Small Punch Creep Property Evaluation by Finite Element of Kocks-Mecking-Estrin Model for P91 at Elevated Temperature.

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**Abstract:** Small punch creep testing (SPCT) of thin disc specimens can be considered as a useful technique for determination of creep properties of exposed components of power generation and other thermal structures. Large viscoplastic strain in materials leads to damage and fracture which are examined from the microstructural aspects. In this work, the Kocks-Mecking-Estrin constitutive model is used to simulate the small punch creep behaviour of the P91 steel at 600 based on a full set of experimental results. An implicit computational algorithm is developed based on the radial return mapping approach. Finite element analyses of a small punch creep tests are carried out using ABAQUS software coupled with a UMAT material subroutine which has been developed by the authors. To demonstrate the applicability of the current model to P91 steel, the small punch creep test results are compared with the corresponding results from modelling using the UMAT code. In addition, a comparison of results of uniaxial tensile and creep tests for the P91 steel at 600 with the corresponding modelling results is also presented. The numerical results obtained have shown the model’s versatility and good predictive capability for representing the visco-plasticity behaviour of the P91 steel at 600.

**Keywords:** Small Punch Creep Test; Visco-Plasticity; Kocks-Mecking-Estrin Model; Finite Element; UMAT

Nomenclature

|  |  |  |  |
| --- | --- | --- | --- |
|  | The magnitude of dislocation Burgers vector |  | Creep compliance matrix |
|  | Stiffness matrix tensor | T | Temperature |
|  | Elastic stiffness matrix tensor |  | Constant |
|  | Creep stiffness matrix tensor |  | Friction coefficient |
| d | Punch diameter | , , | Plastic strain, plastic and creep strain rates |
|  | Receiving hole diameter |  | Effective plastic strain rate |
| EBSD | Electron backscatter diffraction |  | Reference strain rate |
|  | Shear modulus |  | Total, elastic and creep strain rate tensors |
|  | Boltzmann constant |  | Effective creep strain rate |
|  | Dislocation storage constant |  | Steady-state strain rate |
|  | Recovery coefficient |  | Total and creep strain tensor increments |
|  | Constant |  | Effective creep strain increment |
|  | The exponent of stress sensitivity |  | Dislocation density |
|  | Taylor factor |  | Saturation stress |
|  | Dynamic recovery exponent |  | Flow stress |
|  | Flow direction tensor |  | Effective stress |
| p | Creep exponent |  | Stress Tensor |
| P1 | Punch load magnitude |  | The saturation value |
| P2 | Punch clamp magnitude |  | Elastic predictor stress tensor |
| r | Corner radius of holder and support |  | The initial strain hardening at the second stage. |
| S | The diameter of small punch specimen |  | Accumulated creep strain |
|  | Deviatoric stress tensor |  | Kronecker delta tensor |
| t | Time |  | Time interpolation parameter |
| ts | The thickness of small punch specimen |  | Strain hardening constant |

# Introduction

In the last ten years, testing techniques using miniature samples have received increasing attention from the electricity generation industry companies for situations where the amount of material used in the test is limited. Published reviews for small specimen techniques have focused on their applications to conventional and nuclear plants [[1](#_ENREF_1), [2](#_ENREF_2)]. The removal of small amounts of material that are required for miniature specimens testing may not affect the structural integrity of in-service components. Finite element (FE) modelling of small specimen tests can give an estimate of remnant life in the use of these tests for components of power plants [[3](#_ENREF_3), [4](#_ENREF_4)]. Many efforts have been made by various researchers using miniature samples for creep testing to characterise the creep properties of materials used in high-temperature power generation components. One of these tests is the small punch creep test (SPCT), with recommended specimen diameter of 8 mm and thickness of 0.5 mm. The SPCT involves the application of a constant load through a hemispherical end indenter on a small circular flat disk [[5](#_ENREF_5)]. The ease of manufacture and testing of SPCT samples is one of the most important characteristics that distinguish it from other miniature testing techniques. SPCT has one more advantage over other miniature testing techniques, namely that the SPCT can be used to evaluate creep rupture [[6](#_ENREF_6)]. Typically, the test technique has been used for testing materials such as P91, P92, CrMoV steels, 316LN stainless steel, and magnesium and aluminium alloys [[7](#_ENREF_7)] within power plant applications (e.g. steam headers or steam pipes).

