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Quasi-static Normal Indentation of a Circular Disk Shaped Miniature Specimen by Rigid Hemispherical-headed Punches

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ABSTRACT

The influence of diameter of rigid hemispherical-headed punches on a circular disk shaped miniature specimen of medium carbon steel has been investigated, in the small punch test. A 3-D finite-element model carried out the computation of the elastic-plastic solution of different hemispherical rigid punches. The three hemispherical-headed punches were designed and developed to conduct the miniature test. The small punch test was conducted on a circular shaped disk (10.0 mm diameter, 0.5 mm thick), clamped around the periphery and deformed by central load applied by rigid hemispherical indenter. The ABAQUS finite-element software has been used to determine the load *vs* punch-displacement curves, von-Mises stresses, equivalent plastic strain, contact pressure, logarithmic stresses, load-till failure and full-field displacement in the model have been computed. The finite-element model was validated by comparing with the experimental data for load *vs* displacement curves. The effect of punch diameter on load *vs* displacement was observed experimentally as well as by finite-element method. The computational results compared reasonably well with the experimental results.

Keywords: Rigid punches, mechanical behaviour, material testing, punch test method, small specimen testing method, finite-element load

1. INTRODUCTION

Small specimen test method has been utilised for assessing the damage of engineering components in service. In most cases, the component integrity could hardly be evaluated using traditional and well-standardised mechanical test techniques, because there is not enough material sampled non-invasively from the components to allow for determination of mechanical behaviour of materials. In a small punch test method, a specimen with the shape of a small disk and coupons is punched by a shaped penetrator at slow rate, deforming it to failure, and the resulting load *vs* displacement data is analysed. As a result, many workers have investigated small specimen testing methods and one such technique, the small punch test, was proposed by Manahan[1], *et al.* in 1981 which modelled the deformation of the disk with a finite-element code[2]. This test was based on the determination of the load *vs* displacement curve for a small plate specimen when a central load was applied. Initially, the new test was seen as a miniature replacement for Charpy notch test. Baik[3], *et al.* compared the results of the Charpy notch test and the small punch test in the determination of ductile-brittle transition temperature in alloy steel at low temperature. Small square punch specimen of 10.0 mm × 10.0 mm × 0.5 mm cut from a previously tested Charpy specimen were clamped around the

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periphery and subjected to a central load applied via a ball of 1.59 mm diameter. Load *vs* displacement curves were obtained at low temperature and the corresponding fracture energy calculated.

An obvious application for small punch testing was used in nuclear generating systems and Lucas[4] included small punch testing while surveying a number of small specimen techniques to be used for irradiated samples. Lucas distinguished small punch tests which he considered as tests with the specimen supported on a ring around the periphery from the bulge tests with the specimen clamped between circular dies. It was stated that results from the two forms of testing were similar although the pre-load due to dies may have affected the load *vs* displacement curves for softer materials. Mao[5], *et al.* also studied the small punch test for irradiated materials. The ductile-brittle transition temperature from small punch testing of copper-doped alloys was found to rise significantly on neutron irradiation. Based on the load *vs* displacement curves obtained from miniature specimen tests, Baik[3], *et al.* and Cheon[6], *et al.* described that the deformation stages of a specimen during testing are classified into elastic bending, plastic bending, plastic membrane stretching, and plastic instability. The energy for deformation and fracture of the specimen is defined as small punch test energy, the value of which is calculated from the area under the load *vs* displacement curves. Okada[7], *et al.* and Suzuki[8], *et al.* evaluated load *vs* displacement curves of irradiated and non-irradiated ferritic steels.

The present investigation aims to examine the deformation behaviours of rigid hemispherical-headed punches having different tip diameters, by performing experiments as well as by finite-element simulations using small punch test method. The ABAQUS finite-element software with contact algorithm has been used for the determination of the response induced in the miniature sample, due to the quasi-static normal indentation of rigid punches. The load *vs* displacement curves, von-Mises stresses, equivalent plastic strain, load-till failure of specimen, and full-field displacement in the model have been computed.

