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Influence of the notch length on the estimation of the reference temperature by means of the small punch test

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Abstract: The Master Curve approach has been widely applied to characterize the ductile to brittle transition region of ferritic steels. In order to further optimise the available material to be tested, great efforts have been recently performed to combine it with miniature testing techniques. One of the most promising is the small punch testing technique, currently under standardisation process in Europe. In this paper, small punch modified specimens with a lateral notch for the estimation of fracture toughness have been employed to obtain the reference temperature, T_0 , of a pressure vessel steel. The influence of the applied notch length has been analysed and a valid range has been proposed. In addition, the validity criterion of the tests for the estimation of T_0 has been further verified, confirming its suitability. Finally, results have been compared with those obtained with conventional fracture mechanics specimens and previous works. As a result, a methodology to estimate the reference temperature by means of small punch tests with notch lengths of approximately 4.4 mm has been proposed, turning it into a promising candidate for the characterisation of the transition regime.

Keywords: small punch; reference temperature; master curve, notch, fracture toughness, transition region

1. Introduction

The Master Curve (MC) approach enables a full characterisation of the ductile to brittle transition region of pressure vessel steels, or in general, ferritic steels, with a single parameter: the reference temperature. Developed at the VTT [1], the method has been successfully applied to a large number of ferritic steels and, thanks to its numerous advantages, has already been incorporated in several standards and codes, such as ASTM E1921 [2], BS 7910 [3], API 579/ASME FFS [4] or FKM Guideline [5].

One of its main features is the material optimisation: the reference temperature can be determined with a reduced number of tests. For challenging applications with reduced available material, such as the extension of the operating life of nuclear power plants, the MC approach has been combined successfully with miniature testing techniques to further reduce the material to be tested. For instance, micro compact tension specimens have been applied, employing a volume of only 10x10x4 mm per test [6].

The small punch technique is another promising miniature testing technique, which is currently under standardisation process in Europe [7]. It requires reduced volumes of material to estimate its properties, with specimens of only 0.5 mm-thickness and 8mm-diameter. Thanks to its potential, it has been employed in a wide range of applications, although its origins are directly related to the assessment of the embrittlement of pressure vessel steels [8].

One of its most appealing applications is the estimation of fracture toughness, given the size of the specimens employed. Several approaches have been proposed, such as the use of the equivalent fracture strain [9] or finite element modelling [10], among which the use of lateral notches results highly remarkable [11, 12]. This geometry has been recently applied to the estimation of the reference temperature on several ferritic and pressure vessel steels with promising results [13, 14]. In these previous works, a fixed notch length has been employed, which might have had some influence on the results obtained. Consequently, the main goal of this paper is to analyse its effects on the estimation of the reference temperature by means of small punch specimens with a lateral notch. To achieve it, a pressure vessel steel has been analysed and different usually employed notch-length values have been tested, in a range from 4.2 mm to 4.5 mm. In addition, the validity criterion for the tests has been confirmed, by analysing the differences in the estimations with tests exhibiting pure cleavage fractures and mixed fractures.

2. Materials and Methods

2.1. Experimental device

The small punch tests have been performed according to the recommendations of CWA 15627:2008 [15] in a universal mechanical testing machine with a load capacity of 2.5 kN. Given the scope of the research, the testing rig has been assembled inside an environmental chamber cooled by means of liquid nitrogen, which guaranteed the attainment of the testing temperatures required to characterise the ductile to brittle transition region.

Square 10x10 mm specimens have been employed with a lateral notch on it [11, 12], as it can be seen on Figure 1, which enables the use of analytical approaches to estimate fracture toughness and that will be included in the future European Standard for small punch testing of metallic materials. Other notches have been proposed, such as the use of through thickness central notches [16], blind longitudinal notches [17] or sharp circular notches [18], but the lateral notch has been selected for this research given its accurate results, its ease of machining by means of wire electron cutting and the possibility of characterising any orientation of the material.

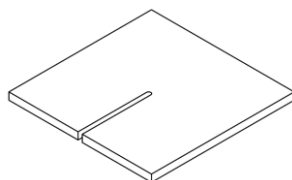


Figure 1. Scheme of a small punch specimen with a lateral notch machined on it.