The SPCT method is still not universally accepted, due to limitations concerning test repeatability for three main reasons: firstly, lack of standardisation of test apparatus and specimen dimensions ; secondly, related to the procedure used to correlate SPCT data with the output of a uniaxial creep test; and thirdly, due to the complex deformation mechanisms (e.g. initial plasticity effect, which is material dependent). To overcome the first and second concerns, the European Committee for Standardisation (CEN) developed a draft code of practice (workshop agreement CWA 15627:20068) for the SPCT of metallic materials.

Historically, more phenomenological creep than physically based models have been obtained and used to model the creep of materials. One of the most popular and well-received models is the Kocks–Mecking–Estrin (KME) model for secondary creep which has been developed for a wide range of materials [[8](#_ENREF_8), [9](#_ENREF_9)]. The constitutive equation describes the viscous relation between von Mises equivalent and plastic strain rate quantities for a given microstructure. The microstructural aspects of materials properties are well known to exhibit a rate and temperature dependent behaviour [[10-13](#_ENREF_10)].

Many numerical types of research have used constitutive models such as those proposed by Kachanov [[14](#_ENREF_14)], which take account of the typical creep curve. FE models have been developed to study the large deformation process for small discs using the constitutive creep laws similar to that proposed by Kachanov. Among the modelling approaches, the Kachanov laws developed initially by Li [[15](#_ENREF_15)] which shows a set of displacement-time curves for given constant stresses values. Abendroth [[16](#_ENREF_16)] used an FE approach but focused on the modelling guidelines: geometry of the SPT, convergence of the chosen mesh and the influence of friction coefficient on load-deflection curve. Manahan et al. [[17](#_ENREF_17)] have modified the plasticity approach to simulate creep curves and compare with corresponding experimental data by using a least squares method to determine the parameters of the model by fitting them to the results of a uniaxial test. The creep and fracture behaviour in high-temperature components by FE modelling of the small punch specimens was also proposed by Shibli et al [[18](#_ENREF_18)]. The influence of friction on the displacement of hemispherical punch is investigated. The von Mises equivalent strain and the continuum damage data showed the strain is raised up at the region located under the punch and the maximum damage occurs on the bottom of the specimen. Evans and Evans [[19](#_ENREF_19)] and Evans and Wang [[20](#_ENREF_20)] have made use of an extended visco-plasticity model of SPCT to take into account the effect of surface morphology [[19](#_ENREF_19)]. Account was taken of the sensitivity of the experiment to many of the parameters including specimen dimensions in order to optimise the method to obtain the best test results [[20](#_ENREF_20)]. They found that the failure time was most sensitive to specimen thickness, support diameter, initial damage and the radius of the punch head but least sensitive to the specimen diameter and applied load.

In the present work, in an attempt to overcome some of the repeatability issues, the multi-axial KME viscoplastic model is developed and implemented without the need to carry out a uniaxial creep test. A user-defined material subroutine (UMAT) was developed. The results of the FE analysis for uniaxial creep and small punch creep tests using the KME model are compared with experimental results to investigate the capability of the numerical model to provide creep behaviour predictions for the small punch creep test.

This paper is structured as follows: the second section presents a brief description of the constitutive equations of the Kocks-Mecking-Estrin (KME) model which are based on microstructural properties. The development of the user material subroutine (UMAT) is also detailed in this section. The implementation of the constitutive model, in the implicit finite element code ABAQUS/Standard, is also presented. The third section details the material and microstructure of the P91 steel. The uniaxial tensile, uniaxial and small punch creep tests for the P91 steel at 600ºC for several loads are presented as well. The fourth section of this paper is devoted to the application of the model by characterising the material using uniaxial tensile, uniaxial creep and small punch creep cases. These simulations are used to calibrate the accuracy of the UMAT by comparing the results from numerical modelling and corresponding experimental tests. Finally, conclusions are given in the last section.

