transition temperature corresponding to a constraint equal to zero and used as reference (197 K for API X65 pipe steel). The Material Failure Master curve of the API X65 pipe steel is given in Figure 5.

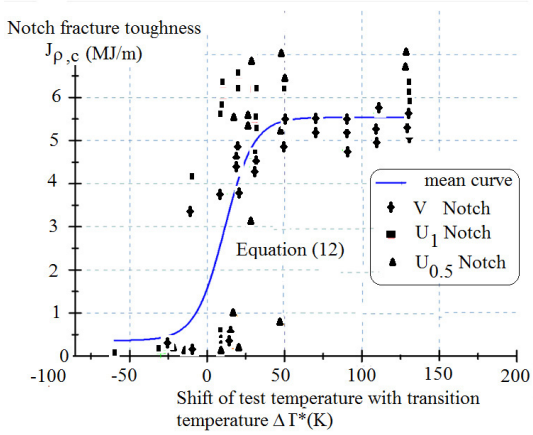

Fig. 5. Material Failure Master curve of the API X65 pipe steel obtained from Charpy V and Charpy U specimens.

The values of $A_{K\rho}$, $B_{K\rho}$,$C_{K\rho}$ and $D_{K\rho}$ are shown in Table4.

Table 4. Values of constants of Eq. (12) for API 5L X65 pipeline steel

$A_{K\rho}$ (J)	$B_{K\rho}$ ((J)	$C_{K\rho}$ ((K)	$D_{K\rho}$ ((K)
141.35	135.65	4.33	179.22

5. Conclusion

The introduction of the constraint in the material failure master curve (MFMC) allows describing the influence of the loading mode and specimen type on the transition temperature. The basis for the introduction of the constraint described by the effective T stress is given by the linear relation between the transition temperature and $T_{ef,c}$ which has been found in API X65 steel. This linear relation confirms previous results of Wallin (2010). The major interest in the material failure master curve notch fracture toughness versus the shift between the test temperature and the transition temperature associated with the constraint is to provide a reference temperature which depends only on the constraint. This ensures its transferability between different types of specimen, loading mode, notch acuity, and thickness.

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