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Correlations between Impact Bending and Fatigue Tests, in Order to Determine the NDT Temperature for API 5L X65 Steel

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Abstract

One of the effect of temperature decreasing on alloy steels is the change of ductile behavior in a fragile one. The influence of the temperature on breaking nature has a considerable importance. Many steels exhibit ductile fracture at elevated temperatures and brittle fracture at low temperatures. The temperature above a material is ductile and below is brittle is known as the transition ductile - brittle temperature, also known as Nil-Ductility Transition (NDT) temperature. This temperature is not precise, varying with the thermal and mechanical treatment applied in advance, and the nature and amount of impurities. NDT is determined according to the standards, using Charpy test. This paper aims to increase the accuracy of the transition ductile - brittle temperature determination, by correlating information from impact bending test with those obtained by the fatigue test.

Key words: *NDT, CT specimen, Charpy test, dynamic critical stress intensity factor.*

Introduction

In technique, the determination of the transition ductile - fragile (NDT) temperature is very important, especially for parts and blanks working at high variations environment temperature. From this category it can be itemized: natural gas or CO2 transportation pipelines, vehicle armor or aircraft components. The temperature above a material is ductile and below is brittle is known as the transition ductile - brittle temperature, also known as Nil-Ductility Transition (NDT) temperature. This temperature is not precise, varying with the thermal and mechanical treatment applied in advance, and the nature and amount of impurities. NDT is determined according to the standards, using the shock bending test. For steels, the transition temperature stability limit is considered the temperature at which breaking energy falls below 40 J for standard bending test specimen used in Charpy test.

Under these conditions, steel manufacturers are more focused on achieving "ultra-clean" steels (without impurities) using the fine control of chemistry.

The current trend in obtaining steel is to maintain a low level of sulfur (S), phosphorus (P) and nitrogen (N). The presence of these elements in quantities above a certain level is detrimental for the steel quality, in particular for ductility and crack strength of the produced steel. To produce a clean, stress relieved steel, the process of steel refining involves the treatment with aluminum (Al) or silicon (Si) or a combination of both elements. Calcium (Ca) is often used to control the shape of inclusions.

Steel production using thermal and mechanical control, together with accelerated cooling is a common method for obtaining a micro alloyed steel with high strength. This combination allows a better control of the microstructure and grain refining, being a very important stage of the process. The degree of grains exceed the reference ASTM E 112: grain size 7 or better, becoming a past time for this type of steel. Improved control on grains, brought better results for CNV and DWTT tests, which are transformed into a very high resistance to the initiation and propagation of the crack. Steel plants aim to achieve grain sizes of 10 or better, to get the best mechanical properties [1].

Theoretical Considerations

Generally, there is no single specific criteria for defining a transition temperature; various definitions are used (fig. 1) [2]:

a. Fracture Transition Plastic (FTP) is the temperature above which the fracture is 100% fibrous/shear (0% cleavage/ductile). This is the most conservatory estimate;
b. Nil Ductility Temperature (NDT) is the temperature below which the fracture is 100% cleavage/shear;
c. Fracture Appearance Transition Temperature (FATT) is the temperature at which the fracture surface is 50-50% cleavage and fibrous. This can alternatively be based upon the mean of the "upper" and "lower" shelf energies

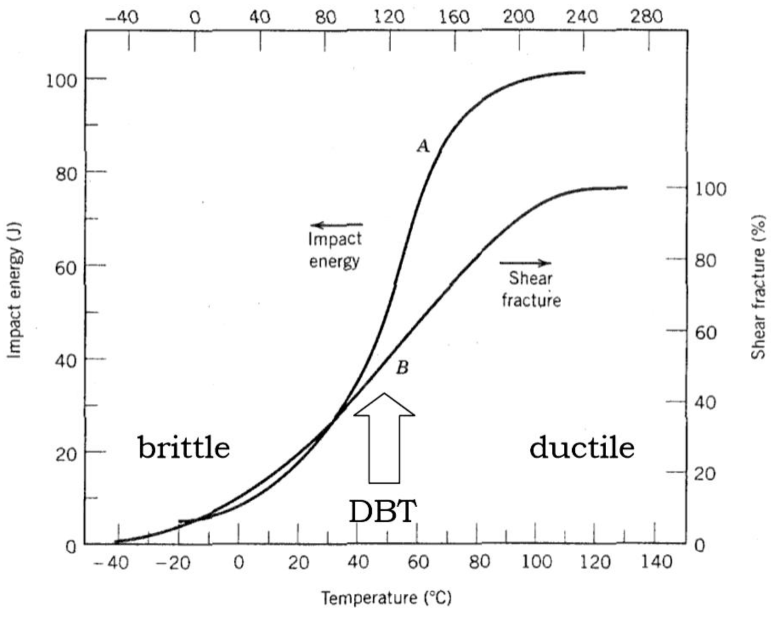

Fig. 1. Fracture Energy and Mode Percentage vs. Temperature [2]

Determination of fracture energy of the specimen can be done by plotting the force - time dependence (fig. 2), knowing the speed of the pendulum at the impact moment [3].