# The Kocks-Mecking-Estrin Model and UMAT Development

## The Kocks-Mecking-Estrin Model

The Kocks-Mecking-Estrin form is a unified elasto-viscoplastic constitutive model which is highly nonlinear and referred to as the kinetic equation by Kocks [[8](#_ENREF_8)] and Mecking [[21](#_ENREF_21)]. An appropriate mathematical formulation has been suggested by Kocks [[8](#_ENREF_8)]:

|  |  |
| --- | --- |
|  | (1) |

where is effective plastic strain rate, is a reference strain rate which is proportional to the mobile dislocation density, is effective stress, and is an exponent of stress sensitivity. The quantity of flow stress, an internal state variable,, represents the microstructural state of a material which is related to the total dislocation density [[22](#_ENREF_22)]:

|  |  |
| --- | --- |
|  | (2) |

Here is a constant, is the magnitude of dislocation Burgers vector, is the shear modulus, and is the Taylor factor. The model assumes that the micromechanical strength of the material is due to piling up of dislocation-dislocation interactions.

The evolution of the dislocation density takes into account the athermal process as well as the dynamic recovery process of dislocations in the uniaxial loading [[23](#_ENREF_23)].

|  |  |
| --- | --- |
|  | (3) |

Here is a constant accounting for the dislocation storage and is the recovery coefficient which represents the thermal process for the low temperature or high-temperature case. In both cases, it can be written as [[23](#_ENREF_23)]:

|  |  |
| --- | --- |
|  | (4) |

where is a constant.

In the above formulation, the dynamic recovery exponent can be written as

|  |  |
| --- | --- |
|  | (5) |

Eq. (5) shows that is inversely proportional to absolute temperature, where is the Boltzmann constant and is the work hardening parameter [[8](#_ENREF_8)].

The constitutive equations of this model can be integrated with the case of constant plastic strain rate [[21](#_ENREF_21)] and with constant stress creep [[22](#_ENREF_22)].

|  |  |
| --- | --- |
|  | (6) |

At the steady state, the evolution of does not change with the strain the Equation (6) may provide a simple description of deformation in creep. Substituting Equation (1) into Equation (6) gives

|  |  |
| --- | --- |
| , | (7) |

where is the initial strain hardening within the second stage and is steady state strain rate. The steady state strain rate,, is used as a function of strain in creep tests at constant stress.

|  |  |
| --- | --- |
|  | (8) |

One can simplify Equation (8) to give

|  |  |
| --- | --- |
|  | (9) |

where and

## The Multi-Axial Formulation

The one-dimensional constitutive equations for the Kocks-Mecking model have been derived by Estrin [[24](#_ENREF_24)]. In this section, the significant aspects of the 3-dimensional version are discussed.

Since in most cases of experimental tests, the materials have shown nonlinear behaviour, the stress state,, is assumed to be a nonlinear function of the strain state,. Thus, using Hooke’s law in chain rule form, these can be re-expressed in direct notation to give

|  |  |
| --- | --- |
|  | (10) |

where, are the Cauchy stress rate and elastic strain rate tensor respectively (a superposed dot refers to the time derivative) while is the fourth order elastic stiffness matrix tensor which depends on the strain, but not on the strain rate.

|  |  |
| --- | --- |
|  | (11) |

In elasto-viscoplasticity, it is usual to split the total strain rate tensor, into two parts, namely an elastic strain rate, and a creep strain rate tensor,, i.e.

|  |  |
| --- | --- |
|  | (12) |

The update of is given by

|  |  |
| --- | --- |
|  | (13) |

The elastic strain rate tensor can be connected with the rate form of Hooke’s law, Equation (12), to give:

|  |  |
| --- | --- |
|  | (14) |

To derive the incremental constitutive relationship, let us consider an integration over one step,, from to .

|  |  |
| --- | --- |
|  | (15) |
|  | (16) |

where is an elastic predictor which is known and obtained by assuming the increment is entirely elastic, while are the creep strain increments [[25](#_ENREF_25)].