To prepare the specimens, firstly the notch has been machined on 10x10 mm prisms. After this first step, it has been cut into pieces of approximately 0.55 mm thickness by means of a liquid-cooled cut-off machine. The samples have then been ground to at least 2000 grit on both sides until achieving the desired thickness of 0.5 ± 0.005 mm, according to the recommendations of CWA 15627:2008 [15].

The notch length has been corrected during the specimen preparation by grinding, if needed, until achieving the desired length. During the tests, the use of an adjustable lower matrix has enabled the reduction of the possible clearance between the matrix and the specimen, which could misalign the notch or vary its length. It is a novel design, which has been manufactured and validated for testing this specific geometry of specimen. It counts with a mobile piece, as shown in Figure 2, which can be adjusted to the length of each specimen, enabling the correction of the notch length if needed, something impossible to achieve by means of the conventional small punch testing rigs.



Figure 2. Adjustable lower matrix.

2.2. Material

A pressure vessel steel, HSST A533B PLATE 13B, has been tested. Its tensile properties have been obtained by means of conventional full-scale testing techniques, as well as its reference temperature. It has a yield strength, σ_y , of 480 MPa, a tensile strength, σ_u , of 608 MPa and a reference temperature, T_0 , of 250 K [19].

2.3. Estimation of fracture toughness

The estimation of fracture toughness by means of small punch specimens with a lateral notch is based on the Crack Tip Opening Displacement (δ) concept [20]. According to it, cracks experience a certain degree of blunting before fracture, which can be related to the toughness of the material. Shih provided evidence of a unique

relationship between δ and J by evaluating the displacements at the crack tip implied by the HRR solution under elasto-plastic fracture mechanics conditions [21]:

$$\delta = \frac{d_n J}{\sigma_y}, \quad (1)$$

where d_n is a dimensionless constant with a strong dependence on the strain hardening exponent of the material [21].

During a small punch test on a modified specimen with a lateral notch, the notch is deformed in a similar way to notch blunting, until a certain point, where a crack usually initiates. This point can be easily identified on the Force-Displacement curve as a sudden change on its slope [11, 12]. If the tests are simulated by means of finite element models, it can be seen that a material independent relationship between the degree of crack blunting or δ_{SP} and the punch displacement can be obtained for a given notch geometry, as seen in Figure 3. Consequently, δ_{SP} can be easily obtained at the point of crack initiation after the test has been performed, by simply identifying the punch displacement correspondent to the crack initiation and then by simply applying the abacus shown in Figure 3.

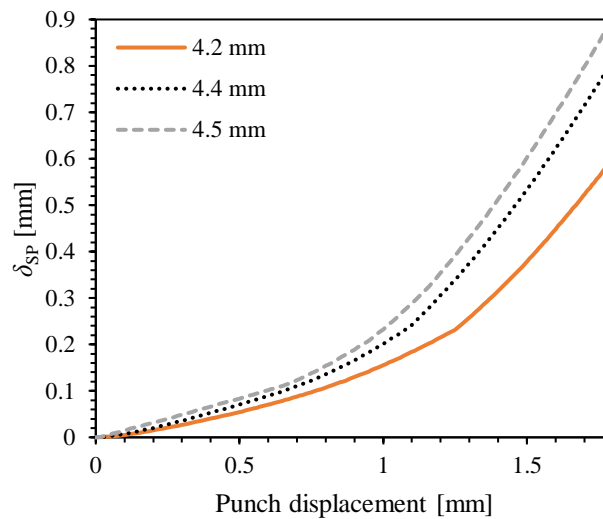


Figure 3. Relationship between δ_{SP} and punch displacement obtained by means of finite element models for notch lengths in between 4.2 and 4.5 mm.

If the tensile properties have already been obtained, by means of small punch tests or any other technique, equation (1) can be applied to obtain J_{SP} . Once it has been determined, equation (2) can be employed to estimate the equivalent K_{J}^{SP} value at the point of crack initiation [2, 20, 22]:

$$K_J = \sqrt{\frac{EJ}{1-\nu^2}}, \quad (2)$$

where E represents the Young modulus of the material and ν is the Poisson's coefficient.