An experimental accepted formula is:

$$\bar{v} = \frac{1}{2}(v_0 + v_i) = v_0\left(1 - \frac{E_I}{4E_0}\right) \quad (1)$$

where: $\bar{v}$ is the average speed of the pendulum for a specific period of time; v_0 is the velocity of the pendulum before the impact; v_i is the speed reduced to a certain time t from the impact; E_0 is the total available kinetic energy of the hammer.

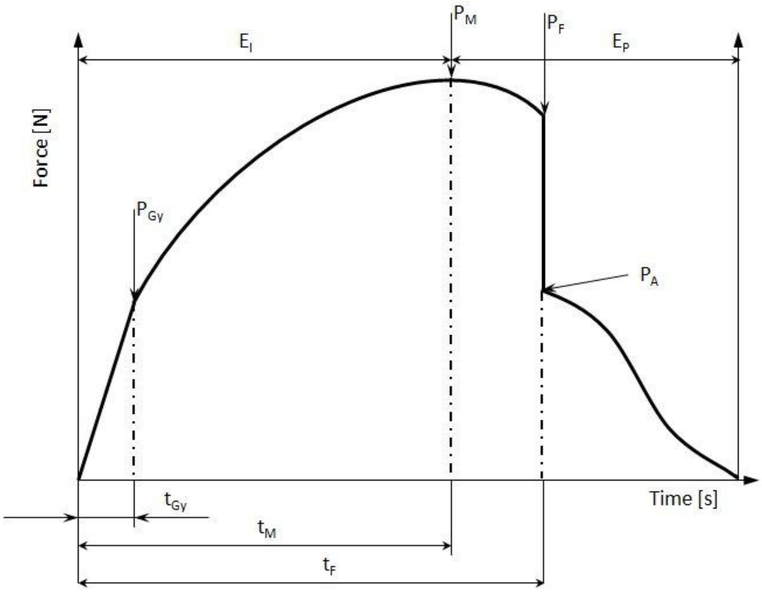

Fig. 2. Force - time dependence at Charpy test [3]:
E_I – the energy required to initiation; E_P – the energy consumed to fracture propagation;
P_M – the initiating force; P_F – the breaking force; P_{GY} – the dynamic flow force;
P_A – the force of stopping the propagation; t_{Gy} – time until the dynamic flow begins;
t_M – the time until the crack initiation; t_F – the time until failure.

Like that a relation is obtained:

$$E_I = v_0 \int_o^t P\,dt \tag{2}$$

where $\int_o^t P\,dt$ is the area under the force - time dependence, as shown in Figure 2 [3]. Since the system is energy loss, the relation 2 is corrected:

$$E_{corr} = E_I \left(1 - \frac{E_I}{4E_0}\right) \tag{3}$$

In Figure 3, the interdependence force - time and energy - time is shown.

$$E_T = E_I + E_P \tag{4}$$

where E_T is the total energy, as indicated by the electronic recording system.

Principle of the Method

The method is based on the recording process of deformation, crack initiation, crack propagation and tearing with a simultaneous analysis of:
- the values of force;
- image analysis.

By determining the breaking tenacity, KIC noted, the following transient parameters are retained for:
- energy absorbed to the general state of flow;
- the shape of the fracture and lateral expansion;
- recording of dynamic load - time dependence [3].

