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Considerations on Establishing the DBTT Depending on the Charpy Specimen and the Use of API 5L X65

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Abstract

The integrity evaluation of a structure involves, among others, the determination of its ability to perform mechanical functions for all loads, normal, occasional or incidental during its entire lifetime. In case of CO_2 *in supercritical state transport, through pipeline crack occurrence is considered major degradation. In this context, fracture mechanics provides the necessary tools for evaluating the steel. Each type of fracture must be the subject of a specific characterization. The authors have determined the ductile-brittle transition temperature (DBTT) of the API 5L X65 steel through different methods according to the international standards: impact bending test (Charpy test) and fracture toughness of the above mentioned steel, to a temperature range of 131K and 293K.*

Key words: *Charpy test, ductile-brittle transition temperature, DBTT*

Introduction

The aspect of the examined fracture reveals that at temperatures below a certain domain, it is entirely brittle, while at higher temperatures the fracture is entirely ductile. Fractured surfaces present both aspects of brittle and ductile fracture. For this reason, that domain has been named the ductile-brittle transition fracture domain, and the temperature corresponding to this value has been named transition temperature. The transition temperature $t_{50\%}$ is the temperature at which half of the surfaces area of the fractured specimens has the aspect of brittle fracture (brilliant crystal) [1].

Fracture phenomenon is preceded by crack occurrence which is the result of the crystalline imperfection. When conditions are favorable, the crack begins to develop and may spread up to the destruction of the structure. The variation of the material ductility depending on the temperature led to the ductility-brittleness determination of the transition temperature range.

The use of these tests has grown after naval disasters, the explosions of the gas transportation pipeline due to brittle fracture, disasters that have highlighted that a steel that is normally ductile, under certain stress conditions, at high speeds of deformation and low temperature, can become brittle.

To assess the ductility, into the conditions described above, the impact bending test is used.

Currently, different types of standardized Charpy specimens are used. These are shown in Figure 1, while the geometrical characteristics of the specimen are presented in Table 1.

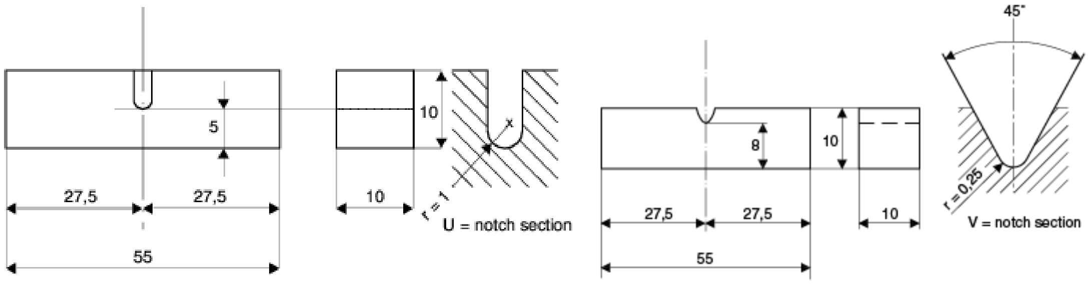


Fig. 1. Different types of Charpy specimens [2]

Table 1. Geometrical characteristics for different types of Charpy specimens [2]

Specimen type	Notch radius ρ [mm]	Notch angle ψ [°]	Notch depth a [mm]
Charpy V	0,25	45	2
Charpy U	1	0	5
Pre-fractured	0	0	5

Ductile-brittle transition temperature is influenced by the notch sensitivity, depending on the type of the used specimen and the operational factors - nature and type of load, the geometry of the specimen and external factors - temperature, environmental action.

Experimental Plan

To establish the ductile-brittle transition temperature are performed comparative experiments on different types of V and U Charpy specimens, with variable notch radius, standardized U_1: $\rho = 1$ mm and not standardized $U_{0,5}$: $\rho = 0.5$ mm. Specimens are prepared according to ASTM E23 [2].

The determination of the DBTT was performed on a total of 59 specimens with variables notch radius, above mentioned.

Solving the identified problem is done by graphical methods, depending on the variable range of temperature 131k - 293K, the dynamic yield stress and dynamic maximal strength.

Equipment and Exploitation

The tests on different Charpy specimens of API 5L X65 steel, were performed according to EN ISO 14556 [3]. The chemical composition of the used material is presented in Table 2, the mechanical properties, in table 3 and the microstructure is shown in Figure 2.

