3D-Modelling of Miniature Shear Punch Test for the Prediction of Mechanical Properties of Metals

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Abstract : The present paper describes the study, carried out with the objective to develop the finite element models using ABAQUS computer code to simulate the process of small punch specimen test technique and carrying out engineering analysis of large deformation of different size miniature samples. The study involves the FE simulation of shear punch test for various miniature specimens with thickness ranging from 0.40mm to 0.80mm for two different steels using ABAQUS code. The experimental method of the miniature shear punch test is used to determine the material response under quasi-static loading. The load vs. displacement curves obtained from the FE simulation miniature disk specimens are compared with the experimental data obtained to predict the mechanical properties i.e. fracture and yield strength of steels and were found in good agreement with the conventional method.

Key words: Fracture toughness, yield strength, Diminutive, shear punch test, FEM, 3D Modeling.

INTRODUCTION

Diminutive specimen test technique is a suitable test technique to determine the mechanical and fracture properties of structural components such as, Nuclear power plant, steam power plants, chemical industry and petroleum units etc. The material behavior of structural components changes due to in-service loading, aging, irradiation embrittlement and some other influences. That requires continuous monitoring of the material state. In order to determine material parameters at various locations e.g. in weldments or gradient materials, the size of the material taken out for a test specimen should be very small but representative. The test setup, shown in figure 1, presents the test technique of a circular disc shaped diminutive specimen of 10mm diameter 0.50mm size. The measurable output is the load displacement curve of the punch, which contains information about the elasto-plastic deformation behavior and about the strength of material [1, 2].

This technique provides the data regarding the properties of a material by using a small volume of material, as compared to the conventional test specimens that needs a large volume of material. Diminutive specimen techniques include a wide variety of types and techniques as described by Husain et. al. [3], Lucas [4] and Cheon et.al. [5] i.e. tensile test, micro hardness test using small punch ball of spherical, and hemispherical head indentation, bending, fracture, impact, and fatigue tests. Manahan et.al. [6] and Huang et.al.[7] were among the earliest to study the small Punch test technique for the determination of mechanical properties of irradiated materials from small circular disks. These techniques largely involve loading a supported disc or coupon with an indenter or punch, deforming it to failure, and analyzing the resulting load-displacement data. Load-line displacement at failure is converted to an effective failure strain.

Foulds and Viswanathan [8] described the determination of material toughness of an in- service low alloy steel components by small punch test. Foulds et.al. [9] in their investigation estimated the material fracture appearance transition temperature (FATT) of a range of components in fossil power plant and carried out fracture toughness evaluation by using small punch test.

Se-Hwan et.al. [10] and Ellen M. R.[11] in their paper evaluated irradiation induced material (12Cr-Mov steel) in terms of changes in energy up to failure by small punch tests.

Husain [16] investigated on the small punch techniques using specimens of 10mm diameter and 0.5mm thickness from four different types of steels (Medium carbon steel-MS, Non-shrinkable steel-D3, Structural steel-STS, Chromium hot work steel-H11) materials and shapes (square and rectangular) and also performed a finite element simulation. A new empirical correlation for the estimation of yield strength has been developed. It was established that the proposed empirical relation is a function of diminutive specimen geometry, inner dimensions of specimen holder (dies) and the punch tip diameter.

The present study carries out small punch test simulation of two different steels with thickness ranging from 0.40mm to 0.80mm. The numerical study pertains to the finite element modeling and simulation of miniature samples adopting small punch test technique with the help of ABAQUS computer code

EXPLICIT 3D FINITE ELEMENT MODELING

The numerical study pertains to the finite element modeling and simulation of miniature samples adopting small punch test technique with the help of ABAQUS computer code. The circular miniature samples of two different materials with different thickness are simulated using finite element method. Direct finite element analyses on different thickness specimen are carried out in the present study. ABAQUS finite element analysis approach has been employed to simulate 3-D model of the miniature samples of different thickness. The quasi-static punch loads are used to simulate the small punch experimental procedure with the help of time amplitude increments option of the code. The 3-D finite element analysis provides the load-displacement curves/data, Von-Misses stresses, equivalent plastic (fracture) strain, and contact pressure at the surface. The finite element results of 0.5mm thickness specimen are validated by comparing with results published in the literature [16].