In the following, we assume that the creep strain rate is expressed using the Levy-von Mises equation as [[26](#_ENREF_26)]:

|  |  |
| --- | --- |
|  | (17) |

where is the effective creep strain rate, is the flow direction tensor, and denotes the deviatoric stress tensor, while the quantities in Equation (18) indicate the equivalent stress and equivalent creep strain rate respectively.

|  |  |
| --- | --- |
| and | (18) |

## The UMAT Coding and Implementation

The FE software ABAQUS permits the addition and implementation of various constitutive models into the ABAQUS library by using user material subroutines (UMATs) [[27](#_ENREF_27)]. In the present study, the Kocks-Mecking-Estrin constitutive model described above for constant stress creep is implemented into ABAQUS by UMAT for the P91 steel at 600.

We here presented the implicit backward Euler integration for the multiaxial case of equations in the previous section. According to Eq. (9), the rate form of the constitutive equation may be written in iterative form as

|  |  |
| --- | --- |
|  | (19) |

and thus may be expressed in a form suitable for Newton-Raphson iterative solution as [[28](#_ENREF_28)]

|  |  |
| --- | --- |
|  | (20) |

Using Newton’s method, one has

|  |  |
| --- | --- |
|  | (21) |

In this method, an additional iteration step is introduced to calculate the increment in accumulated creep strain that gives

The first step, (initial)

|  |  |
| --- | --- |
|  | (22) |

and at the next step, is replaced with so Equation (21) becomes [[28](#_ENREF_28)]

|  |  |
| --- | --- |
|  | (23) |

Now, the effective creep strain increment is updated by

|  |  |
| --- | --- |
|  | (24) |

The final step is to update the stress by

|  |  |
| --- | --- |
|  | (25) |

The flow chart of the implementation of the UMAT for the Kocks-Mecking-Estrin (KME) model is shown in Figure 1.

Given, at time , ABAQUS solver calculates and, set up the elasticity matrix

,

Obtain Material properties:

Compute and normal direction

Return mapping: compute

Elastic predictor

Newton Raphson method for:

Compute

, is converged?

Yes

No

Accept then compute

, and

**Figure 1.** Flowchart of the implementation of the UMAT for KME model.

## Material Jacobian Matrix

The material Jacobian can be described as a partial derivative

|  |  |
| --- | --- |
|  | (26) |

A closed-form solution to the elastic stiffness matrix is always known. A closed-form solution to the creep stiffness matrix may or may not be known. Reversing the expression for creep stiffness matrix, , will furnish the creep compliance matrix, , as follows:

|  |  |
| --- | --- |
|  | (27) |

The matrix was simplified to the following

|  |  |
| --- | --- |
|  | (28) |

To obtain the stiffness matrix the compliance tensor must be inverted

|  |  |
| --- | --- |
|  | (29) |

# Experimental Work on P91 Steel at 600ºC

## The P91 Material and Microstructure

Experimental tensile, uniaxial creep and small punch creep tests were conducted on the P91 steel at 600ºC. The material chemical composition of the P91 steel used in the current work is given in Table 1. The electron backscatter diffraction (EBSD) sample is mechanically grinding by emery grinding papers up to grade 4000. The diamond paste is also used to polish up to 1 and finally then colloidal silicon 0.06 suspension. The EBSD investigations are carried out on field emission gun scanning electron microscopy JEOL 7100F (FEG-SEM). The image shows the grains coming from normalizing heat treatment, the diameter of these scales are vary between 30 to 50. Inside each grain, several very fine carbide precipitates are also observed (shown in Figure 2.). These carbides are relatively stable at high temperature, which are enhancing the creep strength by pinning free dislocations and sub grain boundaries [[29](#_ENREF_29)].

