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A study on the evolution of the contact angle of small punch creep test of ductile materials

B. Cacciapuoti*, W. Sun, D.G. McCartney

Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, Nottingham, NG7 2RD, UK

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ABSTRACT

The work discussed in the present paper reports a novel investigation of the applicability of Chakrabarty's theory, for membrane stretching of a circular blank over a rigid punch, to small punch creep test (SPCT). The Chakrabarty solution was compared with corresponding results obtained by numerical finite element (FE) analyses and experimental tests. The Liu and Murakami creep damage model was used in the FE analyses. The aim of the work is also to improve the understanding of the mechanism governing the deformation and the failure of the specimen and to verify the range of applicability of the CEN Code of Practice CWA 15627, which is based on Chakrabarty's theory. The effects of various parameters, such as the initial thickness of the specimen, the radius of the punch, the load magnitude, the friction coefficient and different plasticity constitutive models, on the variation of the contact angle, θ_0, and the central displacement of the punch, Δ, were identified and correlated by fitting equations. The variation of θ_0 with Δ, obtained from Chakrabarty's solution was compared with that obtained by FE analyses of the SPCT. When the initial thickness of the specimen increased and the radius of the punch decreased, the FE results, in terms of the variation of θ_0 versus Δ, showed to differ from Chakrabarty's solution, therefore new ranges of applicability of the CEN Code of Practice CWA 15627 were determined.

1. Introduction

It is increasingly needed to evaluate creep properties for materials which components operating at high temperature in various industrial fields are made of, e.g. in power generation, aero-engines and petro-chemical plants, in order to estimate their remaining life and avoid premature failures [1,2]. For these applications, established and well-standardised mechanical test techniques, such as the standard size uniaxial creep test, cannot always be used as they require a large volume of material to be sampled from the component. A way forward to overcome the difficulties related to those situations where there is shortage of material to be tested, or sampling of large specimens would however be too expensive, consists of developing miniature specimen testing methods. Several innovative testing techniques, requiring a small amount of material to be sampled, have been developed in the last two decades in the USA, the UK, Europe and Japan [3] and, among these one of the non-traditional test techniques, the Small Punch Creep Test (SPCT) [1,4] has been extensively investigated by many authors. Unlike other miniaturised specimen techniques, such as the impression creep test [5] and the small ring creep test [6], the SPCT potentially allows to entirely characterise the behaviour of materials up to failure, because the specimen is taken to rupture [7,8]. The SPCT can also be used to perform focused analyses on critical locations of operating components, e.g. the heat-affected zone of welds, pipe bends or joint sections of steam headers [8]. Despite of these advantages, some concerns about the applicability of SPCT are still open [2,4]. Indeed, the interaction of several non-linearities, such as large deformations, large strains, non-linear material behaviour and non-linear contact interactions between the specimen and the punch, induces a very complex multi-axial stress field in the specimen which also evolves in time. This affects the SPCT fracture mechanism [2,7] and introduces several challenges into the identification of a robust correlation to convert SPCT data into respective standard uniaxial creep test data [7,9–11]. Another major concern is the non-repeatability of the testing method, since the experimental results depend on the set up geometry [1,4,12,13]. One of the major developments in this matter has been achieved by the Code of Practice proposed in 2006 by the European Committee for Standardisation (CEN), where an experimental procedure and a

* Corresponding author.
E-mail address: eaxbc3@nottingham.ac.uk (B. Cacciapuoti).