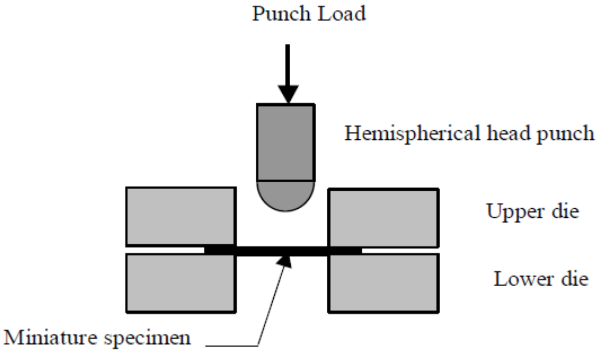


Figure 1. Schematic diagram of Small Punch test Apparatus

The small punch test using circular disk shape miniature specimens is simulated to follow the actual small punch experimental test procedure. The dimensions of the circular shape miniature specimens are considered according to the inner borehole of the dies (specimen holder) i.e. 4mm diameter. The circular disk specimens of 4mm diameter and thickness ranges from 0.4mm to 0.8mm with an interval of 0.1mm are modeled. In order to make the problem more tractable, a three-dimensional finite element model is simulated to follow the actual situation as in small punch test experiments. The three dimensional model of miniature disk specimen is descretized and the mesh is generated using three dimensional isoparametric hexahedron elements.

The miniature disk specimen are modeled and descretized with 8-node brick isoparametric solid elements as shown in **Figure. 2**. The hemispherical headed rigid punches are modeled by analytical rigid surface option. Simulation of the small punch test follows the physical procedure as closely as possible, with the miniature specimen fixed between a lower die and an upper die plate by six clamping screws. To simulate this condition of small punch test on the model of the miniature sample, all the circumferential nodes were constrained (remain fixed or have Zero displacement) by boundary conditions option encaster (rigidly fixed). In such case all peripheral nodes are constrained completely and thus cannot move in any direction. Due to this reason, in the finite element model, the diameter of circular disk sample is considered according to borehole of the dies i.e. 4mm.

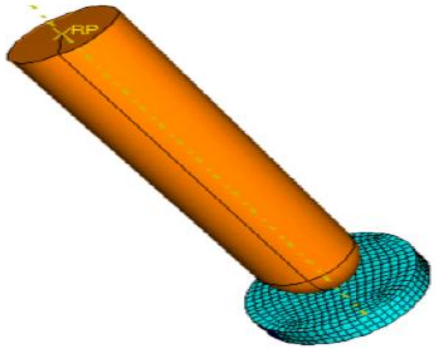


Figure 2. Undeformed specimen along with rigid punch

The hemispherical headed punch is modeled as a rigid body constrained to translate only in the vertical direction normal to miniature sample at a prescribed quasi-static loading using the time amplitude with small incremental step technique. The load is applied at the reference node (NODE No.1). The reference node is constrained in two horizontal directions but is free to move in vertical direction to pierce slowly the sample normal surface at center. Each element of the deformable mesh is characterized by the true stress- true plastic strain relation of the material, as obtained from standard uni- axial tensile test. The tensile specimens are subjected to standard tensile test under continuous loading up to failure. The nominal stress-strain curve for each material obtained from standard Uniaxial test is used by converting the test data defining material plastic behavior in to the appropriate input format for ABAQUS.

Assumptions

1. The hemispherical headed indenters are considered to be rigid because high strength heat treated steel is used as the material.

2. The friction between the specimen and the indenter is included in the calculation. The friction factor used is 0.1; this choice had only a minor effect on the load vs. displacement curve.

3. It is considered that the boundary condition is very close to a rigid fixed boundary condition, because the small punch specimen is fixed firmly by six clamping screws, in between the dies.