Table 2. Typical chemical composition of API 5L X65 steel (wt %) [4]

	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	0,02	0,005	0,25	0,25	0,04	0,08	0,08	0,04

For the experiments RKP 450 pendulum was used, that is shown in Figure 3. The test consists in fracturing the specimens that present a notch of a certain form. The fracture is done by a single stroke applied behind the notch, situated in the middle of the specimen that is placed on two supports.

To determine the stress and the specimen deformation during the impact bending test, based on the registered values, force-displacement diagrams are made for different types of specimens and temperatures.

Table 3. Mechanical properties of API 5L X65 steel at the environmental temperature [4]

Yield stress R_e [MPa]	**Maximal strength R_m [MPa]**	**Elongation at failure A [%]**	**Charpy Energy K_{CV} [J]**	**Fracture Toughness K_{Jc} [MPa√m]**	**Hardness [HV]**
465,5	558,6	10,94	285,2	280	205

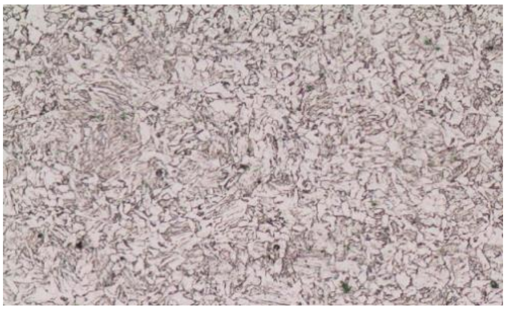


Fig. 2. Microstructure of API 5L X65 steel (x100, nital etching)

Fig. 3. RKP 450 Pendulum [5]

Results

The recorded values of Charpy test are saved during the process. The values of impact average force F_{gy} and the maximum force F_{max}, both extracted from force-displacement curve obtained by Charpy test, according to EN ISO 14556 [3], are shown in Figure 4, for a ductile fracture.

At low temperatures, the form of force-displacement curve is different between brittle and ductile behavior (figs. 5, 6 and 8, 9).

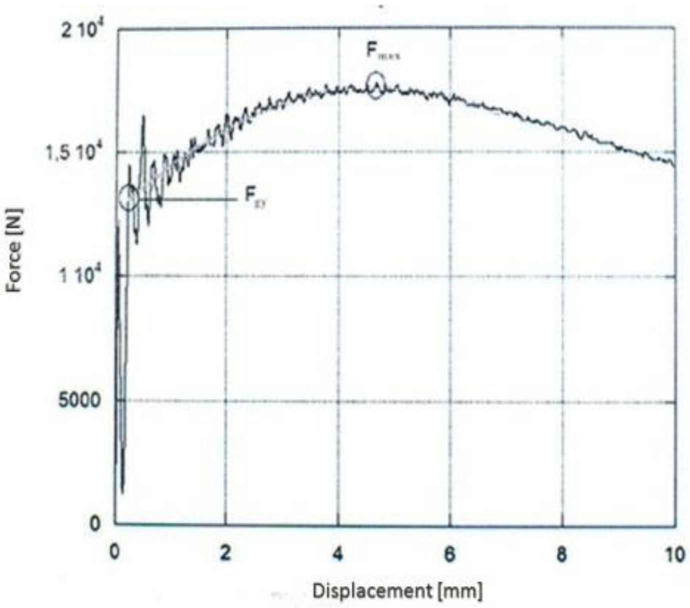
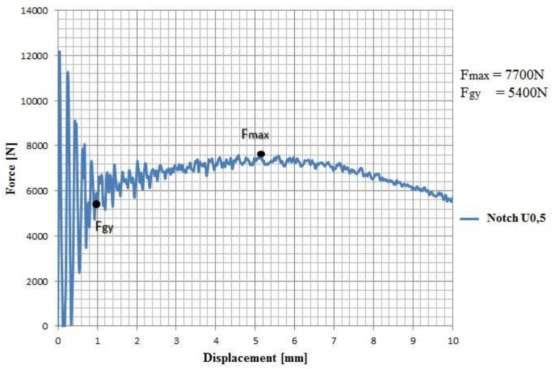


Fig. 4. Force – displacement curve at T = 293 K (ductile fracture)