2. EXPERIMENTATION

The basic elements of the small specimen test techniques are a rigid punch, miniature specimen, and a specimen holder (an upper die and a lower die) with clamping screws as shown in Fig. 1. The small punch specimen is supported on its outer circumference or rim and is deformed into the die by the punch load, which is connected to the load cell for measuring the applied force/load and the corresponding deformation under the tip of the rigid punch.

2.1 Material

The material used was medium carbon steel (0.472 % carbon), which is generally used in construction industry and was procured from the open market, in the form of the rods (1220 mm length, 50 mm diameter). The material was tested

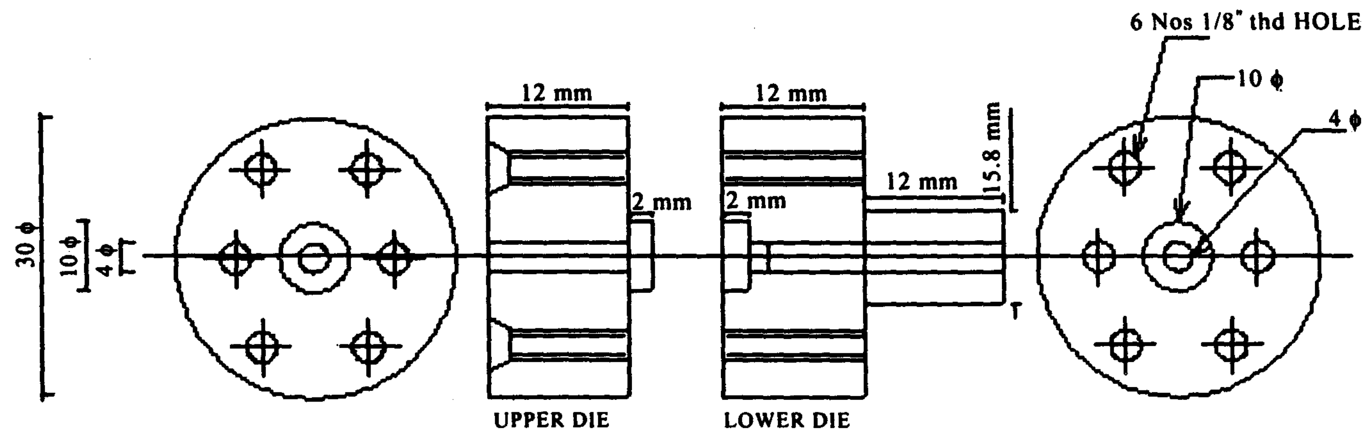

Figure 1. Details of specimen holder (upper and lower dies) for circular shaped miniature sample

at the Spectro Analytical Labs (P) Ltd, New Delhi, for its chemical composition. The chemical composition of the material is given in Table 1.

Table 1. Chemical composition of the test specimen (medium carbon steel)

Elements	Percentage
C	0.4720
Mn	0.6330
Si	0.2170
S	0.0370
P	0.0298
Cu	0.0040
Ni	0.0210
Cr	0.0040
Mo	0.0100
Nb	0.0080
Ti	0.0030
Al	0.0010
Pb	0.0010
Zr	0.0080

2.2 Miniature Samples & Specimen Holder

Circular shaped miniature specimen (10.0 mm in diameter and 0.5 mm thick) were prepared. The specimen were machined from a 50 mm diameter, 1220 mm long rod of medium carbon steel and less than 1 per cent deviation in dimensions was ensured. Initially, miniature specimen of 10 mm diameter, 1 mm thickness were cut for the disk by milling operation. These specimen were then ground on the horizontal surface grinder with permanent magnetic chuck to reduce the thickness up to 0.60 mm.Further, these specimen were mechanically polished by emery paper up to 16 μm (600 grit), to obtain desired thickness (i.e., 0.5 mm). The deviation in thickness was ensured to be less than 1 per cent.

In this investigation, the small punch specimen holder consisted of an upper die and a lower die without any guide cylinder with designed fixture. The inner bores in the upper and the lower dies were kept constant (at 4 mm diameter) for the circular shaped miniature specimen. The specimen holder, rigid hemispherical-headed punch, and a punch holder were installed on the designed fixture. The specimen holder provides uniform support around the outer edge of the miniature specimen and prevents it from cupping upwards during punching.

