The Use of Small Punch Tests for Determination of Fracture Behaviour of Ferritic Steels

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Abstract

The paper summarizes the experience gained with the evaluation of the transition behaviour of steels with BCC lattice from the results of penetration tests. Determination of fracture appearance transition temperature FATT from the results of penetration tests is currently performed only on empirical correlations between FATT and transition temperature TSP determined of the penetration tests in the temperature range from -193 °C to +23°C. Factors that may significantly affect the transition temperature TSP and thus empirical correlations FATT – TSP are discussed.

Introduction

The effort to extend designed lifetime of industrial plants operating for a long time at elevated temperatures requires the knowledge of residual lifetime of the critical components. Residual lifetime assessment is unthinkable without the knowledge of:

1) mechanical properties of materials prior to operation, respecting all technological operations realized throughout the manufacture of the component,
2) mechanical properties after actual time of operation (actual mechanical properties), because the material properties can be reduced throughout the service life by ageing due to service loading and/or temper, hydrogen or radiation embrittlement.
The conventional mechanical tests require relatively large volume of testing material and extracting it from an operating component can impair its integrity. In such situations, mechanical test techniques based on small specimen techniques are promising for characterizing the mechanical properties of components.

The small specimen test techniques can be generally divided into two categories:

1) reduction of test specimen size proportionate to its conventional equivalent while retaining the specimen geometry and loading configuration,
2) Development of innovative and novel specimen designs and loading configurations that has no conventional equivalent.

The need for evaluating the actual mechanical properties of structural components by direct testing method has led to development of Small Punch test technique [1]. It can be used to obtain tensile, fracture and creep data from very small quantities of experimental material.

The use of this method was accelerated by the development of sampling devices (scoop cutter technology and/or electro-discharge machining technology) for obtaining and retrieving a sample of material for analysis in virtually non-destructive manner not requiring post sampling repair. MATERIAL & METALLURGICAL RESEARCH, Ltd. owns two SSamTM-2 scoop sampling machines. It removes a small button of material that is, typically, 25 mm in diameter and 4 mm thick. The actual shape and geometry depend on the component geometry and the depth of the cut setting. The low stress raising dimple left by the cutter, and the low temperature and stress levels induced in the material by the technique, are advantages of the process. The dimple shows minimal surface damage and a high surface finish [2].The principle of penetration test is described in detail in [3]. Currently, the penetration test is used to determine:

- yield strength of the material
- the ultimate tensile strength of the material
- FATT (transit temperatures for 50% of ductile fracture)
- fracture toughness
- creep characteristics

According to CWA 15627 [4], there are two significantly different approaches to determine the tensile characteristics and fracture toughness at laboratory temperature of the results of penetration tests:

1) Empirical correlations between the results of penetration tests and the results of standardized tests.

However transition temperature FATT is still determined only from empirical correlations between the transition temperature FATT determined from the results of standardized Charpy V tests and transition temperature of penetration tests T_sp, determined from the results of penetration tests in the temperature range -193 °C to +23°C in the form

\[ \text{FATT} = \alpha \cdot T_{SP} \]  or rather \[ \text{FATT} = \alpha \cdot T_{SP} + \beta \]

Based on the results of penetration tests in the temperature range from \(-193°C \div +23°C\) has been demonstrated that in steels, in which the temperature dependence of impact energy, determined on test specimens with Charpy V notch, exhibits transition behaviour, transition behaviour can be observed also in the temperature dependence of fracture energy of penetration test. Fracture energy of penetration test is calculated from the area under the force-crosshead displacement until the specimen failure (crosshead displacement of u_f) [4]. According to CWA 15627 transition temperature T_sp is defined as the temperature corresponding to half of the sum of the maximum and minimum fracture energy calculated by the method of least squares from the temperature dependence of fracture energy calculated from the experimentally measured data in transition areas [4]. In the present paper the factors which can significantly affect the determination of transition temperature of penetration tests T_sp and thus empirical correlation FATT vs. T_sp will be discussed.
Factors Affecting the Determination of T_{SP} of the Results of Penetration Tests

According to [4] (chapter B1.3 Embrittlement – Transition Temperature) the SP test orientation is such that the normal to the punch disc plane is parallel to Charpy specimen crack propagation directions (see Fig. 1).