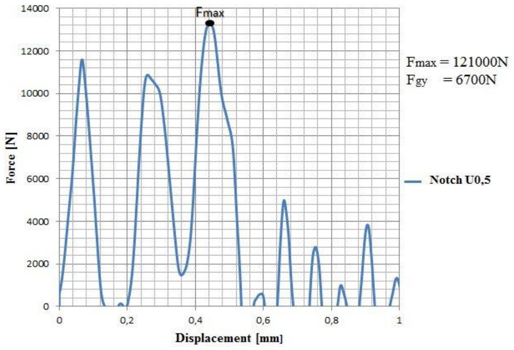


Fig. 5. Force – displacement curve at T = 293K (ductile fracture – notch $U_{0,5}$)

Fig. 6. Force – displacement curve at T = 131K (brittle fracture– notch $U_{0,5}$)

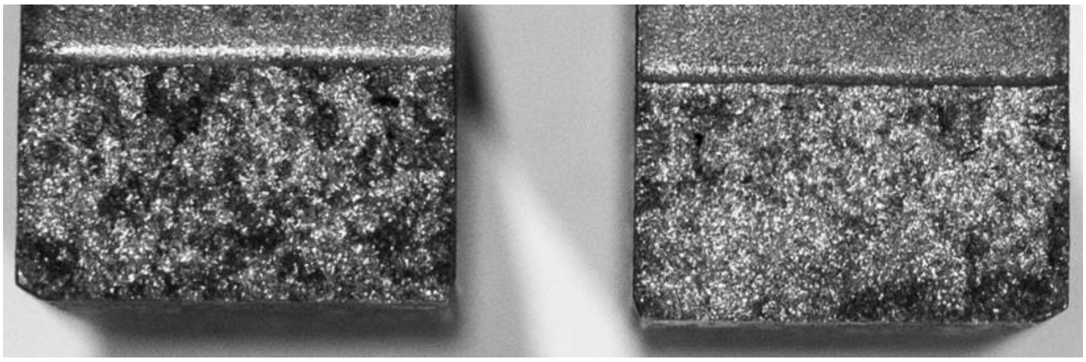


Fig. 7. Charpy specimen – notch type $U_{0,5}$

F_{max} represents the maximum force, the top position on force-displacement curve. F_{gy} – represents the impact average force and is obtained by the intersection between the force-displacement curve and the average curve, see Figure 4. The obtained data for the dynamic yield stress $R_{e,d}$ depending of the average temperature, according to the equation (3).

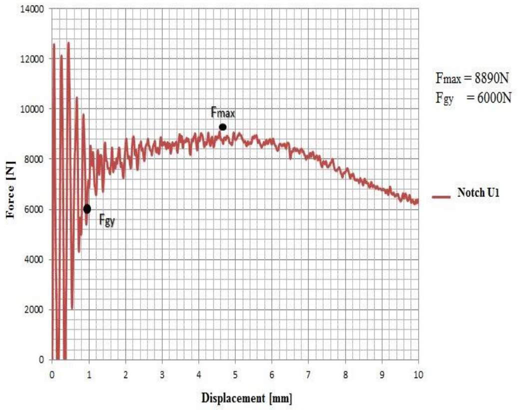


Fig. 8. Force – displacement curve at T = 293K (ductile fracture – notch U_1)

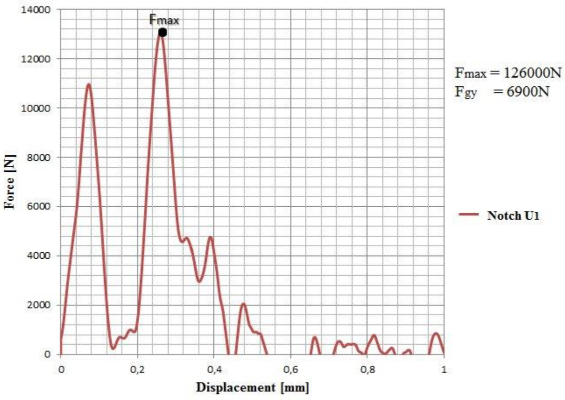


Fig. 9. Force – displacement curve at T = 153K (brittle fracture – notch U_1)