2.3 Rigid Hemispherical-headed Punches & Testing Machine

In the present small punch test technique, the load was applied through the different types of hemispherical-headed tip punches made of heat-treated D2 tool steel. The lower portion of the punch was 15.0 mm in length and 6.3 mm in diameter, and this was kept constant for all the punches. There was no difference in the upper portion of the punches; however, the tip diameters were different. Three tip diameters (2.309 mm, 1.633 mm, and 1.115 mm) of rigid punches were designed on the basis of borehole area (of dies) to tip area ratios of 3, 6, and 12. The names of these rigid punches were given as P1, P2, and P3, respectively. However, the tip lengths was kept constant at 3.5 mm for all the punches as shown in Fig. 2. An MTS-810 machine of 250 kN load capacity was used for small punch tests. The small punch tests were conducted at a crosshead speed of 0.25 mm/min. During small punch test, the loads *vs* displacement curves were obtained.

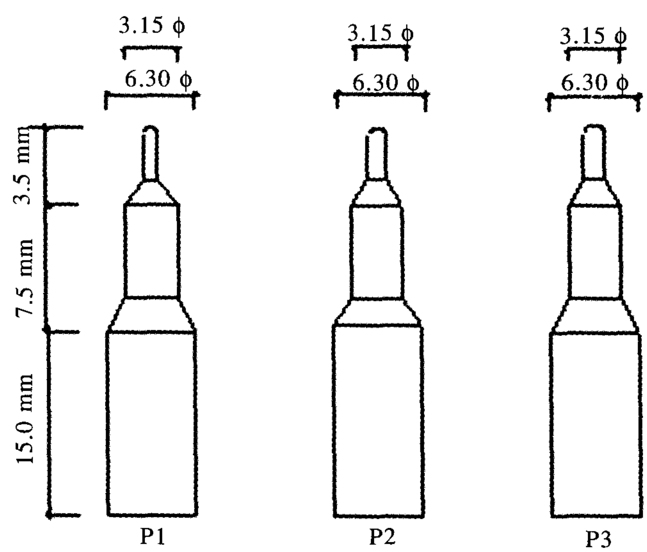

Figure 2. Details of designed different hemispherical tip-headed punches (P1, P2, and P3).

3. RESULTS

Small punch load *vs* displacement curves of medium carbon steel with three hemispherical-headed rigid indenters of different diameters, at room temperature have been plotted. The load *vs* displacement curves were obtained as shown in Fig 3 by slowly pressing the rigid punches on the circular shaped

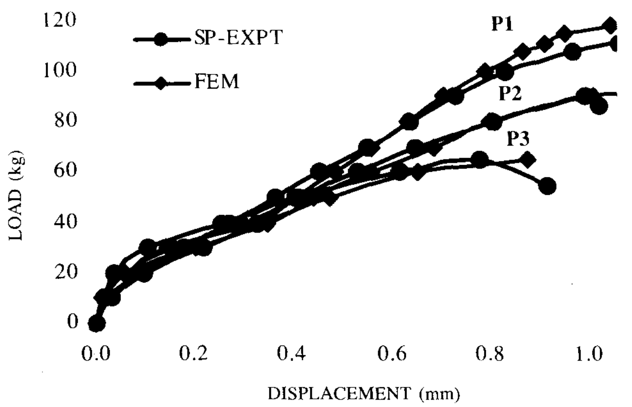

Figure 3. Load *vs* displacement curves obtained by small punch test and finite-element simulation using P1, P2, and P3.

miniature disk specimen in normal direction. The influence of rigid hemispherical-headed punches was observed on load *vs* displacement curves. When rigid hemispherical indenters were pressing slowly (quasi-static manner) on disk, the load *vs* displacement curves were monitored closely. The maximum load (P_{max}) at failure of the disk and corresponding displacement (δ_{max}) of each indenter was noted manually (Table 2) on micro console of MTS machine. The displacements were noted on nano voltmeter in terms of volts, and later converted to millimeter with the appropriate calibrations. For each load *vs* displacement curves, maximum load at failure, and corresponding displacements have been analysed for studying material behaviour.