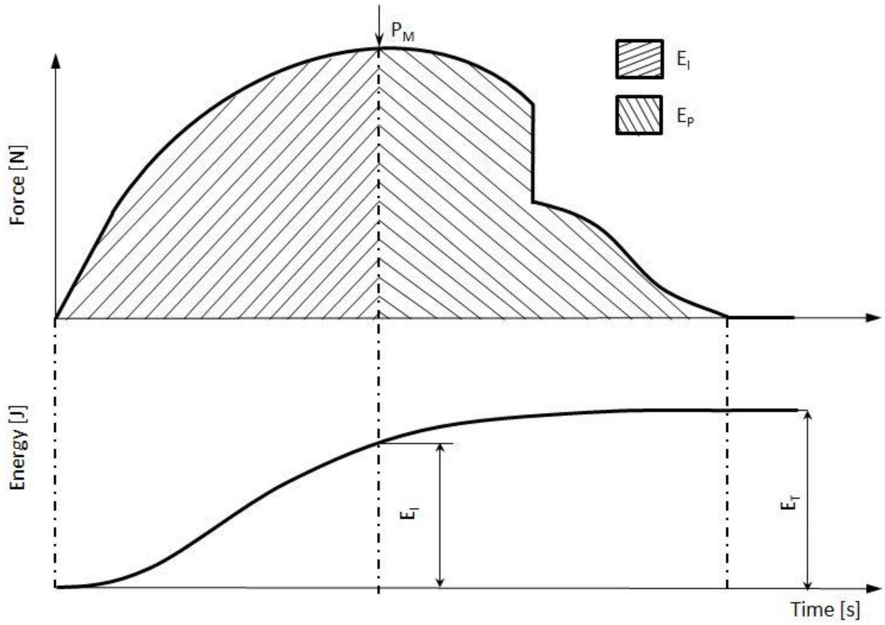

Fig. 3. The interdependence force - time and energy [3]

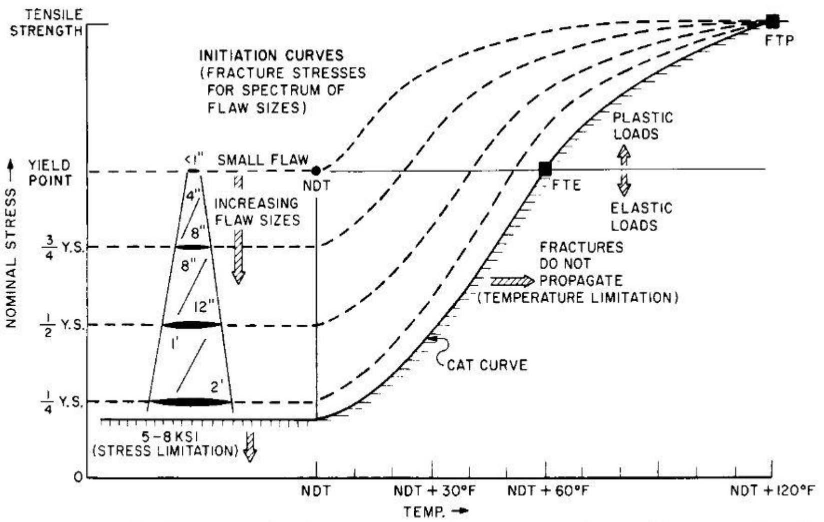

Fig. 4. Generalized Fracture Analysis Diagram Indicating the Approximate Range of Flaw Sizes Required for Fracture Initiation at Various Levels of Nominal Stress, as Referenced by the NDT temperature [4]

Crack resistance of CT specimens made of ferrite steels is strongly affected by the temperature. For a given "low" temperature, the size and sharpness of the notch determine the intensity of stress required to initiate a brittle fracture. The significance of this test method is to set that the temperature, defined in this case as NDT temperature, whose curve starts at the beginning of the crack (Figure 3), decreases in the nominal yield stress with temperature decreasing, the point NDT being marked as in Figure 4 [4].

Materials and Method

The used material for testing, was alloyed steel API 5L X65. This steel is widely used in the construction of pipes for the carbon dioxide or liquid gas, transport but also in armor manufacturing (with appropriate modification of alloying elements). Chemical and mechanical characteristics are presented in tables 1 and 2.

Table 1. Chemical composition of API 5L X65 steel [5, 6]

Carbon [%]	Magnesium [%]	Phosphate [%]	Sulfur [%]	Hydrogen [%]	Silicon [%]
0.1	1.5	0.015	0.005	0.007/0.015	0.35

Table 2. Mechanical characteristics ofAPI 5L X65 steel [5; 6]

Young's modulus	Yield point	Tensile strength
210	510	650

The microstructure of the steel is shown in Figure 5 [7] and the steel heat treatment is given in Table 3 [7].