2.4. Master Curve approach

The Master Curve approach is a statistical, theoretical, micromechanism based, analysis method for fracture toughness in the ductile to brittle transition region (DBTR) [1]. It enables the full characterisation of the DBTR with a single material-dependent parameter, the reference temperature, which can be defined as the temperature corresponding to a K_{Jc} value of 100 MPam^{0.5} for a failure probability of 50%, obtained with a 25 mm-thickness specimen [1T].

The MC method also takes into account the scatter of the results at the DBTR, as well as the size effects and the temperature dependence of the fracture toughness [2]. Consequently, T_0 can be obtained with a reduced number of tests with limited volumes of material by applying equation (3):

$$K_{Jc} [1T] = 20 + [11 + 77e^{[0.019(T-T_0)}] \left(\frac{25}{B}\right)^{\frac{1}{4}} \left[\ln \frac{1}{1-P_f}\right]^{\frac{1}{4}}, \quad (3)$$

where T represents the temperature in Kelvin, B is the thickness of the specimen and P_f is the probability of failure [2].

3. Results and discussion

3.1. Results of the small punch tests

The small punch tests have been performed at several temperatures, ranging from 143 to 158 K, for the estimation of the reference temperature. As it can be seen in Table 1, notch lengths of approximately 4.2, 4.3, 4.4 and 4.5 mm have been tested. The length values have been measured after the test, taking into account the possible deviations that the specimens might have suffered during the test, which introduce some scatter to the values. In addition, K_J^{SP} values have been estimated according to the methodology aforementioned.

Table 1. Results obtained from the small punch tests.

Temperature [K]	Notch length [mm]	K_J^{SP} [MPam ^{0.5}]	Sudden force drop
158	4.19	110	
158	4.19	103	
153	4.22	105	×
158	4.22	103	
158	4.24	84	
158	4.24	110	
148	4.25	82	×
148	4.27	119	
153	4.29	108	
153	4.29	104	
153	4.29	128	
153	4.30	110	
158	4.38	121	
148	4.39	129	
143	4.40	99	×
148	4.43	105	
153	4.43	133	
143	4.45	122	×
148	4.46	122	
153	4.46	116	
148	4.49	125	
153	4.51	119	×
148	4.53	98	×

3.2. Analysis of the validity criterion

According to previous works [13, 14], to guarantee the applicability of the MC approach, the onset of cleavage cracking is the criterion of validity. After performing analysis of the micromechanisms present at the crack initiation, it has been proven that those tests exhibiting a sudden drop of the force at maximum force or those tests with a discontinuity on its slope on the proximity of maximum force exhibit pure cleavage or mixed fracture mechanisms respectively, being both valid for the determination of T_0^{SP} [13, 14].

In this paper, the effect of using the most restrictive case (sudden drop load during the test) on the reference temperature has been analysed. Consequently, the reference temperature has been estimated by applying equation (3). In one case, by only taking into account those tests with a sudden drop load and, in the other, taking into account all of the tests, as shown in Figure 4. T_0^{SP} from pure cleavage fractures has been 146 K, while the reference temperature obtained from the whole of the tests has been 147 K.

As a result, it can be seen that the use of only pure-cleavage-fracture tests does not introduce nearly any change on the estimation of the reference temperature, being it of only 1 K in this case, in good agreement with previous analysis.