Table 2. Maximum load and corresponding displacement of small punch test by experiments and finite-element method

Parameter	Miniature specimen test			Finite-element analysis		
Punch →	P1	P2	P3	P1	P2	P3
P_{max} (kg)	111.000	90.000	65.000	121.000	90.650	65.000
δ_{max} (mm)	1.063	0.995	0.779	1.089	1.011	0.880

4. FINITE-ELEMENT MODELLING

The small punch experiment was simulated on a workstation by means of the finite-element software ABAQUS. To make the problem more tractable, a 3-D finite-element model was simulated to follow the actual situation as in the experiment. Although the actual size of the miniature disk specimen was 10.0 mm in diameter and 0.5 mm thick, but in the case of finite-element simulation, the size of miniature disk was taken as 4.0 mm in diameter and 0.5 mm thick. These dimensions of the specimen were decided on the basis of die borehole (boreholes of the lower die and the upper die were of 4 mm diameter as shown in Fig. 1). The periphery of the specimen was fixed by the boundary conditions encastre (fixed) because the small punch specimen was fixed firmly in the upper and the lower dies by six-clamping screws. The details of the simulated finite-element model are shown in Fig. 4.

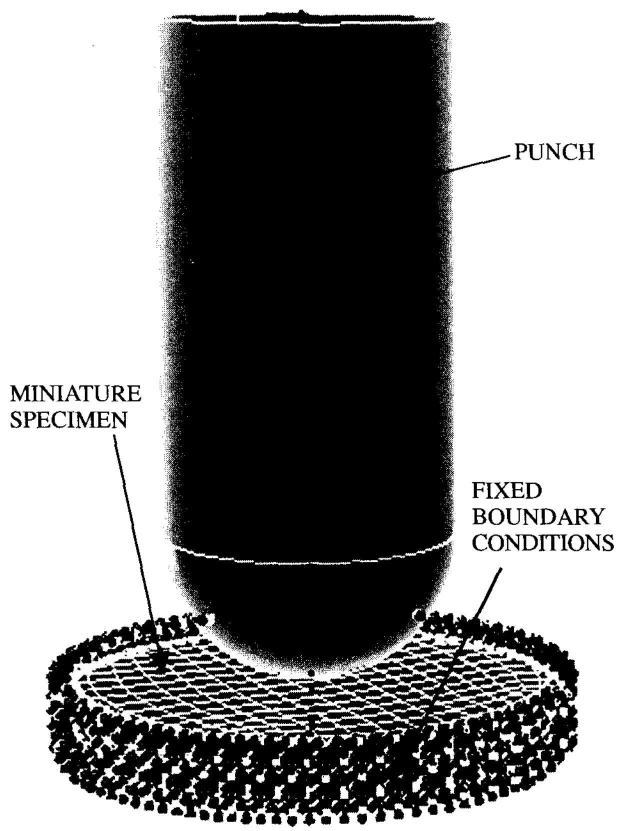

Figure 4. Finite-element simulation of small punch test

Large strain analysis and plasticity were enabled. A 3-D finite-element model for small punch test method was used to represent the rigid hemispherical punch and miniature sample with actual experimental situation (boundary conditions, crosshead motion, etc.). Two mesh densities were studied to allow testing for convergence. Although only a small difference was observed in the results from the two densities, the results presented in the paper were obtained with the finer mesh. This consisted of 3021 nodes and 512, 20-node quadratic brick solid elements. Figure 5 shows the finite-element mesh prior to the application of the test load (un-deformed model).