Table 3. Lamination conditions for API 5L X65 steel [5; 6]

Reheating temperature [^{0}C]	Initial lamination temperature [^{0}C]	Final rolling temperature [^{0}C]	Non-crystallized rolling area reduction [%]	Initial cooling temperature [^{0}C]	Final cooling temperature [^{0}C]	Cooling rate [^{0}C/s]
1,200	985	832	81	801	465	9.1

Results

In order to determine the brittle - ductile transition temperature, tests have been performed according to ASTM E208, varying the temperature of the specimens between 248 K and 333 K. According to the literature [8], the temperature range investigated, it is most common in operation of gas transport pipelines, but for armored vehicles too.

Therefore, impact bending and fatigue tests were made, upon kits of specimens conditioned at the following temperatures: 248 K, 268 K, 293 K, 313 K and 333 K. If during the impact bending test rupture energy and the variation of the impact strength was followed, at the fatigue test, using specimens conditioned in the same conditions, the variation of internal energy to crack initiation and subsequent rupture of the specimen was followed. Using finite element analysis provided a good graphical representation of internal energy and total energy for the tested specimens.

Figure 6 presents the associated mesh for CT specimen used in the fatigue test. Crack development depends on the temperature, as is shown in Figure 7a and 7b. Also, the direction of crack propagation is branched by the quasi-polygonal ferrite perimeter, while cracks progress remains in the same direction when they encounter the needle-shaped ferrite area. The presence of the quasi-polygonal ferrite, homogeneously dispersed into the needle-shaped ferrite structure, force the crack to a jag propagation. A reduced needle-shaped ferrite grain size, handle an improvement of the tensile strength.

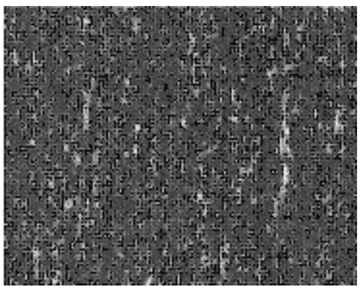

Fig. 5. Typical microstructure - 100X, grain size - 11 or higher

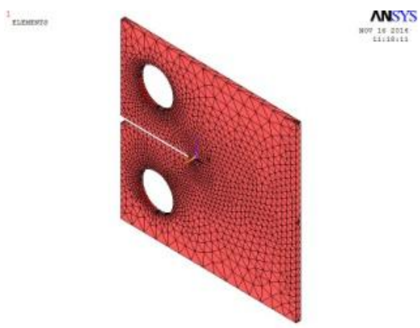

Fig. 6. Mesh for CT specimen

The correlation between recorded Charpy impact for internal energy and force, for the two extreme temperatures of the bounded interval, is shown in Figures 8 and 9.

Representation of internal energy variation from the fatigue test, at the same temperatures used in Charpy test, is shown in Figures 10 and 11.

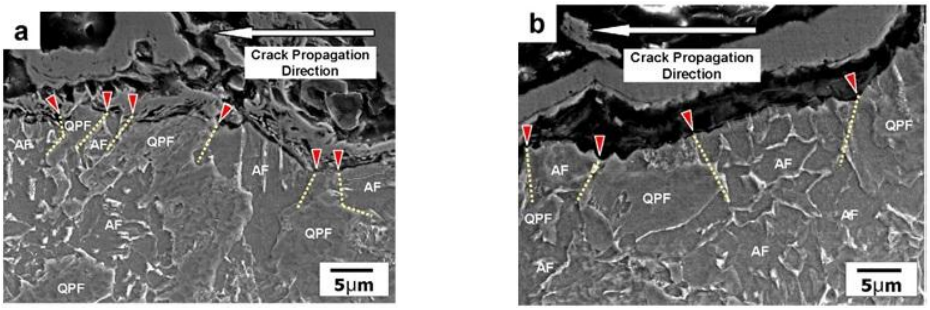

Fig. 7. Microstructure and crack propagation direction for the fatigue tested specimen at the temperature of 333 K (a) and at 248 K (b)

