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On the Influence of Thickness Non-uniformity on Mechanical Behaviour under Small Punch Load

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Abstract. The Small punch (SP) test is an alternative method to determine the mechanical properties of various materials, including metallic and non-metallic. It uses a relatively small amount of material as a test sample and causes minimum damage to the components during sample extraction, giving it advantages over conventional test methods. However, preparing SP samples with accurate and uniform thickness is challenging. This issue leads to inconsistency in the mechanical properties data obtained from the SP test. The present study numerically investigates the effect of non-uniform sample thickness on the displacement-force data of alloy steel under small punch load at room temperature. The thickness of the sample varies in both radial and through-thickness directions to simulate real material conditions during the laboratory sample preparation stage. This variation in thickness is modelled in Finite Element (FE) Abaqus v6.14 software, considering axis-symmetric conditions. Appropriate load, boundary conditions, and mesh design are assigned to the model. It is found that the non-uniformity of the sample in through-thickness direction affects the displacement-force behaviour of the material. Furthermore, the stress and strain distribution are also affected. The displacement-force response, however, remains constant under the effect of radial non-uniformity. Based on the study, it can be concluded that sample preparation is a critical stage which requires exceptional attention to obtain reliable results in the SP test.

Keywords: *Deformation, Mechanical Behaviour, Non-uniform, Small Punch, Thickness.*

1. Introduction

Small punch test (SPT) has been widely employed as an alternative procedure for determining various mechanical properties such as yield strength, ultimate tensile strength, ductility, fracture toughness, ductile-to-brittle temperature, and creep strength [1], [2], [3], [4], [5]. The size of the specimen required to perform the test is much smaller than the one used in conventional mechanical testing. Due to this reason, the extraction of the specimen from the real components caused minimum damage and, therefore, required little repair. However, in order to yield accurate dimensions as suggested in [6], [7], [8], [9], a proper preparation process is required. Disc-shaped specimens have dimensions of 8 mm diameter and 0.5 mm thickness are commonly used. Achieving this dimension often requires a special type of specimen holder during preparation. While exceptional attention is given, obtaining uniform thickness readings over the entire specimen is sometimes not easy.

Previous studies [10] have emphasized the importance of proposing an optimum range for specimen thickness to obtain consistent and meaningful results in SP tests. The effect of thickness on the load-displacement response of Grade 91 has been studied recently [11]. They claimed that thickness plays an important role in determining the mechanical properties of the material. The thickness range of 0.4 mm to 0.75 is reported to give an acceptable value of yield strength. The observation by Moreno [9], confirmed the finding by Imam et al. [11] which shows the load increases with thickness. Furthermore, Moreno [9] claimed that reducing the thickness-to-diameter specimen ratio extends the membrane stretching regime. Wang et al. [6] argued that the thickness of the specimen gives an insignificant effect on the fracture patterns. They also add that the grain size across the specimen thickness affects the material's strength which can be related to the dislocation movement. Later, Kumar et al. [12] showed that specimen thickness has little effect on yield stress. The impact of surface condition of the specimen on the results of Small punch test (SPT) has also been investigated. For instance, Wynne et al. [13] conducted Small punch Tests on Eurofer-97 steel specimens with varying surface finishes, ranging from coarse to fine. Despite these variations, the results indicated no significant impact on the SPT data. This finding is further corroborated by the work of Mitchell et al. [14], who observed that variations in surface roughness had negligible effects on the test results for aluminium and titanium alloys.

As far as the author's knowledge is concerned, no or limited study discusses the effect of thickness non-uniformity on mechanical behaviour under small punch load. Therefore, this study aims to numerically investigate the abovementioned effects.