**Table 1.** Chemical of the P91 steel composition [[30](#_ENREF_30), [31](#_ENREF_31)].

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Cr** | **Mo** | **C** | **Si** | **S** | **P** | **Al** | **V** | **Nb** | **N** | **W** | **Fe** |
| 8.60 | 1.02 | 0.12 | 0.34 | 0.002 | 0.017 | 0.007 | 0.24 | 0.070 | 0.060 | 0.030 | Bal |



**Figure 2.** EBSD texture of the virgin P91 steel used for the tests.

## Uniaxial Tensile and Creep Tests

The conventional uniaxial tensile and creep specimens were manufactured from a P91 pipe. The gauge length of the specimen is 50mm, and the diameter of the gauge length is 10mm. The dimensions of the tensile and uniaxial creep specimen are shown in Figure 3.



**Figure 3.** Uniaxial tensile and creep test specimen, all dimensions in mm.

The complete stress-strain curve obtained from the uniaxial tensile test at 600ºC and a strain rate of 0.001. The Young's modulus of P91 steel is determined to be 145GPa at 600ºC, while the elongation of the specimen is 18% at fracture. Stress levels of 140, 150, 160, 170, 180MPa were used in uniaxial creep tests for the P91 steel at 600.

# Modelling the SPCT Using the Kocks-Mecking-Estrin Model

## Identification of Model Constants

### Characterization of Uniaxial Tensile Test

FE modelling of the uniaxial tensile test of the P91 steel at 600ºC was carried out using the UMAT coding within ABAQUS standard. The mesh used is shown in Figure 4 which consists of 673 axisymmetric quadrilateral elements. Only a quarter section was modelled due to symmetry. By including the geometrically non-linear effect, the uniaxial tensile specimen can induce significant deformation and neck with large localised strains.



**Figure 4.** FE mesh used for a uniaxial tensile test for the P91 steel at 600ºC.

Figure 5 is a contour plot of the von Mises stress at failure for a strain rate of 0*.*0005, while Figure 6 shows the stress/strain curves obtained using the UMAT with the KME model and the corresponding tensile test carried out for the P91 steel at 600ºC. The material constant, the magnitude of dislocation Burgers vector, and Taylor factor were taken from [[31](#_ENREF_31)]; these and other material constants previously used in calculations for the P91 steel are listed in Table 2.



**Figure 5.** Contour plot of the von-Mises stress at failure for the P91 steel at 600ºC.



**Figure 6.** Experimental and numerical stress-strain curves for the P91 steel at 600ºC.

**Table 2.** Notation and material constants used in numerical FE for the P91 steel at 600ºC [[31](#_ENREF_31), [23](#_ENREF_23), [32](#_ENREF_32)].

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Name** | **Value** |  |
|  | Initial Dislocation Density |  |  |
|  | Elastic modulus | 145 Gpa |  |
|  | Poisson’s ratio | 0.3 |  |
|  | The magnitude of Burgers vector |  |  |
|  | The exponent of stress sensitivity | 55.89 |  |
|  | Reference strain rate | 1 |  |
|  | Dynamic recovery | 55 |  |
|  | Constant | 0.8 |  |
|  | Taylor factor | 3.06 |  |

### Characterization of Uniaxial Creep Tests

The axisymmetric model represented the FE geometry of the uniaxial creep specimen. The implementation of UMAT was carried out with load controlled condition in the Y-direction for five levels of stress, i.e., 140, 150, 160, 170, 180MPa, Boundary conditions were applied in X and Y directions of the specimen. Firstly, displacements were constrained to zero in the X-direction for all nodes located on the Y-axis. Secondly, movements were limited to zero in the Y-direction for all nodes situated on X-axis as shown in Figure 7. The fundamental objective of FE analysis of the uniaxial creep tests is to validate and display capability of creep aspects in the KME model.