The present finite element analysis using ABAQUS is very versatile and gives a wide spectrum of information concerning the small punch test, e.g. von-Misses stresses, equivalent plastic strain, contact pressure, deformation, logarithmic strain components, different stress components, load till failure, full field displacement, load vs. displacement curves, and von-Misses stress vs. equivalent plastic strain curves etc.

Load- Displacement Behavior of Circular Specimens

During the deformation process in finite element analysis, the rigid hemispherical headed punch moves slowly (quasi-statically) by pressing the miniature disk specimen normally under the tip of punch until all the elements under the punch are badly damaged (distorted). The deformation behavior during punching is closely monitored at each incremental step. A typical run for the finite element analysis of the problem comprise of nearly 512 elements and 846 nodes and require about more than 100 small incremental steps. Figure 2.shows the un-deformed finite element models for circular shape miniature specimen. It is observed that the computed load vs. displacement curve from FEM and from small punch experiments are in good agreement on an average but generates moderate gaps between two values after substantial deformation. In a similar way finite element analysis is carried out for small specimens of different thicknesses. The minor differences between two curves can be attributed to crack initiation before the load approaches its maximum. And a limitation of small strain theory in the ABAQUS program would also cause such difference at a high deformation stage.

RESULTS AND DISCUSSION

In the present study, the finite element analysis and simulation of the small punch test technique is successfully carried out on different miniature specimens of different thickness of four materials using the ABAQUS code. The FEM load vs. displacement curves of 0.5mm thick specimens are compared with the load-displacement curves taken from literature [16]. These simulated models have been used to obtain wide range of information. The small punch experimental method provides only the load-displacement curves where as the finite element method provides a lot of information such as deformation behavior of miniature specimens, load-displacement curves, von-mises stress, equivalent plastic strain, logarithmic strain components, contact stress etc. The load at the breakaway (P_y) from the linearity can be used to estimate the yield strength (σ_y) of the material. Simulation results in the form of load displacement curves of different miniature samples with different thickness are shown in Figure 3 to Figure 10. The deformed shapes of specimen of thickness 0.5mm and 0.6mm are shown in Figure 11and Figure 12.