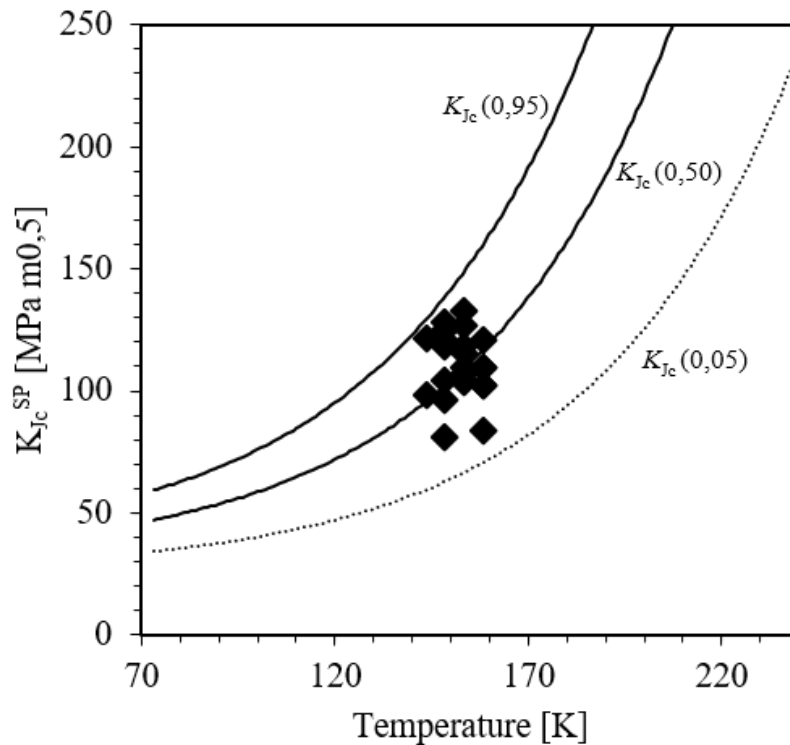


Figure 4. Small punch Master Curve obtained for all the tests performed.

3.3. Influence of the notch length on T_0^{SP}

To analyse the influence of the notch length on the estimation of the reference temperature by means of small punch tests, T_0^{SP} has been determined by applying equation (3) on groups of tests of different notch lengths, organised as following:

- 4.2 mm: tests with a notch length between 4.15 and 4.25 mm (average value: 4.22 mm).
- 4.3 mm: tests with a notch length between 4.25 and 4.35 mm (average value: 4.28 mm).
- 4.4 mm: tests with a notch length between 4.35 and 4.45 mm (average value: 4.41 mm).
- 4.5 mm: tests with a notch length between 4.45 and 4.55 mm (average value: 4.48 mm).

The reference temperature values obtained for each notch length are shown in Figure 5. It can be clearly seen that for the shorter notches, higher small punch reference temperatures have been obtained, with a maximum difference of 20 K. On the other hand, an apparent stabilisation of the temperature seems to occur for the lengths in between 4.4 and 4.5 mm, for which practically the same T_0^{SP} value has been obtained. This effect could be due to a possible influence of the notch length on the estimations of fracture toughness for the shorter values. According to the obtained results, the use of notches shorter than 4.4 mm (for this material) leads to lower estimations of fracture toughness values, which could have risen the estimation of the reference temperature. Further research should be performed in order to achieve a better understanding of its influence.

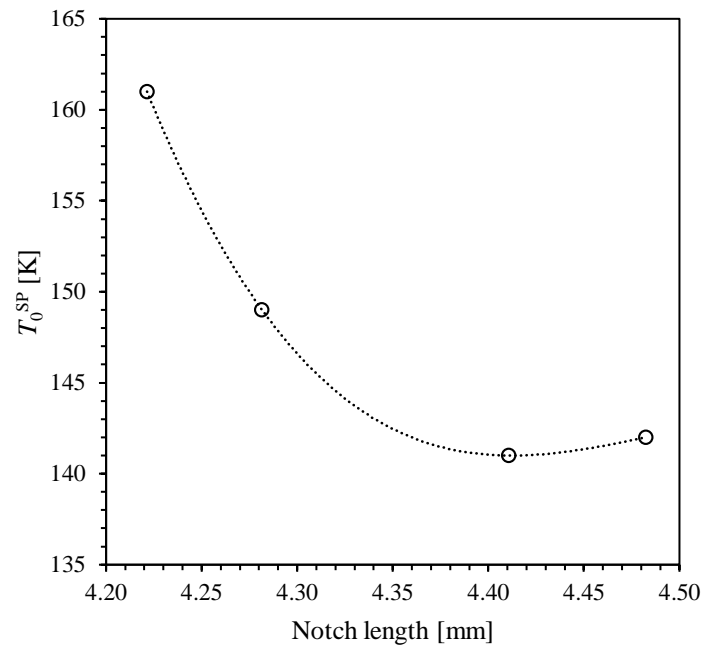


Figure 5. Small punch reference temperature obtained for each notch length.