2. Numerical Modelling Technique

The small punch test was simulated using finite element (FE) software, Abaqus v6.14. The FE model consists of a deformable specimen with 8 mm diameter and 0.5 mm thickness. It also comprises rigid upper and lower dies that is utilized to position and clamp the specimen. A hemispherical rigid puncher with a diameter of 2.5 mm was also modelled which is used to deform the specimen by means of punch load. Considering the thin cylinder of the specimen, circular test rig and load symmetry, a 2-dimentional axis-symmetric model was constructed for optimum computational time. The elastic and plastic properties of the specimen employed in the FE simulation are given in Table 1 and 2.

Table 1: Elastic property of the specimen

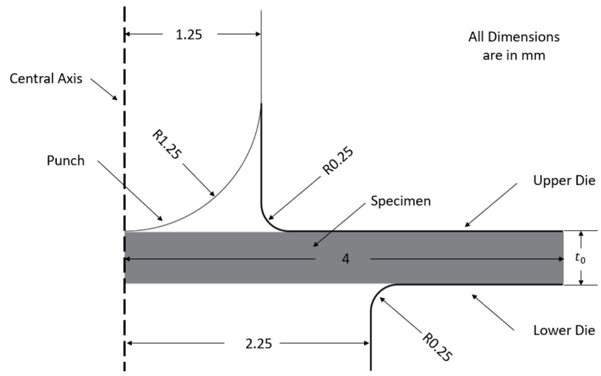
Young's Modulus (GPa)	Poison ratio
210	0.3

Table 2: Plastic property of the specimen

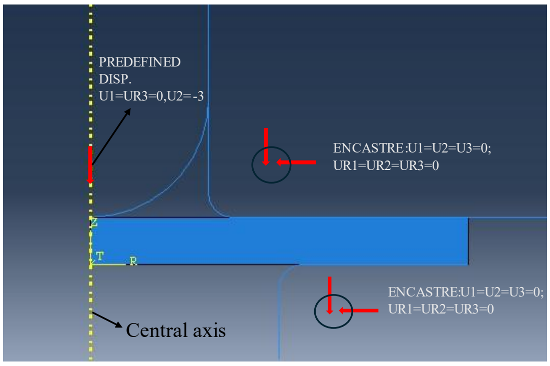
Stress (MPa)	Plastic strain (mm/mm)
512	0
566	0.011904
603	0.020271
641	0.0286

Stress (MPa)	Plastic strain (mm/mm)
676	0.036453
730	0.048454
784	0.060459
836	0.071906
885	0.082796

Figure 1(a) illustrates the axis-symmetric FE model of the small punch test setup while Figure 1(b) presents the employed boundary conditions. The horizontal translation and z-rotational of the punch were fixed to any motion and a predefined displacement of 3 mm was imposed in the y-direction. This displacement value is chosen so that it is higher enough to deform the material until fracture. Furthermore, the lower and upper dies were constrained in all directions. A coefficient of friction of 0.3 (rough surface) was assigned to the interface between the puncher, upper/lower dies, and the specimen. Surface-to-surface contact was selected, and finite sliding model was chosen for sliding formulation. Prior to the simulation work, a mesh sensitivity analysis was performed to determine the optimum mesh size. The simulation incorporates for geometric nonlinearity and the automatic stabilization option was activated to minimize instabilities problems that could lead to mathematical calculation issues.



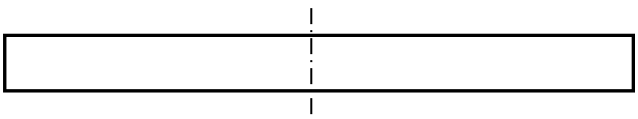
(a)



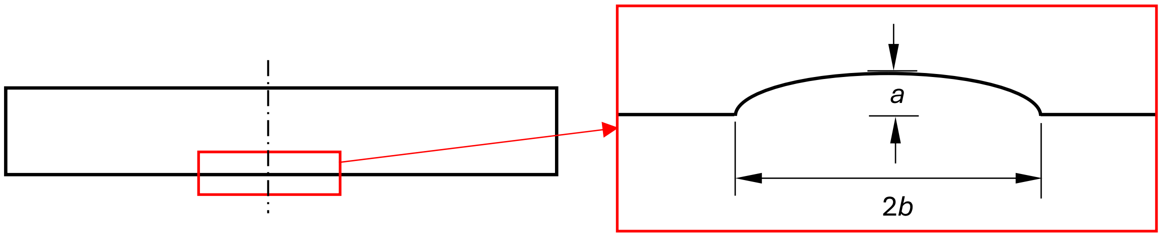
(b)