Fig. 1 Orientation of disc test specimen in accordance with CWA 15627

Fig. 2 shows the effect of orientation of the disc on transition temperature T_{SP} determined from the temperature dependence of fracture energy E_{SP} for disks taken in the direction T-L in accordance with CWA 15627 and penetration discs taken away from a tube ø219x16 mm made of 14MoV6-3 steel by SSam™-2 (R-L orientation). The results of penetration tests indicate significant effect of the orientation of test specimen on the temperature dependence of fracture energy in the transition area and thus on the transition temperature T_{SP}.

Fig. 2 Effect of orientation of test disc on transition temperature T_{SP} determined for material of the tube ø219x16 mm made of 14MoV6-3 steel after exposition of 256000 hours at 510°C. Crosshead speed 1, 5 mm/min.
Fig. 3 shows the effect of punch diameter (2.0 mm, 2.5 mm) at the temperature dependence of fracture energy of the pipe made of 14MoV6-3 steel in as received state. The results show that in the transition region both the temperature dependence of fracture energy and transition temperature $T_{SP}$ is not affected by diameter punch.

![Fig. 3](image.png)

Fig. 3 Effect of punch diameter on temperature dependence of fracture energy $E_{SP}$. Crosshead speed 1.5 mm/min.

Fig. 4 shows the temperature dependence of fracture energy obtained for the cast plate made of steel P91. From the figure it is clear that temperature dependence of fracture energy in the transition area (red and green dots) shows considerable scatter, which may be attributable to the local inhomogeneity of the structure of the casting. The results have been described with two temperature dependencies with significantly different transition temperatures $T_{SP}$.

The principal difference between the SP testing technique and standardized Impact testing lies in the fact that the penetration tests carried out in accordance with CWA 15627, use a disc-shaped test specimens without a notch. Especially in tough materials, the temperature dependence of fracture energy in the transition area is very steep and is close to the temperature of liquid nitrogen. The procedure recommended in the CWA for the determination of $T_{SP}$ and can in this cases lead to significant errors in its determination. Efforts to move the transition area of penetration testing closer to the transition area of standardized Impact tests led to the proposal of the disc-shaped specimen with a “U” notch in the axis plane of the disk (see Fig. 5).

![Fig. 4](image.png)

Fig. 4 Temperature dependence of fracture energy for casting made of P91 steel. Crosshead speed 1.5 mm/min.
Initial results indicate that the use of the specimen with a notch shifts significantly transition temperature $T_{SP}$ to higher temperatures and the temperature dependence of fracture energy is also less steep (see Fig. 6).

When the penetration tests are carried out at low temperatures sudden drops in force are occasionally recorded on the force – crosshead displacement record (see Fig. 7). By scanning the sample surface during the penetration test using a camera has been shown that the occurrence of the first force drop is due to the initiation of the first circuit cracks. In such cases, the fracture energy should be calculated as the area under the force – crosshead displacement in the first crack initiation.

Fig. 6 Effect of the notch on temperature dependence of fracture energy. Pipe made of 14MoV6-3 steel. Crosshead speed 1,5 mm/min.
Conclusion

Based on the experimentally determined temperature dependences of fracture energy can make the following conclusions:

1) Orientation of the disc may significantly affect the empirical correlation FATT – TSP.
2) The diameter of the punch influences the temperature dependence of fracture energy particularly outside the transition area.
3) Temperature dependence of fracture energy depends significantly on the type of material and its operating exposure.
4) The use of notched specimens significantly shifts transition temperature TSP to higher temperatures.
5) The fracture energy should be calculated as the area under the force – crosshead displacement to initiation of the first crack.

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Literature