**Figure 7.** FE axis-symmetric uniaxial creep specimen.

The strain-time curves for uniaxial creep test of 140, 150, 160, 170, and 180MPa at 600ºC are shown in Figure 8. Uniaxial creep data at 600 was used to compare with the corresponding FE results. The results obtained show excellent agreement though the FE results for the 180MPa test predict a much shorter failure life. The unified mechanical model produces typical primary, secondary, and tertiary creep responses for all stress levels. The primary creep strain increases with stress. The minimum creep strain rate observed in the secondary creep regime increases as stress increases. The amount and rate of tertiary creep strain increase with stress.

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**Figure 8.** Experimental and calculated uniaxial creep curves for stresses at (a) 140 and 150, (b) 160 and 170, and (c) 180MPa.

## Modelling of Small Punch Creep Tests

### FE Model

Finite element modelling of small punch creep for P91 steel at 600 was carried with five levels of punch loads P1= 25, 28, 30, 34 and 40 kg using the UMAT code and the material properties given in Table 2. An axisymmetric finite element model was used. Figure 9 shows the geometry of the FE model where the punch radius is 1.04mm, the holder and the support radius is 0.25mm, the thickness, and radius of the specimen are 0.5 and 4mm, respectively, the receiving hole radius is 2mm. The punch, the holder, and the support were modelled as rigid parts. Approximately half of the surface of the bottom of the specimen is constrained by a support to simulate clamped surface to surface. The friction coefficient between these surfaces is assumed to be 0.8 [[33](#_ENREF_33)]. The SPCT specimen was considered as a deformable part and was meshed with rectangular elements. The contacting interfaces between the top surface of the sample with rigid punch were assigned as a surface to surface contacts with a coefficient of friction assumed to have a value of 0.2. The simulation was carried out with three types of boundary conditions. Firstly, the axial movement and rotation around the axis of symmetry of the support were constrained entirely. Secondly, the horizontal movement and rotation of punch and holder were also restricted. The complete displacement and rotation constraints were applied on the left side of the specimen in the X-direction for all nodes located on the Y-axis. The loads are directed in the Y direction and are applied to the reference point of for the punch which is assumed to be rigid, while a clamping load, 500N, is used on to the reference point of holder die. The FE mesh consists of 891 nodes and 800 bilinear axis symmetric 4-nodes elements.



**Figure 9.** Schematic representation of a FE model for small punch creep testing analysis (D=4mm, S=8mm, d=2.08mm, r=0.25mm, ts=0.5mm). (a) Schematic three-dimensional of rig for small punch creep testing. (b) Schematic two-dimensional of rig for small punch creep testing. (c) Representation loads and boundary conditions of finite element modelled part.

The punch, holder and support dies were considered as rigid bodies. The specimen was implemented as a deformable body with two elements type groups. The first group consists 1480 of 4-node bilinear axisymmetric quadrilateral, reduced integration elements, (CAX4R) while the second group involves 10 of 3-node linear axisymmetric triangle elements (CAX3). Figure 10 shows the mesh used for the SPCT analysis. The specimen was refined along the contact region between the punch and the specimen. The minimum element size, in the refined zone, is 0.025mm.



**Figure 10.** FE mesh used for SPCT specimen.

### Displacement-Time Curves

The relationship between the coefficient of friction and the magnitude of the friction forces is directly proportional. A parametric study of the different friction coefficients between the specimen and punch is carried out. The contact between the sample and punch was modelled using surface to surface contact with various friction coefficients. Figure 11 shows the effect of friction coefficient for three values (, and,) each with two cases of loads, namely 34 and 40kg. From these results, it can be observed clearly that the effect of the coefficient of friction on the FE outputs is significant. For a given load level, when the friction coefficient increases, the minimum deflection rate will drop and the failure time will increase. From above, one can conclude that the value of the friction coefficient of that gives the best approximation between modelling and practical data.



**Figure 11.** Calculated SPCT curve at the variation of the friction coefficient for punch load (a) 30Kg and, (b) 34Kg.

The experimental SPCT curves at five different load levels and the corresponding predicted curves are compared in Figure 12. The coefficient of friction between punch and specimen is assumed to be constant for all applied loads.