Figure 1. Small punch test setup: (a) Detail dimension and (b) FE model

In this study, a series of non-uniformity of the specimen thickness was modelled by introducing the elliptical profile of thickness reduction as shown in Figure 2. Here, the two parameters, 'a' and 'b' represent the through-thickness and radial thickness non-uniformity, respectively. In the present study, the non-uniformity is modelled in both the upper and lower surface of the specimen as illustrated in Figure 2(b) and (c). The effect of each case is investigated. The values of 'a' and 'b' varied following the one stated in Table 3. By varying these dimensions, the impact of the non-uniformity of the thickness on various mechanical behaviours like maximum force, stress distribution, and deflection at maximum load is evaluated.



(a)



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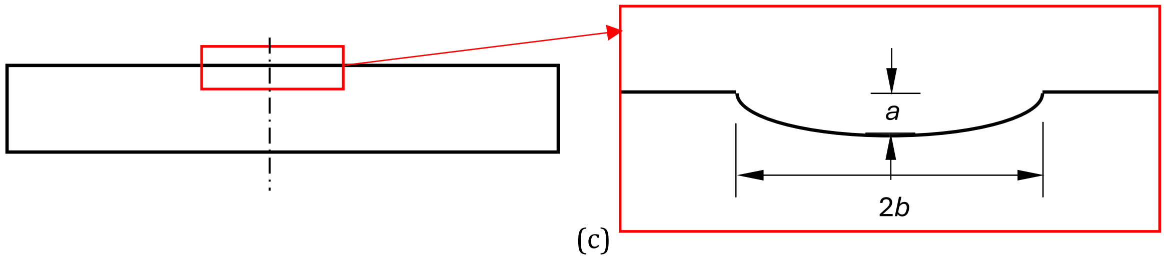

(c)

Figure 2. (a) Sample with uniform thickness, (b) Sample with non-uniform thickness on lower surface (c) Sample with non-uniform thickness on upper surface

Table 3. Test matrix and parameter values

Case	Through-thickness non-uniformity, *a* (mm)	Radial uniformity, *b* (mm)
1	0.05	0.25
2	0.05	0.5
3	0.05	0.75
4	0.05	1.0
5	0.1	1.0
6	0.15	1.0
7	0.2	1.0

3. Results and Discussion

3.1 Load and Displacement

Figure 3 depicts the force against displacement curve that represent the mechanical response of a specimen under small punch load for four different cases, labelled as Case-1 through Case-4. In those figures, the value of '*a*' was fixed, while the value of 'b' was varied. All four cases show similar behaviour in the initial stage, where the displacement is approximately less than approximately 0.25 mm. This suggests the material's elastic properties are nearly identical across all cases. Furthermore, in the plastic region, all cases also show similar plastic behaviour until the maximum force. However, with the increase of '*b*', the maximum force declines slightly. A similar phenomenon (as seen in Figure 3) is observed for the specimen with thickness reduction on the upper surface as shown in Figure 4. Hence, from the above trend, it can be said that changes in the value of '*b*' on the upper and lower surface have little effect on the mechanical response. However, comparing the maximum force (see Table 4), it can be inferred that the strength decreases slightly with the increase of '*b*'.

