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Improved small punch testing and parameter identification of ductile to brittle materials

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ABSTRACT

Minimal invasive material testing is of special interest, when only small amounts of material are available or the material degradation of structural components in service has to be evaluated. The disc-shaped specimens used in the small punch test are small enough for local material sampling but representative for characterizing the macroscopic material behaviour. A small punch test device was developed which enables the testing of materials in the whole range from ductile to brittle failure and from ambient temperature down to −190 °C in a unique experimental set-up. The specimens are not clamped as usually in the small punch test. This is crucial for brittle fracture behaviour with little or without plastic deformation. The measured load displacement curve of the punch represents the non-linear response of the material due to elastic–plastic deformation. It contains relevant information about true material parameters, which can be made accessible by solving the inverse problem. Thus, plastic yield curves and Weibull parameters were identified by combining finite element simulations with non-linear optimization techniques. Examples for measured load displacement curves and related results of parameter identification are shown for a pressure vessel steel and a laser welded joint. The results obtained from the small punch test are verified by data from standard specimen tests.

1. Introduction

The mechanical material behaviour in components is altered due to in service loading, ageing, irradiation, embrittlement or other influences, which affect adversely the strength and reliability. To ensure the safety of structural components, an in situ monitoring of the actual material state is required. In the early 1980s Manahan et al. [1] and Huang et al. [2] developed independently a miniaturized disc bending test in order to determine the degradation of mechanical properties of irradiated metallic materials used in nuclear power plants. Since the publication of Baik et al. [3], who additionally clamped the disk, the test is called small punch test (SPT). It combines a minimal invasive sample taking [4,5] with very small but representative test specimens and is also well suited to determine local material properties [6–8], e.g. in welded joints, functionally graded materials, composite layers or coatings, where the sampling of traditional bulk specimens is not possible. The measurable output is the load displacement curve of the punch, which contains information about the deformation behaviour and about the strength and toughness properties of the material. In recent years the SPT has been established as a suitable and versatile miniaturized test method. In contrast to conventional material testing techniques, its great advantage consists in the small amounts of material required. Furthermore, the experimental handling is comparable easy, which is the reason why the test is preferred for testing irradiated nuclear material inside a hot cell, where the handling with manipulators is necessary. Additionally, the stress state in the specimen is bi-axial, which meets the conditions in many structural components (vessels, pipelines etc.). Across the globe much effort has been spent in the past to find correlations between SPT results and standard material properties as yield strength, ultimate stress, Charpy energy etc. However, true material parameters in the sense of constitutive laws in continuum and damage mechanics seem to be more general and allow the transferability to larger specimens and even structural components with complex but realistic stress states. To exploit the full information coming out from an SPT experiment, a qualified numerical analysis must be performed. For more than ten years the Institute of Mechanics and Fluid Dynamics (IMFD) at TU Bergakademie Freiberg does research work on the SPT focused on the identification of

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true material parameters and the extension to a variety of different materials [9–19].

In the SPT typically a disc-shaped specimen of 8 mm diameter and 0.5 mm thickness is centrally positioned in a receiving die and then deformed up to failure by a spherically tipped punch. The European "Code of Practice" CWA 15627:2006 [20] suggests this standard geometry, but also smaller specimens with 3 mm diameter and 0.25 mm thickness [1,2,21–27] or specimens with quadratic shape of 10 mm edge length [3,14,24,28–33] are often used in agreement with the mentioned guideline. The outer part of the disc is clamped rigidly between receiving and counter die (Small Punch Bulge Test) or only positioned loosely between them (Small Punch Drawing Test) to prevent vertical deformation. The usually screwed counter die is named as *downholder* in the following. In contrast, the improved experimental setup in recent use at IMFD does not clamp the specimen or prevent the vertical movement of the disc perimeter and is therefore similar to the original disc bending test [1,2] prior to the modification of Baik et al. [3]. A similar SPT device without downholder is used inside of hot cells at Forschungszentrum Dresden-Rossendorf, Institute of Safety Research [14,15]. For an appropriate naming referring to the guideline [20], which distinguishes between "Small Punch Bulge Test" and "Small Punch Drawing Test", this modified version of SPT should be called "Small Punch Bending Test".

The present paper recommends the use of the SPT without downholder for testing ductile to brittle and purely brittle materials. It will be shown, that the abandonment of clamping has clear advantages when testing brittle materials and can even be favourable for ductile materials. The examination of cleavage fracture of steels and other metals often needs very low temperatures. Therefore the incorporation of the SPT into a small size cooling apparatus with liquid nitrogen is presented. Finite element simulations of the test are the basis of parameter identification to find the temperature dependent yield curves and Weibull parameters. The experimental design is supported by systematic numerical sensitivity analyses. Finally, application examples are shown for the laser beam welded steel EMZ 355 and the pressure vessel steel 22NiMoCr37.

