ASSESSMENT OF BRITTLE FRACTURE PROPERTIES BY SMALL PUNCH TEST

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Abstract

Small punch test is an advantageous method for evaluation of mechanical properties of components because much less material is required for sampling and subsequent material testing. This is especially valuable in cases where not enough bulk material is available, and the repair of sampled place is complicated e.g. power industry. The testing material is sampled by a special sampling device that ensures no component damage and the sampled volume is so small that no component repair is necessary after sampling. Small punch testing is viable not only for evaluation of mechanical properties but can also be used for evaluation of brittle fracture properties (transition temperature, fracture toughness), which play integral part in lifetime of some power components and structures. This paper introduces and compares two different approaches to the evaluation of the transition temperature. Also, a way to evaluate J-integral value using small disc specimen with side notch which is suggested by EN 10 371 standard is introduced and compared to J-integral evaluation via standard fracture mechanics approach using multiple CT specimens and plotting crack growth resistance curve.

Keywords: Small punch test, transition temperature, fracture toughness, J-integral, J-R curve

1. INTRODUCTION

This article summarizes evaluation of ductile-brittle transition temperature (T_{SP}) by two different (two-curve fit method and hyperbolic tangent fit method) approaches using small punch test (SPT). Two-curve fit method is older, and more skill and experience based on the other hand, the hyperbolic tangent fit method is newer approach based purely on mathematics recommended by EN 10 371 standard which is dedicated to small punch test method. Both approaches will be described in more detail later in the article. These two approaches will be compared on the same material (215 mm thick plate of 1%Cr-0.5%Mo steel) in two different heat treatment states (as-delivered, quenched + tempered – Q+T) and in 3 areas of interest because of the large thickness of the sample: T – top, M – mid-thickness, B – bottom.

Second part of the article focuses on using SPT for toughness evaluation, few different approaches are mentioned. Experimental work focuses on evaluation of toughness (J-integral) by use of notched small discs specimen and small punch test on nickel superalloy Inconel 617. Fracture toughness results from SPT are then compared to J-R curve evaluated with standard fracture mechanics approach and CT specimen.

2. TRANSITION TEMPERATURE EVALUATION COMPARISSON

To evaluate transition temperature value, the small punch test energy E_{SP} must be defined. E_{SP} is defined as area under the force x punch tip displacement (deflection of the sample) curve from zero up to the maximum test force, as seen in **Figure 1**. This figure also shows how different characteristics are obtained from the force x deflection curve and what are they used for. **Figure 1** is also completed with appearance of small discs sample before and after the small punch test.

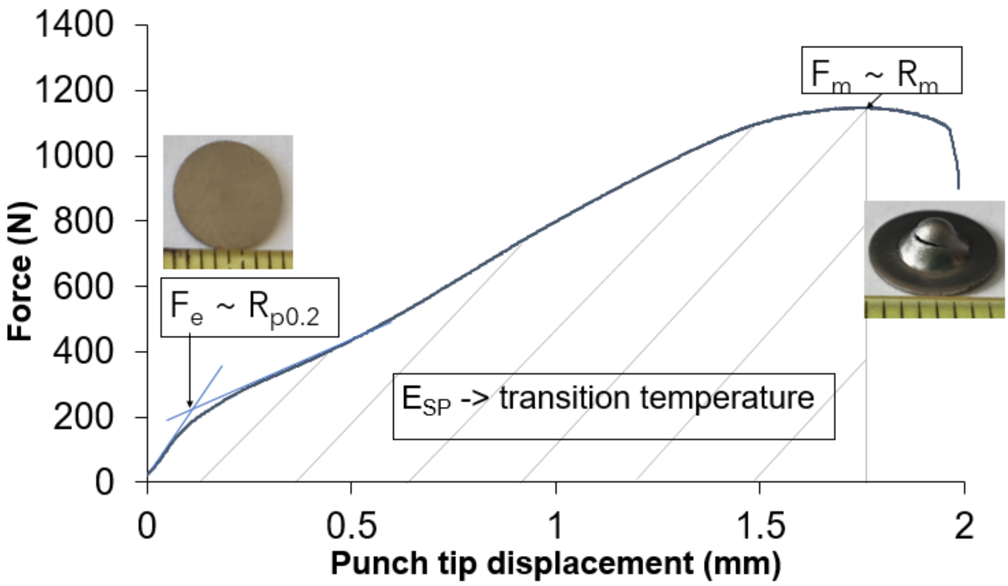

Figure 1 Force x deflection curve with different characteristics defined

With E_{SP} defined, transition temperature evaluation can be evaluated by following methods [1, 2]:

- the **two-curve method** (**Figure 2 left**), which is based on finding the highest and the lowest energy of the test by exponential fit of the lower and upper shelf of the dataset, their intersection determines the highest energy value. T_{SP} is then calculated as the mean value of the highest and the lowest energy.
- the **hyperbolic tangent (tanh) fit method** (see **Figure 2 right**), which is based on normalizing the test energy E_n according to Equation (1):

$$E_n = E/F_m \qquad (1)$$

Where:

E – test energy (mJ)

F_m – maximum force achieved during small punch test (N)

By use of the least square method, all other variables can be calculated, and T_{SP} is defined as the inflection point of fitted curve given by the Equation (2).

$$E_n(T) = A + B \cdot tanh\left[\frac{T-T_{sp}}{C}\right] = \frac{E_{US}-E_{LS}}{2} + \frac{E_{US}-E_{LS}}{2} \cdot tanh\left[\frac{T-T_{sp}}{C}\right] \qquad (2)$$

Where:

$E_n(T)$ – normalized test energy at temperature T (m

E_{LS} – lower shelf energy (mJ/N)

T – temperature (K)

T_{SP} – transition temperature of small punch test (K)

A, B, C – constants

Both methods are explained in more detail in [1-3].

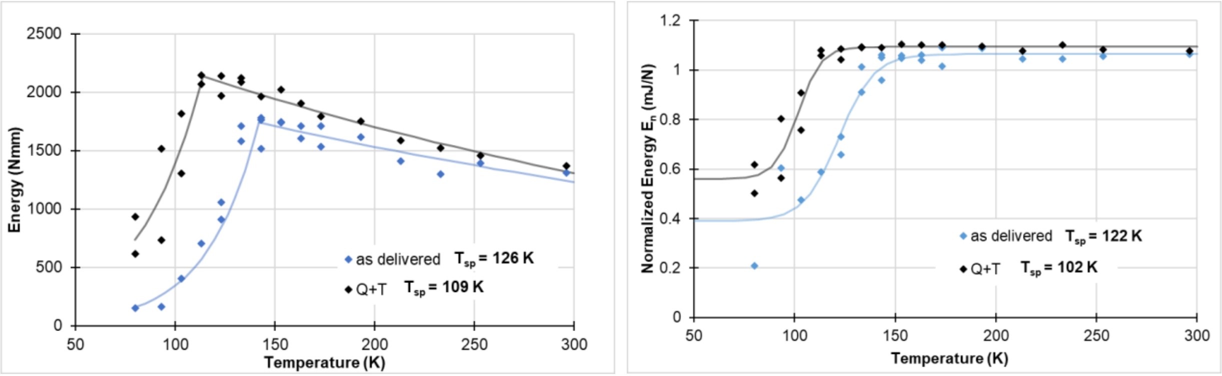

Figure 2 Same location of the sample evaluated by two-curve method (**left**), by hyperbolic tangent fit (**right**)

Table 1 compares the evaluated results in all locations of the sample and by both above-mentioned methods. No matter the evaluation method, the trend stays the same, meaning the transition temperature is always lower and material is more ductile after quenching and tempering.

Table 1 Comparison of T_{SP} by location and evaluation method used

Sample	**Location of sample**	***T_{SP}* – two-curve method (K)**	***T_{SP}* – tanh fit method (K)**
as delivered	T – top	131	116
	M – mid-thickness	123	121
	B – bottom	126	122
Q+T	T	109	98
	M	121	111
	B	109	102

3. FRACTURE TOUGHNESS EVALUATION BY SPT

Since there is no unique parameter for determining the fracture toughness, but it needs to be chosen according to the behavior of the material, the EN standard [1] also offers three different approaches to estimate the fracture toughness. The first approach is a two-stage correlation, which relates the plane strain fracture toughness K_{Ic} and the transition temperature FATT (brittle-to-ductile fracture). This correlation was determined experimentally mainly for Cr-Mo-V steel and is characterized by Equation (3):

$$K_{Ic} = \frac{6600}{60-(T-FATT)} \tag{3}$$

Where K_{Ic} is fracture toughness in the plane strain mode, T (°C) is the test temperature and FATT (°C) is the fracture appearance transition temperature at 50% ductile fracture found on the fracture surface as determined by a Charpy impact test [1].