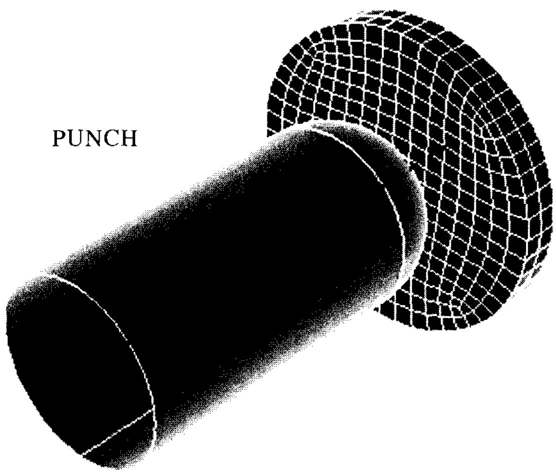

Figure 5. Un-deformed finite-element model

In the finite-element model, the disk specimen was set to be in contact with the rigid hemispherical-headed punch through a special contact algorithm. The hemispherical punches were assumed to be perfectly rigid, without yielding or denting, by applying rigid analytical rigid surface option in FEM simulation. A finite-element analysis was performed using rigid punches of three diameters on circular shaped miniature specimen. The modulus of elasticity as 210E9 N/m^2 and Poisson's ratio of 0.30 were taken for analysis. A uni-axial strain-hardening curve was determined from the tensile tests and supplied to the ABAQUS program in the form of a look-up table. In all the tests, a disk thickness of 0.5 mm was used. The deformed finite-element models as shown in Figs 6(a), 6(b), and 6(c) were used to determine load *vs* displacement curves for miniature disk when the rigid punch was slowly pressed normally into its surface at the centre. A clear visual comparison was made among the different rigid hemispherical-headed punches and deformed finite-element mesh of the miniature disk as shown in Fig 3 and in Figs 6(a), 6(b), and 6(c).