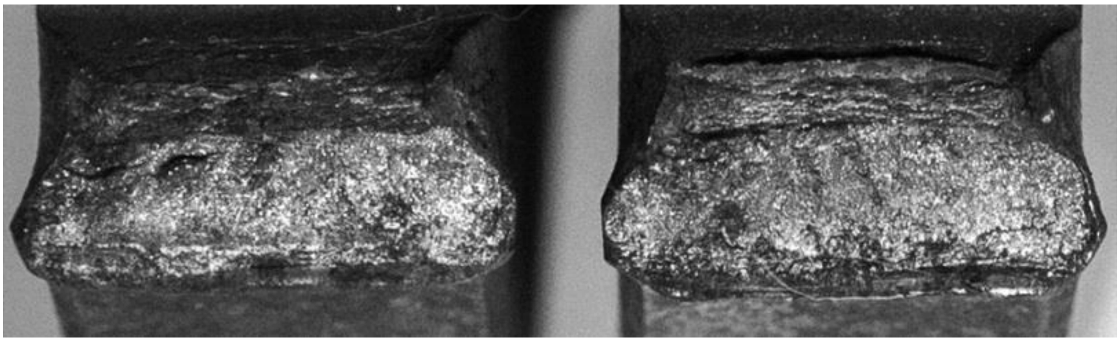


Fig. 10. Charpy specimen – notch type U_1

In order to calculate the dynamic yield stress R_{ed} and the dynamic maximal strength R_{md}, the equations of Green and Hundry are used [6]:

$$R_{ed} = \frac{4 \cdot W \cdot F_{gy}}{B \cdot L \cdot (W-a)^2} \quad (1)$$

$$R_{md} = \frac{2W \cdot (F_{max}+F_{gy})}{B \cdot L \cdot (W-a)^2} \quad (2)$$

where: W – the width of the specimen; B – the thickness of the specimen; a – the depth of thespecimen; F_{gy}– the impact average force; F_{max}– the maximum force.

$$R_{ed} = \sigma_\mu + (R_{ed}^0 - \sigma_\mu) \cdot e^{-mT} \quad (3)$$

where: R_{ed}^0– is the yield stress at 0 K; σ_μ – the athermal stress; m – the temperature exponent.

Yield stress value R_e^0at 0K is independent of specimen geometry, loading rate and equal to 2343MPa. This value is generally considered as equal to cleavage stress.

Constraint factor L is varying function of specimen notch type. Assuming that yield stress is independent of notch geometry, it can be found the corresponding values of constraint factor. Its values are given in table 6.

Figure 11 shows that the dynamic yield stress decreases exponentially with the temperature. Introducing the equality $R_{ed} = R_{md}$ (according to transition temperature definition [4]) the transition temperature $t_{50\%}$, can be determined with a different method (fig. 12).

Table 4. Values of dynamic yield stress for Charpy specimens with notch typeU_1, $U_{0,5}$ and V

Temperature [K]	**R_{ed} U_1 [MPa]**	**R_{ed} $U_{0,5}$ [MPa]**	**R_{ed} V [MPa]**
293	849.557	691,2	556,944
213	877.3	716,8	606,752
193	905.6	742,4	558,269
183	931.07	-	592,316
173	940.975	768	600,203
153	976.35	793,6	642,822
133	976,35	793,6	657,501
131	-	857,6	-

Table 5. Values for the coefficients in equation (3) for Charpy specimens with notch typeU_1, $U_{0,5}$ and V

Specimen	**σ_μ [MPa]**	**m**	**R_e^0[MPa]**
U_1	86,963	0,01508	2343
$U_{0,5}$	676,366	0,01689	2343
V	568,240	0,02212	2343

Table 6. Values of constraint factor L for Charpy specimens with notch type U_1 , $U_{0,5}$ and V

Specimen	U_1	$U_{O,5}$	V
L	1,13	1,25	1,38

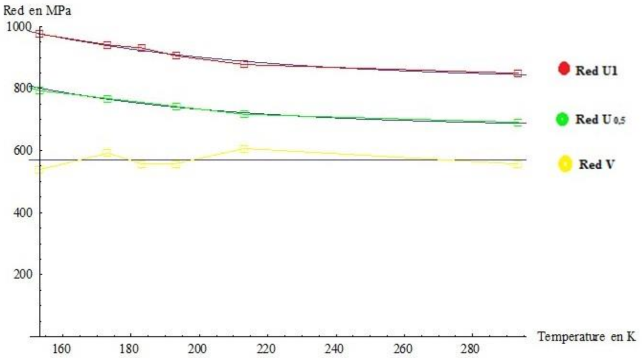


Fig. 11. Transition curve of dynamic yield stress (Charpy test)

The method involves the intersection of dynamic yield stress at 0K and the dynamic maximal strength. The transition temperature may also be defined as the temperature where the yield stress becomes equal to the maximal strength (fig. 12). Dynamic tests were performed, the dynamic yield stress and dynamic maximal strength were calculated using the equations 1 and 2 (the relationship between the Charpy forces at yield stress and maximal strength). According to this theory, the authors were determined the transition temperature $t_{50\%}$.