The second approach to determining the fracture toughness assumes that the so-called effective fracture strain ε_f, determined by Equation (4), should reflect the fracture toughness of the sample, especially when comparing materials with similar structure.

$$\varepsilon_f = \ln(h_0/h_f) \tag{4}$$

Where ε_f is effective fracture strain, h_0 is initial thickness of sample before the test and h_f is the lowest sample thickness at the point of fracture after being pushed through the punch. The relationship between effective fracture strain and fracture toughness is described by the standard with Equation (5):

$$J_{Ic} = k \cdot \varepsilon_f - J_0 \tag{5}$$

Where J_{Ic} is the fracture toughness, ε_f is the effective fracture strain, k and J_0 are material dependent constants [1].

As conventional test samples for determining fracture toughness are provided with a crack (notch), one possibility is also to use small samples with a notch. Due to the difficulty of creating a sharp crack on small samples, the EN 10371 [1] standard suggests the use of samples with a side notch with tip lying approximately in the middle of the sample, **Figure 3**.

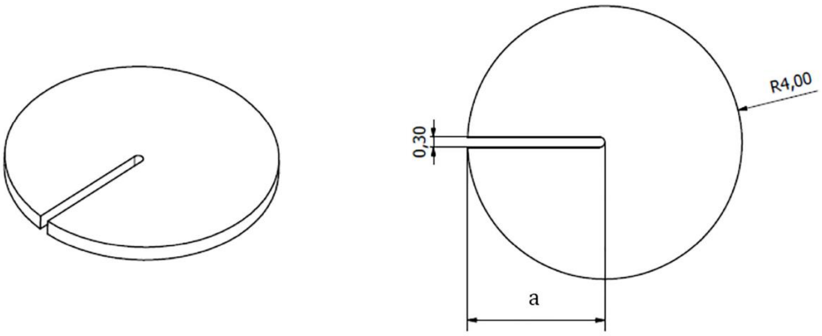

Figure 3 Notched small disc specimen for toughness evaluation (dimensions in mm)

Based on the maximum measured displacement of the punch or deflection and the notch length, it is possible to determine the approximate value of δ_{Ic} according to the charts created using the finite elements method, **Figure 4**, which we can subsequently use to calculate J_{Ic} according to Equation (6):

$$J_{Ic} = R_{p0,2} \cdot \delta_{Ic} \tag{6}$$

Where $R_{p0.2}$ is the yield strength of the material determined using a uniaxial static tensile test and δ_{Ic} is the notch opening value derived from the length of the notch and the punch displacement or sample deflection achieved during the test [1].

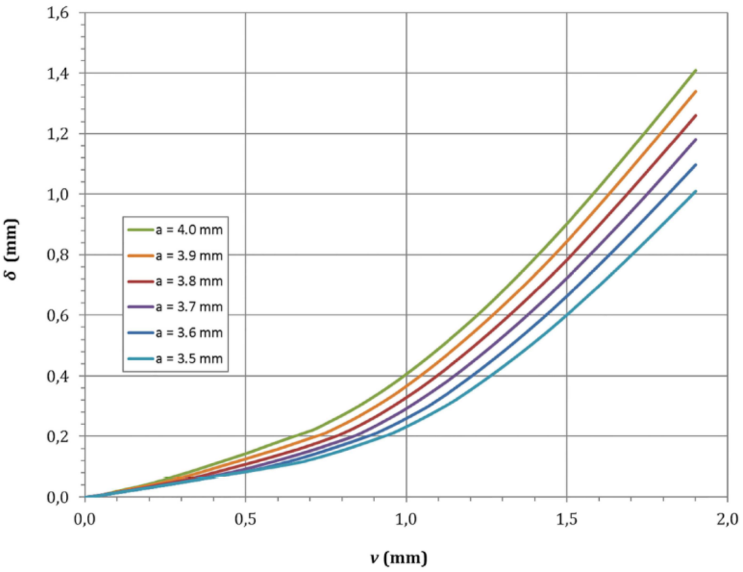

Figure 4 δ_{Ic}, punch displacement and notch length dependence [1]