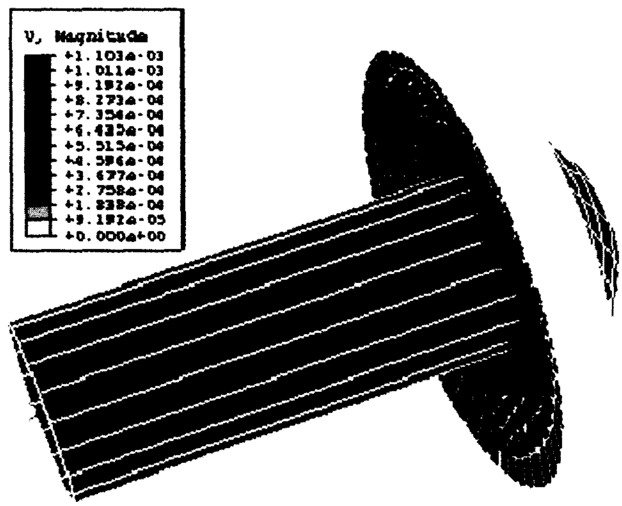

Figure 6(a). Deformed small punch specimen for punch P1

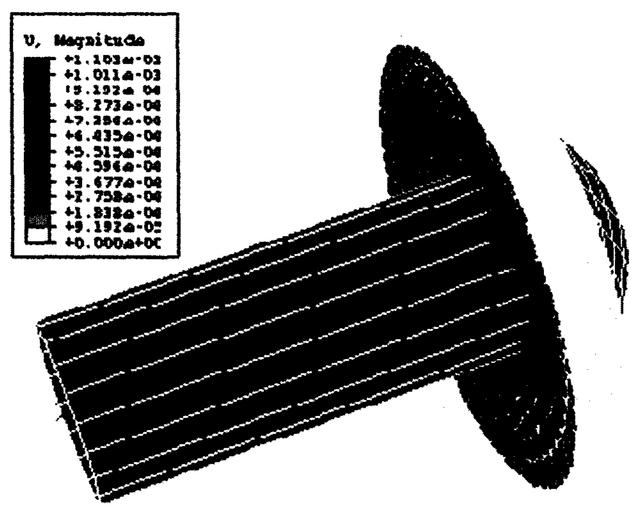

Figure 6(b). Deformed small punch specimen for punch P2

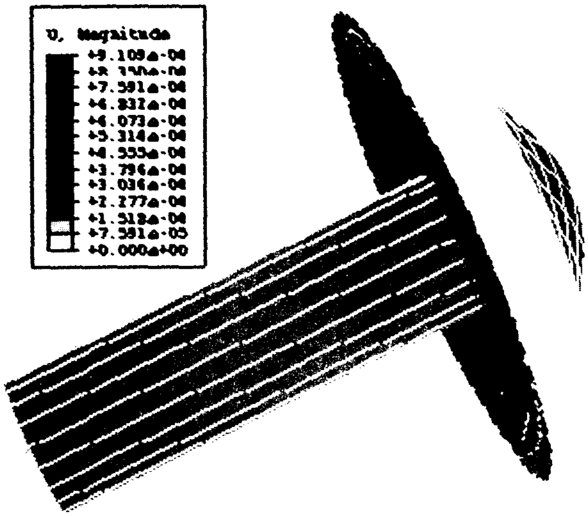

Figure 6(c). Deformed small punch specimen for punch P3

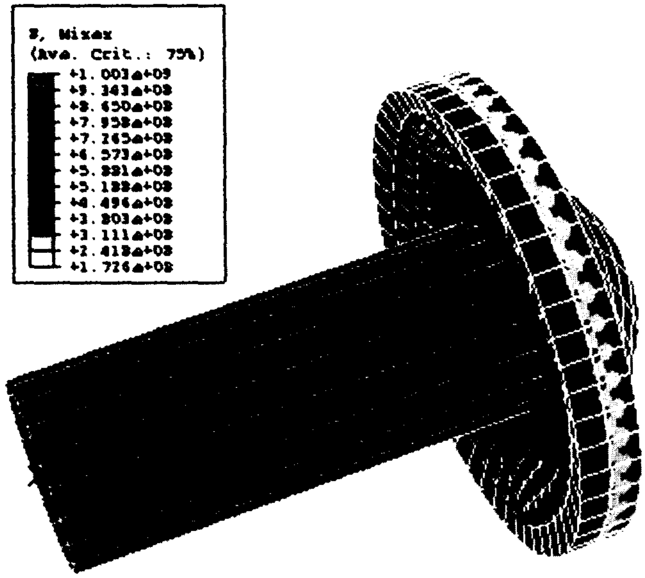

Figure 7(b). Contour of von-Mises stress for punch P2

Figures 7(a), 7(b), 7(c), 8(a), 8(b), and 8(c) illustrates the von-Mises stress and equivalent plastic strain contour of medium carbon steel computed near the maximum load at the failure of the miniature disk specimen for all the three punches. For the small punch specimen, the main stress components contributing to the von-Mises stress are compressive and shearing underneath the rigid indenter and the bending at the bottom surface of the disk. The material underneath the punch was deformed by propagations of stresses, which started from the point where the tip (of punch) contacted the specimen. The plastic bending deformation was developed around it on the bottom surface before the small punch specimen deviated from the initial nonlinearity. The yield front propagated downwards. A yield surface by bending was also developed from the bottom surface. Beyond the brakeaway load (nonlinearity formation), the yield zone grew radially outwards.