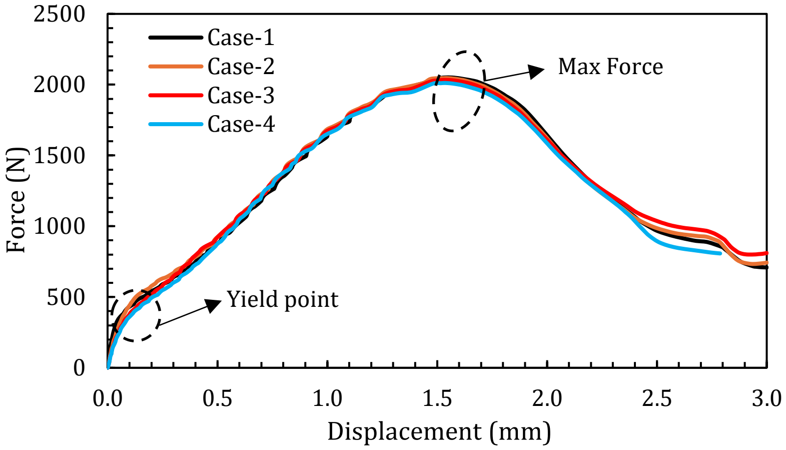

Figure 3. Force against Displacement curve for cases 1-4 (lower surface).

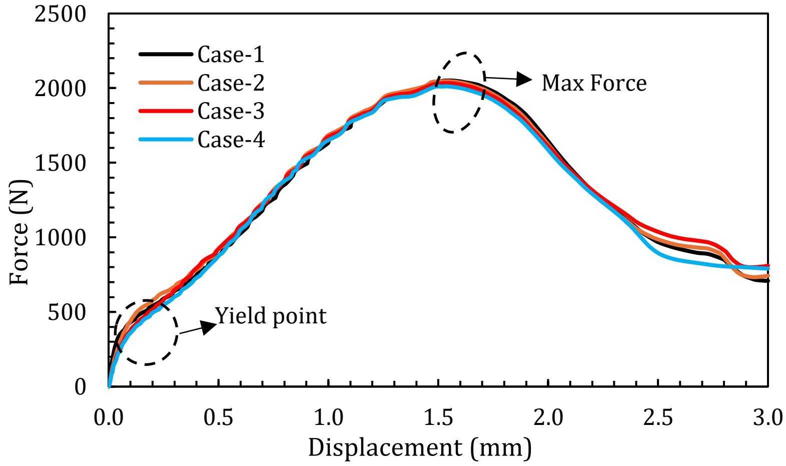

Figure 4. Force against Displacement curve for cases 1-4 (upper surface).

Table 4. Maximum force and displacement values for cases 1-4

	Lower Surface		Upper Surface	
	Max. Force (N)	Displacement at Max. Force (mm)	Max. Force (N)	Displacement at Max. Force (mm)
Case-1	2052.18	1.57	2049.25	1.58
Case-2	2049.82	1.60	2046.03	1.55
Case-3	2039.64	1.59	2034.07	1.54
Case-4	2009.37	1.57	2011.75	1.53

Figures 5 and 6 depict the force-displacement curve that illustrates the mechanical behaviour of a specimen under small punch load for four different cases, labelled as Case-4 through Case-7 (non-uniformity at lower and upper surfaces). In those figures, the value of 'b' was fixed, while the value of 'a' was varied. From Figure 5, a significant reduction in maximum force is observed as the parameter 'a' increase. Specifically, in Case-4 of lower surface nonuniformity, the maximum force recorded is 2009.37 N at a displacement of 1.57 mm while in Case-7 the maximum force and corresponding displacement is 1893.48 N and 1.55 mm. This reduction in maximum force aligns with the result presented in [11], as an increase in parameter 'a' leads to a decrease in specimen thickness. However, the displacement at which the maximum force occurs remains almost unchanged. Following this point, the force consistently decreases due to tensile instability until fracture [9]. In contrast, Figure 6 shows a decline in both the maximum force and the corresponding displacement. In Case-4 of upper surface nonuniformity, the maximum force recorded is 2011.75 N at a displacement of 1.53 mm while in Case-7 the maximum force and corresponding displacement is 1871.40 N and 1.39 mm, respectively. Table 5 tabulates the value of maximum force and corresponding displacement for Case-4 to Case-7.