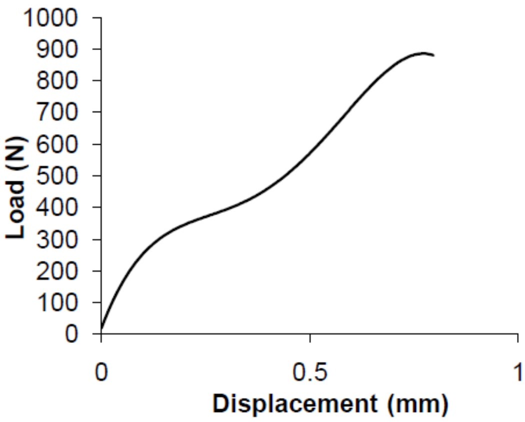


Figure 3: Load displacement diagram of 0.4 mm D3 steel specimen

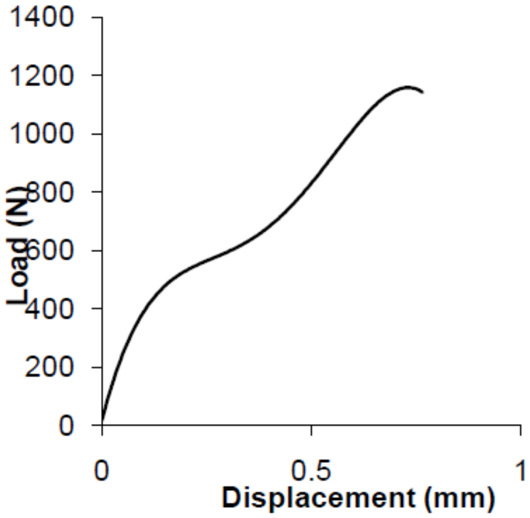


Figure 4: Load-displacement diagram of 0.5mm thick D3 specimen

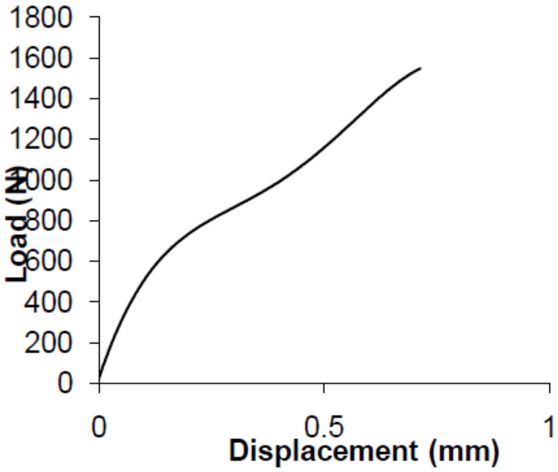


Figure 5: Load-displacement diagram of 0.6mm thick D3 specimen

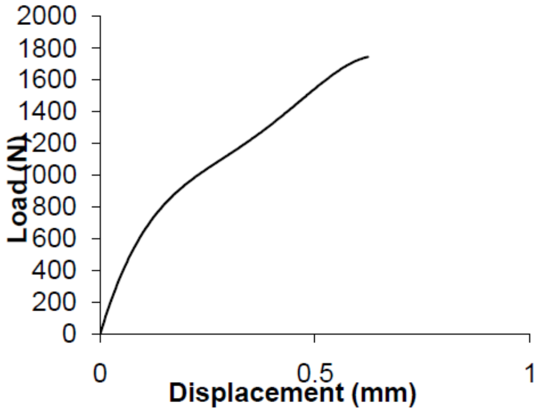


Figure 6: Load-displacement diagram of 0.7mm thick D3 specimen

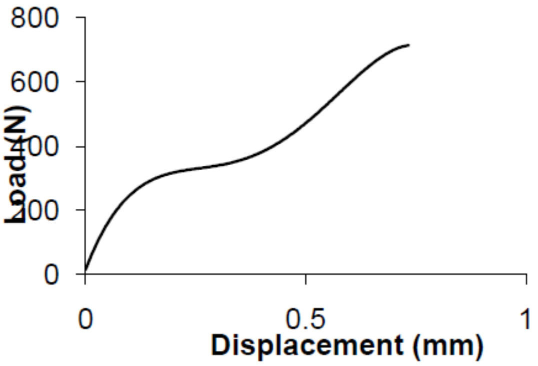


Figure 7: Load-displacement diagram of 0.4mm thick STS specimen

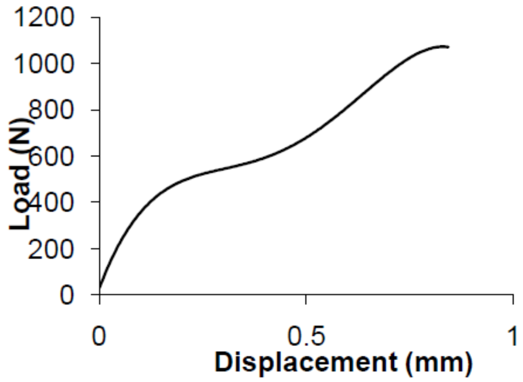


Figure 8: Load-displacement diagram of 0.5mm thick STS specimen

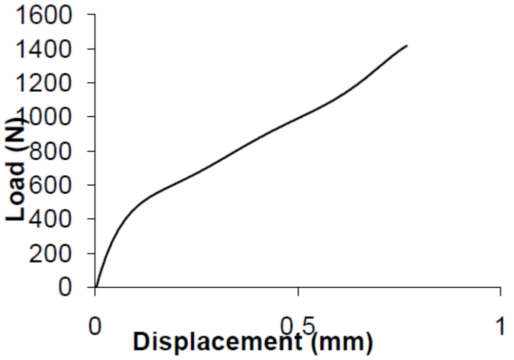
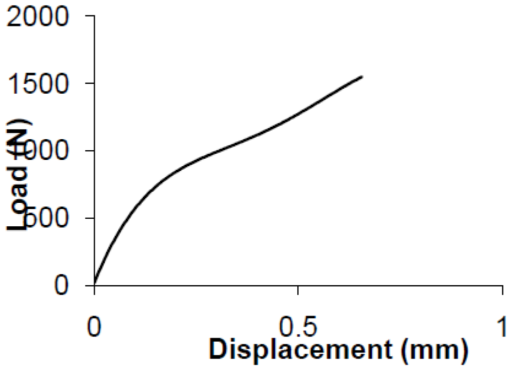