The obtained reference temperatures for the different notch lengths have been compared with previous research [13, 14], where S275JR and S460M steels had been tested with a notch length of approximately 4.4 mm and a correlation factor between T_0^{SP} and T_0 of 0.52 had been established. It can be seen that the relationship provides accurate results for all the materials tested at the same notch length, of approximately 4.4-4.5 mm. On the other hand, shorter notches lead to higher correlation values, which would increase the error of the estimation, proportional to the reduction of the notch length.

As a result, special attention should be paid to the notch length for the estimation of the reference temperature. According to the obtained results, different relationships between T_0^{SP} and T_0 should be established for each specimen geometry or a single geometry should always be used. In the latter case, values in between 4.4 and 4.5 mm seem to be the most appropriate for this material, since both lengths have led to similar results.

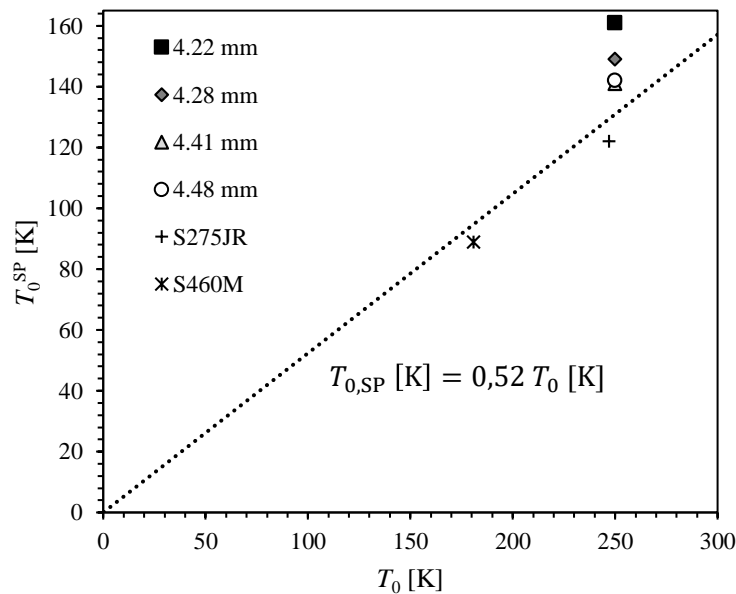


Figure 6. Relationship between the reference temperature obtained by means of small punch tests and full-scale conventional tests for several notch lengths on A533B and for a length of 4.4 mm for S275JR and S460M.

5. Conclusions

In this paper, the small punch testing technique has been successfully applied to the characterisation of the ductile to brittle transition region of pressure vessel steel, in combination with the Master Curve approach. Since it is a model based on the direct estimation of fracture properties, small punch specimens modified with a lateral notch have been employed to estimate K_{J}^{SP} . It has been proven that the notch length can influence the estimated reference temperature, leading to higher values of T_0^{SP} for lengths shorter than 4.4 mm for A533B. The use of values between 4.4-4.5 mm has shown an apparent stabilisation of T_0^{SP} , with a similar correlation coefficient $T_0^{SP}-T_0$ to the one obtained in previous works. This could suggest that material-independent relationships between T_0 and T_0^{SP} can be determined for the different notch lengths.

In addition, the test validity criterion has been further validated. It has been proven on A533B steel that both mixed fractures and pure cleavage fractures can be used to estimate T_0^{SP} without any influence on its value. Consequently, small punch tests exhibiting a discontinuity on the slope of the Force-Displacement curve or a sudden force drop can be regarded as valid. However, in case of doubt, a micromechanism analysis is encouraged to guarantee the validity of the results.

Briefly, this new approach results in a promising candidate for the characterisation of the ductile to brittle transition region of ferritic steels with an optimised use of the material. Further research is required on different materials to confirm the trends observed and achieve a better understanding of the influence of the different parameters.

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