The mentioned three approaches are not the only ones, other approaches for determining the fracture toughness of the material on notched and non-notched samples with different configurations of notches can be found in the literature [4-7]. There is no consensus on which method is the best or most suitable for determining the fracture toughness, the general consensus is only in that it is preferable to use notched specimens, which allow characterizing different orientations of the material, compared to the use of non-notched samples, which are only able to characterize properties in the weakest direction.

For toughness evaluation notched specimens were used. Toughness was evaluated on Inconel 617 nickel superalloy on 5 notched small specimens. Results were then compared to J-R curve, **Figure 5**, which was constructed by traditional fracture mechanics approach and ½ CT specimens. **Table 2** compares the toughness given by SPT and by J-R curve.

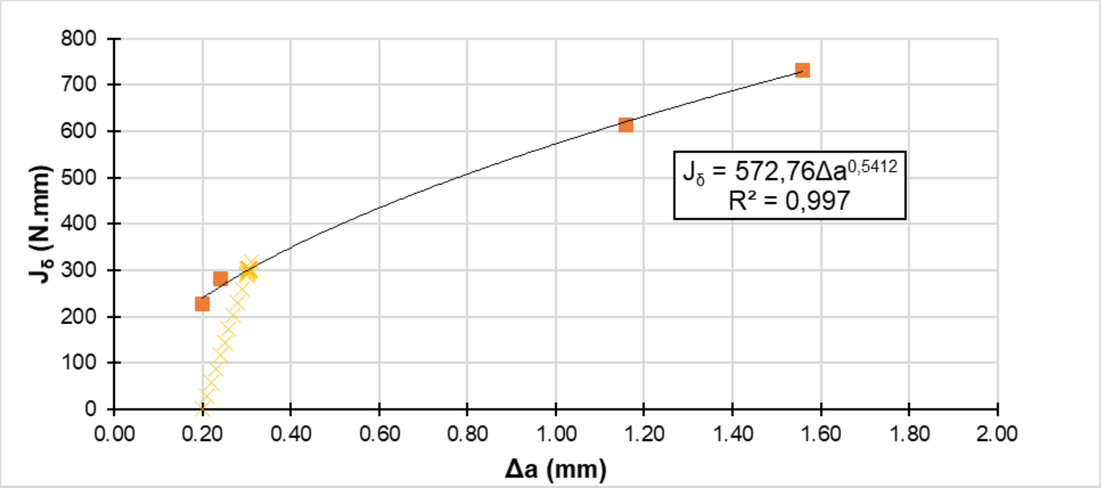

Figure 5 J-R curve for Inconel 617

Table 2 Toughness values for different evaluation approaches

Material	J SPT ($N \cdot mm^{-1}$)	$J_{0.2}$ ½CT ($N \cdot mm^{-1}$)
INCONEL 617	320	301

Because SPT produces just a single value and a J-R curve cannot be constructed, $J_{0.2}$ value was used from J-R curve for comparison purposes. As seen from **Table 2** the toughness value given by SPT is fairly like $J_{0.2}$ from the J-R curve.

4. CONCLUSION

Both methods for transition temperature evaluation can determine certain changes in transition temperature (change of transition temperature with change of structure, etc.) even though exact numerical values are not the same. While the two-curve fit method tends to exaggerate the transition temperature by small margin and is therefore a little more conservative (safer), on the other hand, the hyperbolic tangent fit is more straight-forward and less user-dependent so it probably would be better for potential commercial use of SPT method.

The use of notched specimens and SPT for toughness evaluation and subsequent comparison to J-R curve constructed from ½CT specimens from the same material proved that the small punch test can be used for toughness evaluation successfully. This can be exploited in cases where little material is available or specific location (heat affected zone, weld metal etc.) require toughness evaluation.

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