Figure 9: Load-displacement diagram of 0.6mm thick STS specimen



10: Load-displacement diagram of 0.7mm thick STS specimen

Correlations For The Prediction of Fracture Strain

Based on experimental observation that fracture in small punch (SP) test specimen occurs after membrane stretching, the fracture strain ε_{qf} can be calculated by using membrane theory proposed by Chakraborty [1970].

$$\varepsilon_{qf} = \ln\left(\frac{t_0}{t^*}\right) \quad (1)$$

Where t^* is the minimum thickness at fracture point and t_0 is the initial thickness of the miniature specimen

The biaxial fracture strain can be estimated from the empirical relation using small punch test, suggested by Kameda [1994] is as follows.

$$\varepsilon_{qf} = 0.12\left(\frac{\delta^*}{t_0}\right)^{1.72} \quad (2)$$

Where δ^* is maximum deflection at fracture.

Similarly, another empirical relationship proposed by Mao, Shoji and Takahasi [1987] is as follows

$$\varepsilon_{qf} = 0.15\left(\frac{\delta^*}{t_0}\right)^{1.5} \quad (3)$$

Husain et. al. [2003] proposed the relation for fracture strain in case of circular shape miniature specimen as

$$\varepsilon_{qf} = 1.688\left[\ln\left(\frac{t_0}{t^*}\right)\right]^{1.24} \quad (4)$$

Correlations For The Prediction of Fracture Toughness

The experimental correlation between equivalent fracture strain and fracture toughness (J_{IC}), based on the single specimen technique proposed by Takahashi et al. [1988], is linear, as follows:

$$J_{IC} = 280\varepsilon_{qf} - 50 \qquad (for \quad \varepsilon_{qf} \rangle 0.2) \quad (5)$$

Where J_{IC} is in $\left(kJ / m^2 \right)$

Similarly another empirical relationship for fracture toughness, suggested by Mao et al. [1987], is

$$J_{IC} = 345\varepsilon_{qf} - 113 \qquad (for \quad \varepsilon_{qf} \rangle 0.4) \quad (6)$$

Where J_{IC} is in $\left(kJ / m^2 \right)$

Husain et. al. [2003] proposed the relation for fracture toughness in case of circular shape miniature specimen as

$$J_{IC} = 722.28\left(\varepsilon_{qf}\right)^{2.837} \quad (7)$$

The fracture strains are calculated from the following method:

Chakraborty [1970] (Eqn. 1), Kameda et al. [1994] (Eqn. 2),Mao et al. [1987] (Eqn. 3) ,Husain et al. [2003] (Eqn. 4) and Present work .

Further, using each of above fracture strains, the fracture toughness is calculated from the following method:

Takahashi et al. [1988] (Eqn. 5), Mao et al. [1987] (Eqn. 6), Husain et al. [2003] (Eqn. 7) and Present work

The predicted mechanical properties of two different materials by standard conventional tests, by empirical relations s for two different materials are tabulated in Table 1 to Table 4.