2. Experimental procedure

2.1. Experimental set-up

A sketch of the axisymmetrical small punch bending test geometry in use at IMFD is shown in Fig. 1. The standard geometric parameters are given in Table 1. Other dimensions are easy to realize by changing to another punch or die.

The circular disc with diameter D and thickness h is loaded centrally by the punch with hemispherical tip of Radius R. The specimen is put into the receiving die (bore diameter d, drawing radius r), concentric to the bore hole. The die has a circular notch, preventing the specimen from unintentional support at the perimeter. Otherwise undefined bearing conditions may lead to not negligible experimental errors. Between the disc perimeter and the concentric boundary of the die there is only a narrow gap, which guarantees a centring of the disc without becoming jammed during deformation. The presented small punch bending test design avoids any clamping of the specimen. The usage of a downholder has disadvantages, especially when materials with brittle fracture behaviour have to be tested. The clamping would introduce undefined stresses at the upper side of the specimen, which falsify the measurements, see Fig. 12. Moreover the propagation of radial cleavage cracks would be influenced or even prevented, depending on the clamping pressure or gap between specimen and downholder. Furthermore the abandonment of the downholder leads to a simpler device and handling.

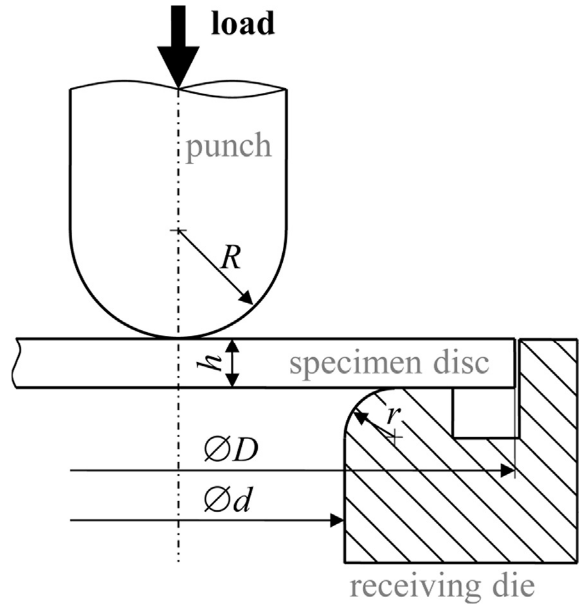

Fig. 1. Sketch of the small punch bending test.

Its simple geometry allows the SPT to be incorporated in a small cooling device (Figs. 4 and 5), which was installed in an electromechanical universal testing machine with a 10 kN load frame (Fig. 3). A half cross-section through the cooling chamber is shown in Fig. 2. The cooling system is based on liquid nitrogen, which flows through the outer chamber, but does not overflow the

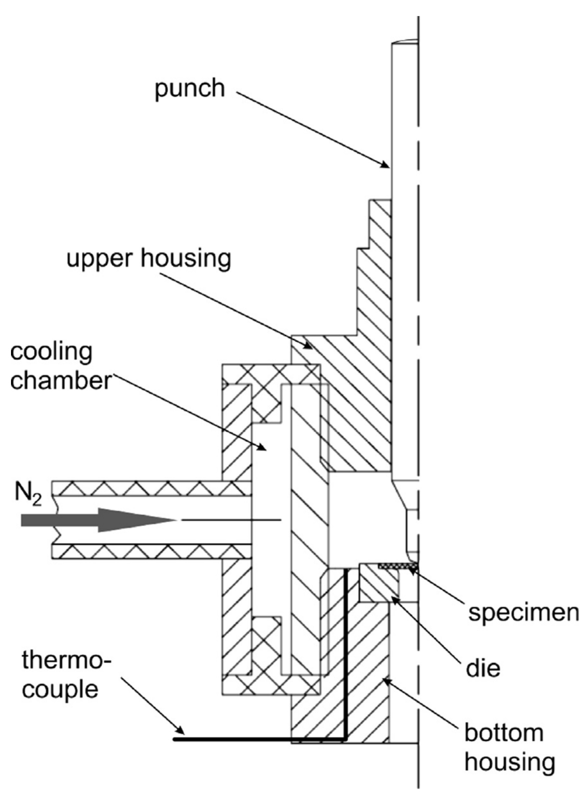

Fig. 2. Half section through cooling chamber (without isolation).