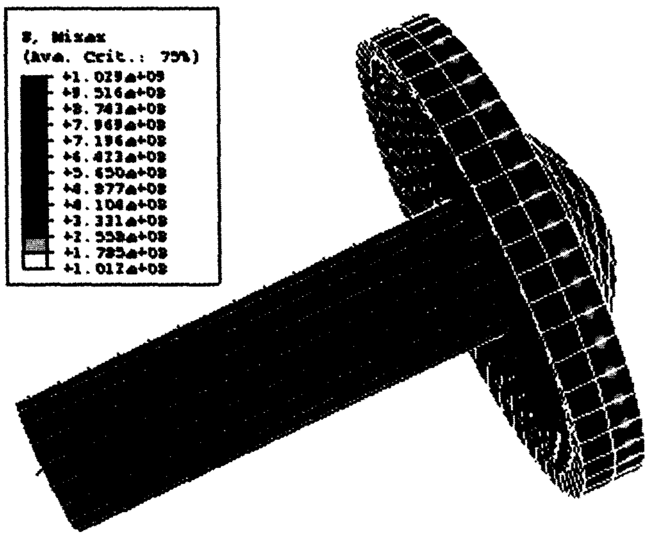

Figure 7(c). Contour of von-Mises stress for punch P3

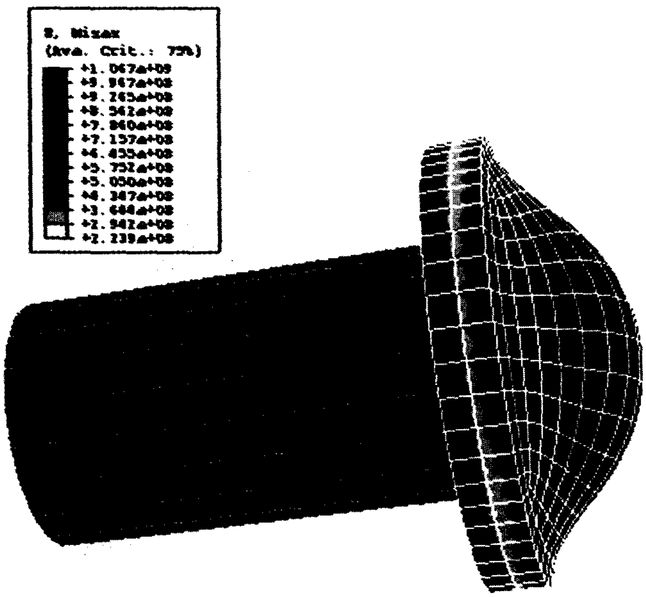

Figure 7(a). Contour of von-Mises stress for punch P1

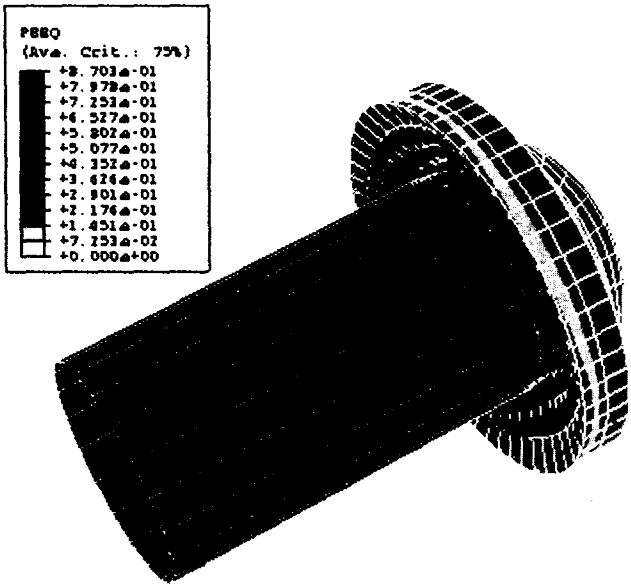

Figure 8(a). Contour of equivalent plastic strain for punch P1.

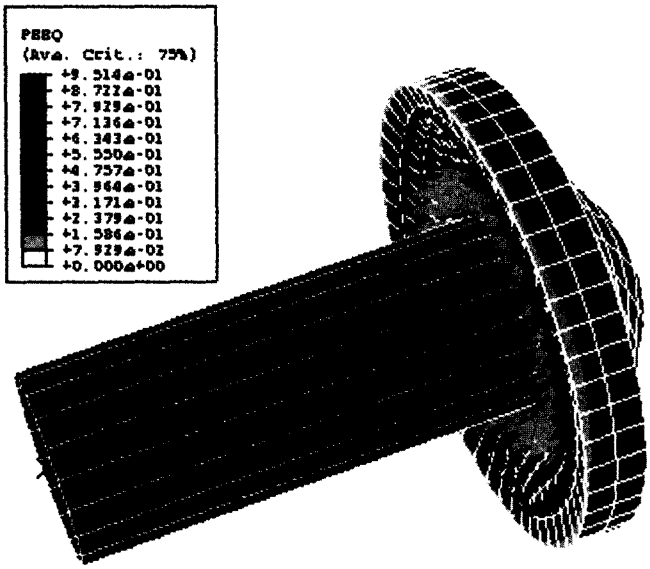

Figure 8(b). Contour of equivalent plastic strain for punch P2.

The deformation under the punch tip is maximum at failure loads. The displacement and the failure load due to punch P1 are maximum as compared to punch P2 and punch P3, respectively. It has been observed that the maximum load and the corresponding displacement are decreasing with reduction in the diameter of the rigid punches. The