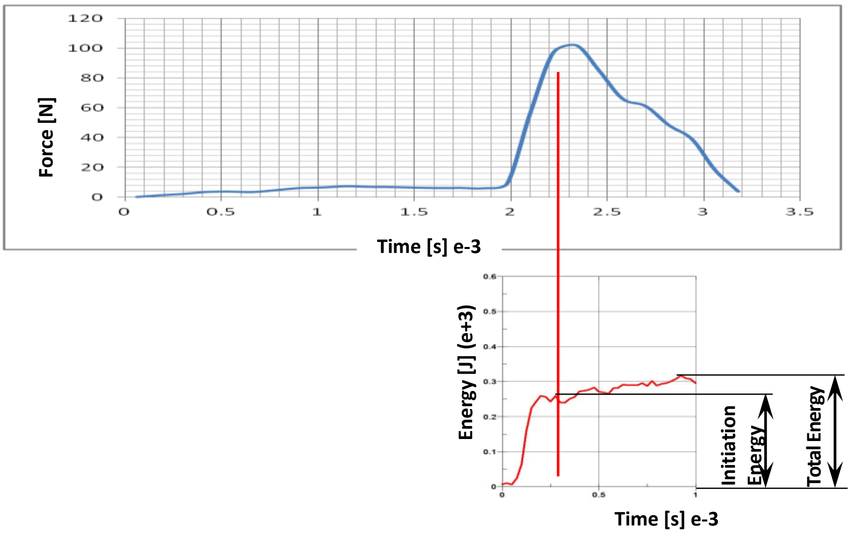

Fig. 8. Correlation force - energy at Charpy test, temperature: 248 K

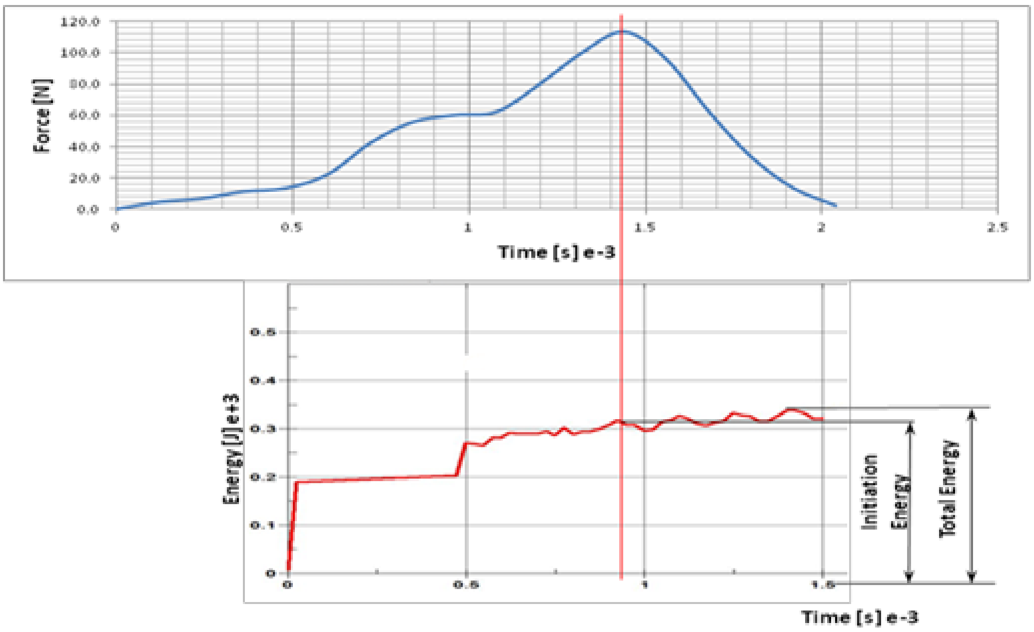

Fig. 9. Correlation force - energy at Charpy test, temperature: 333 K

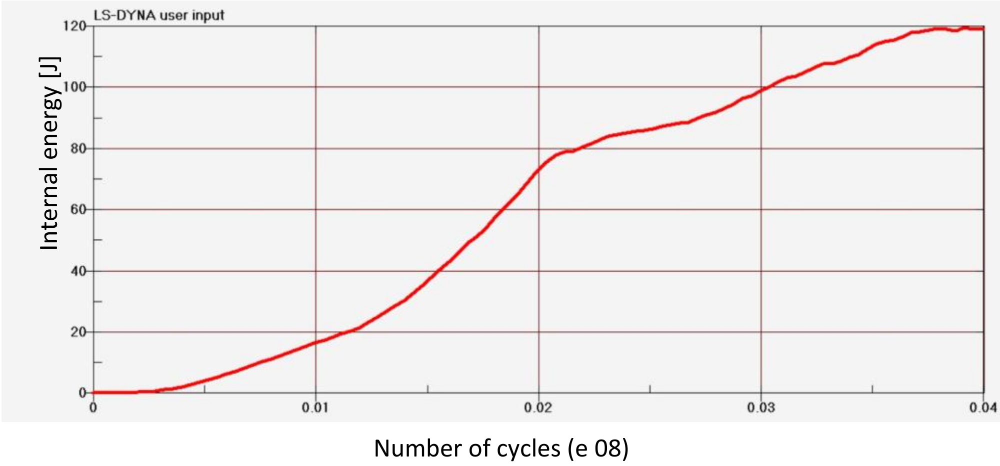

Fig. 10. Internal energy for fatigue test at the temperature of 333 K

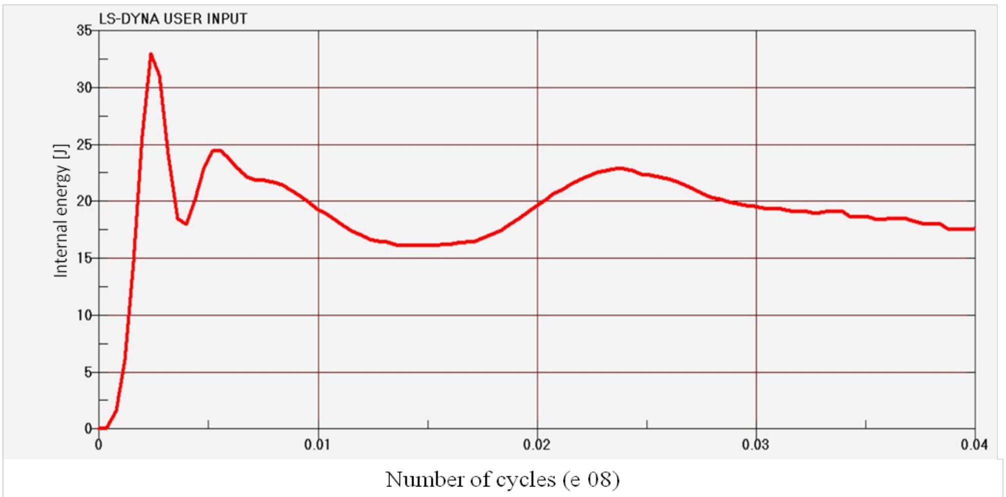

Fig. 11. Internal energy for fatigue test at the temperature of 248 K

As it can be seen, the internal energy representation differs fundamentally between the two types of tests, but into the same type of test too, depending on temperature. Representation of internal energy for fatigue test is more accurate, considering the microstructure above.

Conclusions

This paper aimed to reveal more accurately the value of ductile - brittle transition temperature (NDT) for API 5L X65 steel, considering that the value of this temperature depends on the degree and quality of impurities, and on the advance heat treatment of steel. This goal was achieved by completing the Charpy test - recommended by standards - with the fatigue test. In addition, a correlation was made between impact strength and internal energy at the impact bending test. After the tests, the following conclusions were highlighted:

- The moment for changing the characteristic from ductile to a brittle of the material is difficult to estimate only after the results obtained from Charpy test. NDT is considered the point where the dynamic critical stress intensity factor reaches the value of 100MPa/m^2;
- For the analyzed steel, according to dynamic critical stress intensity factor criterion, 153 K is the value obtained for NDT, with a large deviation (62%) compared to standard ASTM E208 previsions;