**Figure 12.** The experimental and calculated SPCT curves at punch load of (a) 25 and 28, (b) 30 and 34, and (c) 40Kg [[5](#_ENREF_5)].

### Contours of Displacement, von Mises Stress and Strain

The FE analysis of SPCTs was carried out using UMAT code through the ABAQUS package. Figure 13 shows the results of punch deformation at loads 28 and 30Kg. The displacements of the punch range from 0.727mm for a load of 25kg up to 0.946mm for a load of 30kg at 5.2 hrs.



**Figure 13.** Contour plot of punch direction deformation of SPCT at punch load (a) 25Kg, (b) 30kg.

Figure 14 shows the distribution of stress at the cross-section of the specimen after 6 hours under a constant punch load of 34Kg and 40Kg respectively. The highest equivalent stress value is observed at a point located about 0.9 mm from the centre of the initial specimen at the start of SPC test (the black arrows in the figure indicate the locations of the maximum stress value.), while it drops down at the zone located at about 2.0mm from the centre of the specimen.



**Figure 14.** Contour plot of the equivalent stress with the SPCT at a punch load of (a) 34Kg, (b) 40kg.

Figure 15 shows SEM images of experimental SPC tests for punch load of P1= 25 kg which are suspended after (a) 2hrs, (b) 200hrs and, (c) 669hrs and the corresponding effective strain contour plots. The regions of local deformity were nearly identical to those of the experimental specimen tested.



**Figure 15.** Contour plot of strain and SEM images of SPCT at punch load 25Kg for P91 steel at 600ºC.

Figure 16 shows the variations of equivalent strain under applied loads of 34 and 40kg. The directions and locations of the strain data are identified in both figures. Equivalent strains also suddenly increase at the region located at about 2.0 mm from the centre of the specimen. This deformation may be due to severe bending of specimen at the corner of lower die located at 2.0 mm from the centre of the sample. Except for this region, maximum equivalent strains occur identically at the location of about 0.7 mm. In addition, it is seen that the position of the maximum effective strains did not effected by the applied load.



**Figure 16.** Contour plot of a strain of SPCT at punch load (a) 34Kg, (b) 40kg.

The mechanisms of the SPCT deformation contrast sharply with those in uniaxial creep tests. During the first SPCT regime, the specimen undergoes a severe development in shape. Change of the structure causes a decrease in the specimen’s stiffness and a change in the deformation mechanism, from bending dominated to ‘membrane stretching’ dominated. In the second SPCT regime, the controlling mechanism is tensile stretching of the annular region around the contact edge between the punch and the specimen. Material creep damage is still observed to occur in the secondary SPCT region. The third SPCT region, symbolised by developing deformity rate, is governed by creep material degradation and specimen necking.

# Conclusions

The constitutive equations of KME model rely on the basic physical microstructure which was implemented in the finite element modelling through the user material subroutine (UMAT) and evaluated by the experimental results. The testing procedure involved SPCT, uniaxial tensile and uniaxial creep tests on the P91 steel at 600ºC.

* The KME model has been implemented into the finite element scheme ABAQUS using UMAT code. The predicted results of SPC, uniaxial tensile, and uniaxial creep simulations have a good agreement with the corresponding of experimental tests.
* The additional advantage of using the current model is the capability to determine the creep model parameters from utilizing microstructure information in addition to uniaxial creep data.
* The influence of friction behaviour of the contact between punch and specimen was considered for SPCTs at different levels of load. The failure time gradually increases with an increase of the friction coefficient.
* The maximum equivalent strain was observed within an annular zone on the underside of the specimen and this weakest location did not change even though the timescales to reach failure varied greatly across the different loading cases.

In the future work, the KME model will be extended to include material damage taking into account the effect of grain size. The determination of material parameters will be identified using a suitable optimisation strategy based on physical measurements.

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