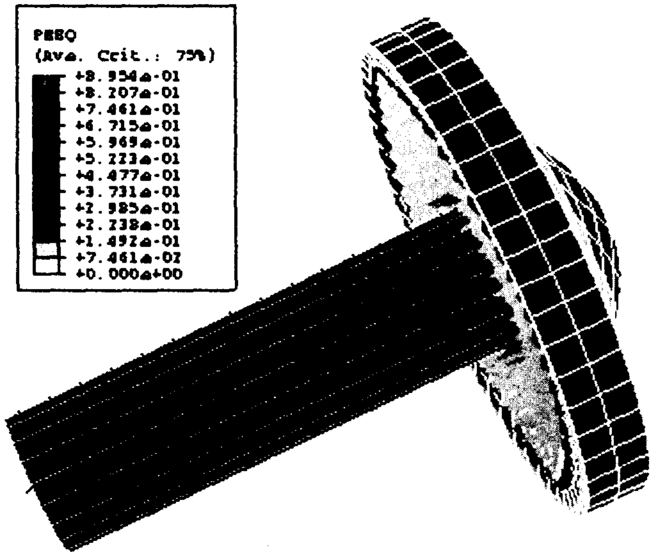

Figure 8(c). Contour of equivalent plastic strain for punch P3.

plastic deformation occurs at the centre after the first contact of the small punch specimen with the rigid indenter, but the location of the maximum shear stress moves outwards due to the distribution of the contact stress. Around the edge of the contact area, further plastic deformation occurs by shear in the material underneath the rigid punch, which is deformed, and causes the higher increasing rate in plastic bending regime and plastic membrane-stretching regime. This deformation behaviour is similar for all the three rigid punches (except the magnitude of the ultimate load) or failure load and their corresponding displacements as shown in Table 2.

5. CONCLUSIONS

It has been observed that the computed load *vs* displacement curves obtained by simulating all the three designed rigid hemispherical-headed punches on miniature disk are in good agreement with those obtained experimentally for medium carbon steel. The von-Mises stresses and the contact pressures computed by finite-element method are shown in Figs 8(a), 8(b), and 8(c) and Fig. 9, respectively. The contact stresses between the small punch disk specimen and the rigid punch are the highest at the edge of the contact area after the

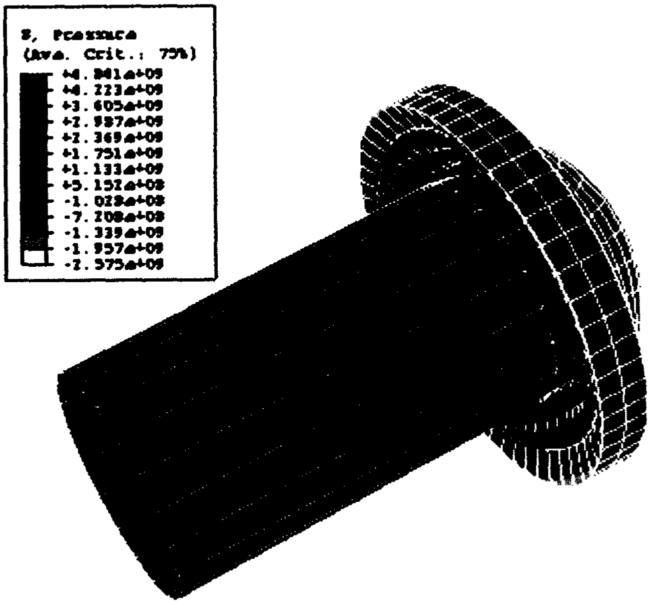

Figure 9. Contour of contact pressure for punch P1

yielding. The maximum value of equivalent plastic strain is at the centre of the bottom surface of the miniature disk specimen. The stresses underneath the rigid punch play a dominant role in the deformation. The contact stresses and the logarithmic strains are also computed by finite-element method. The influence of diameter of the rigid hemispherical-headed punches is observed by clear visual comparison on load *vs* displacement curves and from contours of von-Mises stresses, equivalent plastic strain, and contact pressure. It has been noticed that the values of von-Mises stress is maximum under punch loads P1 (i.e., 1.067E9 N/m^2) and minimum under punch P3 (i.e., 1.003E9 N/m^2) at the ends of incremental steps. Similar observation is made in the case of contact pressure, but the values of equivalent plastic strain are not significantly influenced by the punch tip diameters. The computational results compared reasonably well with the experimental results.

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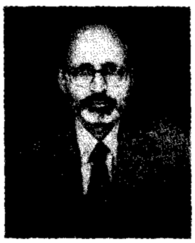

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