The values of ductile-brittle transition temperature, determined after the experiments, for the analyzed Charpy specimens, are presented in table 7.

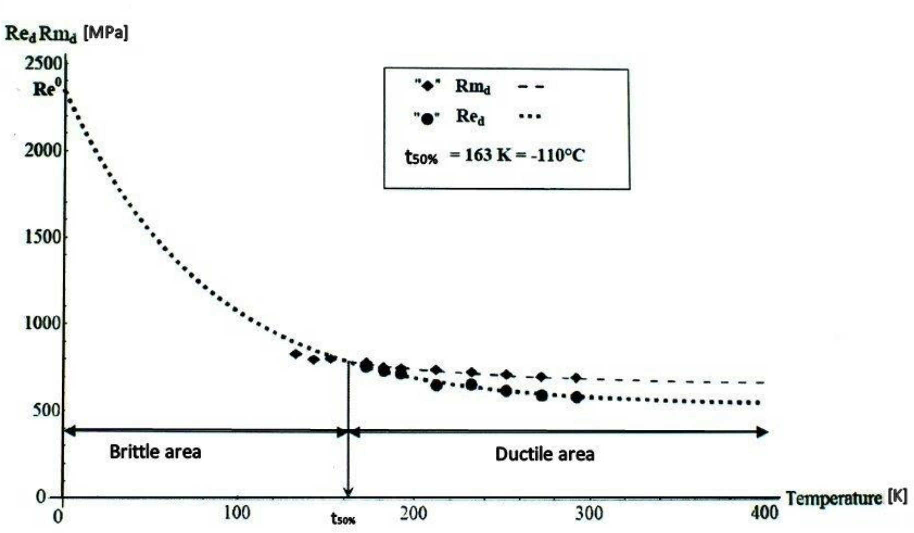


Fig. 12. Brittle-ductile transition area, for dynamic load

Table 7. Experimental values of ductile-brittle transition temperature for different type of Charpy specimens

Specimen	U_1 [K]	$U_{0,5}$ [K]	V [K]
$t_{50\%}$	175	152	170

Table 8. Values of ductile-brittle transition temperature for different type of Charpy specimens, based on the proposed method

Specimen	U_1 [K]	$U_{0,5}$ [K]	V [K]
$t_{50\%}$	180	155	176

The transition temperature values $t_{50\%}$ obtained by the proposed graphical method, by introducing the dynamic yield stress and the dynamic maximal strength, have a deviation of 5%, which validates the proposed method.

Conclusions

The validated graphical method is easy to apply, with very precise results.

Using the impact bending test and materials characteristic curve, $t_{50\%}$ may be determined by graphical methods.

The API 5L X65 steel is recommended for the use of supercritical CO_2 transportation through pipeline, considering the 304,1K temperature and a pressure of 7,38MPa to transport the agent.

The method is suitable for determining $t_{50\%}$ in any laboratory for materials testing, even if it has lower equipment.

Considering the large number of tested specimens, it can be stated that the behavior of API 5L X65 steel, for the brittle fracture, is stable.

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Consideraţii privind stabilirea DBTT funcţie de tipul epruvetei Charpy şi utilizarea oţelului API 5L X65

Rezumat

Evaluarea integrităţii unei structuri comportă, printre altele, determinarea capacităţii sale de a-şi îndeplini funcţiile mecanice pentru toate încărcările, normale, ocazionale sau accidentale, pe întreaga sa durata de viaţă. În cazul transportului de CO_2 *în stare supercritică, pentru tubulatura de transport, se iau în considerare degradări ce implică apariţia fisurilor. În acest context, mecanica ruperii oferă instrumentele necesare pentru evaluarea unei tubulaturi realizate din oţel API 5L X65. Fiecare tip de rupere trebuie să constituie obiectul unei caracterizări specifice. Autorii au determinat temperatura de tranziţie ductil-fragil DBTT a oţelului API 5L X65, prin diferite metode conforme standardelor internaţionale: încercarea la încovoiere prin şoc (încercarea Charpy) şi determinarea tenacităţii oţelului menţionat, la temperaturi variind între 131K şi 293K.*