Table 1. Comparison of Fracture toughness $\left(kJ / m^2 \right)$ of D3 steel predicted by different studies

S No	Proposed Method	1	2	3	4	5
a	Mao et.al. (1987)[1]	106.1	14.05	48.49	97.13	95.48
b	Takahashi e al.(1988)[2]	21.91	98.91	87.84	44.34	47.16
c	Husain et.al. (2003)[11]	37.55	84.70	73.29	44.39	45.52
d	Present work			42.708		
e	Standard three point bend test			44.04		

Table 2. Comparison of Fracture toughness $\left(kJ / m^2 \right)$ of STS steel predicted by different studies

S No	Proposed Method	1	2	3	4	5
a	Mao et.al. (1987)[1]	90.6	211.17	217.1	145.1	153.8
b	Takahashi e al.(1988)[2]	127.4	209.0	209.0	163.4	169.8
c	Husain et.al. (2003)[11]	123.3	346.6	346.6	194	209.5
d	Present work			211.239		
E	Standard 3 point bend test			220.77		

Table 3. Comparison of Yield strength (MPa)of D3 steel predicted by different studies

Sl No.	Empirical equations given by	σ_Y, Estimated by SPT	σ_Y, Estimated by standard tensile test	Percentage Error
a	Mao et.al. (1987)	345.6	478.03	27.28
b	Xu et.al. (1995)	457.92	478.03	4.21
c	Husain et.al. (2003)	492	478.03	2.92
d	Present work	456.24	478.03	4.5

Table 4. Comparison of Yield strength (MPa) of STS steel predicted by different studies

Sl No.	Empirical equations given by	σ_Y, Estimated by SPT	σ_Y, Estimated by standard tensile test	Percentage Error
a	Mao et.al. (1987)	338.40	475	28.75
b	Xu et.al. (1995)	448.38	475	5.6
c	Husain et.al. (2003)	481.84	475	1.44
d	Present work	430	475	9.47

Tables 1 to 4 gives the comparison of different studies made in order to predict the fracture toughness and yield strength of different materials. It is observed that the present works seems to be very much close to the actual values where as in other studies there is a large variation..It is observed that the variation of yield strength with actual values in the present study is more than the values predicted from the empirical relations established by Xu et.al. (1995) and are less than the values predicted from empirical relations established by Mao et.al. (1987).

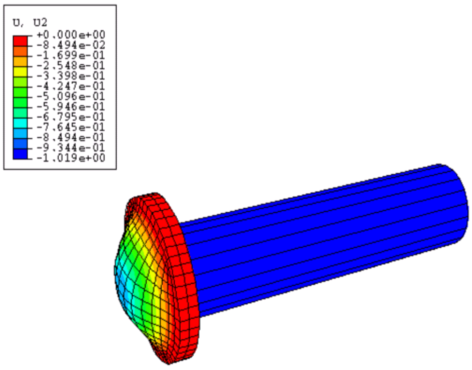


Figure 11: Deformed miniature disk shape specimen of 0.5mm thickness

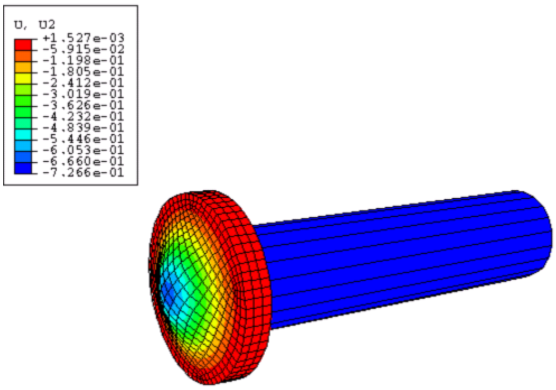


Figure 12: Deformed miniature disk shape specimen of 0.6mm thickness

CONCLUSION

From the present study it can be concluded that the load-displacement curves obtained from the FEM simulation of shear punch test using are in good agreement with the experimental curves available in the literature.

It is observed that the plastic deformation occurs at the center of shear punch test specimens, after contact with the rigid indenter, but the location of maximum shear stress and maximum plastic deformation moves outward with increasing load due to the distribution of contact stress.

The maximum value of von-mises stress occurs near the peripheral edges of the specimen.

Further it can be concluded that the contact pressure between the hemispherical headed punch and the specimen is the highest at the edge of contact area after the breakaway point.

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