- Taking into account the fatigue test, by analyzing the internal energy stored in the specimen during the test, with the ambient temperature as reference, the NDT value obtained is closer from the one obtained after Charpy test, using the dynamic critical stress intensity factor criterion;
- Fatigue test presents practical difficulties, especially at low temperatures of CT specimen, due to the fastener system of the machine;
- Finite element analysis for CT specimen offers a good accuracy in predicting NDT if a certain number of cycles at environment temperature is taken as reference, corresponding to the distance of crack propagation

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Corelaţii între încercările de încovoiere prin soc şi oboseală pentru determinarea tranzitiei ductil-fragil la oţelul API 5L X65

Rezumat

Unul dintre efectele scăderii temperaturii asupra oțelurilor înalt aliate este schimbarea comportamentului ductil intr-unul fragil. Influența temperaturii asupra naturii ruperii este de o importanță considerabilă. Multe oțeluri prezintă caracteristică de rupere ductilă la temperaturi ridicate și ruperi fragile la temperaturi scăzute. Temperatura peste care un material este ductil și sub care este fragil este cunoscut ca temperatura de tranziție ductil - fragil (NDT). Aceasta temperatura nu este precisă, variind în funcție de tratamentul termic și mecanic aplicat în prealabil, precum și de natura și cantitatea impurităților. NDT este determinată, conform standardelor, cu ajutorul încercării Charpy. Lucrarea își propune creșterea acurateții determinării temperaturii de tranziție ductil - fragil prin corelarea informațiilor obținute în urma încercării la încovoiere prin șoc cu cele obținute prin încercarea la oboseală.