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Nomenclature

a	Fitting constant for the contact angle evolution
a_i	Fitting constants for the depth of 2D profiles of the deformed specimen
a_p	Receiving hole radius
A	Material constant in Liu and Murakami's model
A', A_0	Undamaged and initial area of the specimen
b	Fitting constant in the contact angle evolution
b_i	Fitting constants for the depth of 2D profiles of the deformed specimen
B	Material constant in Liu and Murakami's model
c	Fitting constant for the contact angle evolution
d	Fitting constant for the contact angle evolution
e	Fitting constant for the contact angle evolution
E	Young's Modulus of the damaged material
E'	Tangential modulus
E_0	Young's Modulus of the undamaged material
f	Fitting constant for the contact angle evolution
$f(y)$	Depth of 2D profiles of the deformed specimen
g	Fitting constant for the contact angle evolution
n	Material constant in Liu and Murakami's model
p	Punch pressure
p_i	Fitting constants for the correlation of the contact angle at fracture
P	Punch load magnitude
q_2	Material constant in Liu and Murakami's model
$r_{contact}$	Contact radius
R_s	Punch radius
S_{ij}	Deviatoric stress tensor
t, t_f	Time and time to rupture
t_c, t_0	Current and initial thicknesses
t^*	Thickness at the contact boundary
T	Temperature
w	Angular frequency
y	Radial distance from the specimen axis of symmetry
α	Material constant in Liu and Murakami's model
Δ, Δ_f	Punch displacement and punch displacement at failure
ε, $\dot{\varepsilon}$	Strain and strain rate
$\dot{\varepsilon}_{ij}^c$	Creep strain rate components
θ_0, θ_{0f}	Contact angle and contact angle at failure
μ	Friction coefficient
ν	Poisson's ratio
ρ_c, ρ_r	Circumferential and meridian radii of curvature
σ_1	Maximum principal stress
σ_c, σ_m	Circumferential and meridian components of stress
σ_{EQ}	von Mises equivalent stress
σ_{RUP}	Rupture stress
σ_y	Yield stress
σ^*	Meridian stress at the contact boundary
χ	Material constant in Liu and Murakami's model
ω, $\dot{\omega}$	Damage variable and damage rate
ω_{MAX}	Upper bound of damage variable

range for the specimen and the test ring components geometry was recommended [1,11]. Another achievement of the CEN Code of Practice consists of a correlation proposed between the load level to be applied to the small disc specimen and the stress induced in a conventional uniaxial creep test which exhibits the same time to rupture. Various equations have been proposed in the open literature to correlate the quantities involved in the SPCT, i.e. the load-stress ratio [1,14–16], but a common problem is faced in determining the angle between the axis of symmetry and the normal to the specimen's surface at the contact edge, θ_0 [1], as it is an implicit variable in the mentioned relationships.

In order to develop a robust procedure to interpret the experimental output of SPCTs and a reliable correlation technique with conventional uniaxial creep test data, the understanding of the complex behaviour of the specimen during testing is still to be improved.

The research presented in this paper is aimed to investigate the applicability of the Chakrabarty solution, which forms the basis for small punch creep data interpretation in the CEN code of practice [1], to the SPCT behaviour, by use of numerical finite elements (FE) calculations and by comparing experimental, numerical and analytical solutions. An improved understanding of the SPCT specimen deformation and failure behaviour is necessary, in order to carry out a step forward for the realization of the improved code of practice based on the existing CWA 15627 [1].

2. Chakrabarty's membrane stretching theory

Chakrabarty's membrane stretching theory [15] is used by the CEN Code of Practice as it provides a complete set of relations for establishing the correlation between the load level to be applied to the SPCT specimen and the stress induced in a conventional uniaxial creep test which exhibits the same time to rupture [1]. As well as the other equations suggested by the Code of Practice and reported by Liu and Šturm [17] in 2005, and others [14,16,18], Chakrabarty's relation between load and stress is derived from equilibrium between load and membrane stresses with bending stresses neglected [15]. As a matter of fact, large deformations (larger than 20% of the maximum structural dimension, according to an engineering judgment) are involved in the SPCT, allowing the bending stresses to be neglected [15].

2.1. Problem description

A representative analytical model of SPCT would be significantly complicated, as it should account for the effects of moving contact edges, nonlinear friction conditions between the test rig components and the tested specimen, and highly localized initial plastic deformation [7,10,15,19]. However, Chakrabarty's theory of membrane stretch forming over a rigid hemispherical punch head, reported in Refs. [15], is able to provide an analytical tool for the interpretation of small punch creep test data [10,11,15]. In Chakrabarty's study large plastic deformations are taken into account and the geometry and the loading conditions partly reflect those encountered in the SPCT [20]. Furthermore, the model hypotheses can be very restrictive in comparison with the true material behaviour: an isotropic material is adopted; the punch head is taken to be covered by a film of lubricant, therefore friction between the blank and the punch can be neglected; since large strains are considered, the material is assumed to be rigid-plastic; the thickness of the blank is at least one order of magnitude smaller than the radius of the punch, therefore, the bending rigidity of the blank can be neglected, and, as a consequence, the deformation mode can be assumed to be governed by membrane stretching [15]. Fig. 1 is a schematic diagram showing the components Chakrabarty's model comprises of.