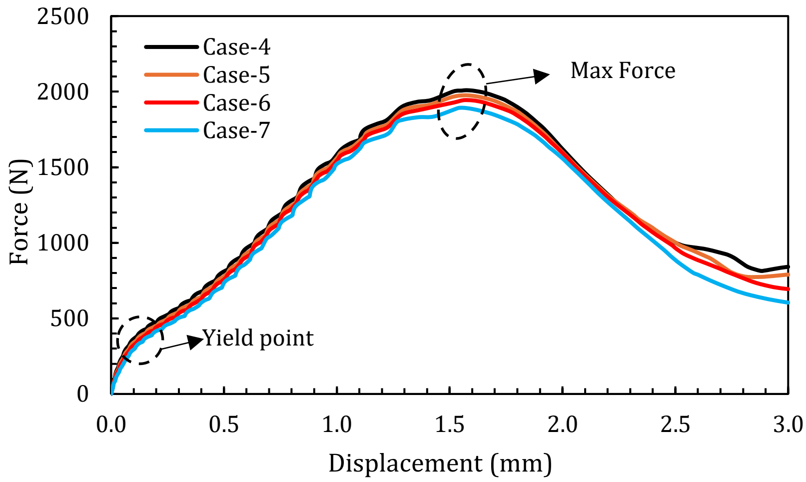

Figure 5. force vs. displacement for cases 4-7 (lower surface).

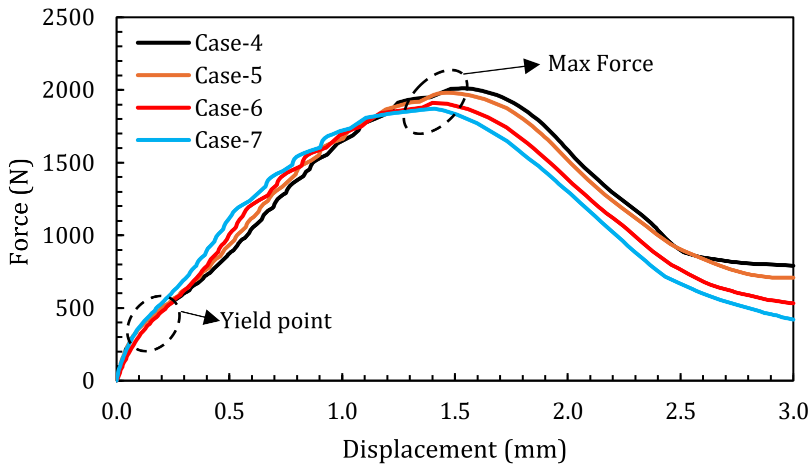

Figure 6. Force against displacement curve for cases 4-7 (upper surface).

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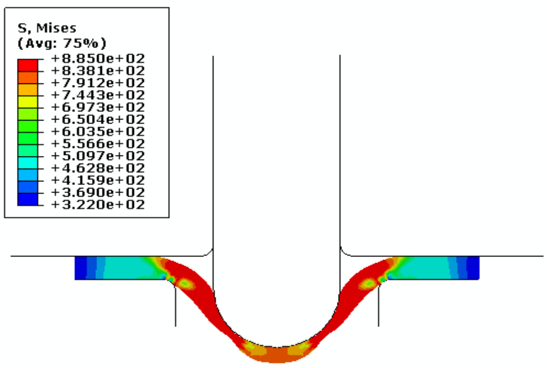
Table 5. Maximum force and displacement values for cases 4-7

	Lower Surface		Upper Surface	
	Max. Force (N)	Displacement at max. force (mm)	Max. Force (N)	Displacement at max. force (mm)
Case-4	2009.37	1.57	2011.75	1.53
Case-5	1976.15	1.57	1980.56	1.47
Case-6	1944.43	1.57	1910.48	1.40
Case-7	1893.48	1.55	1871.40	1.39

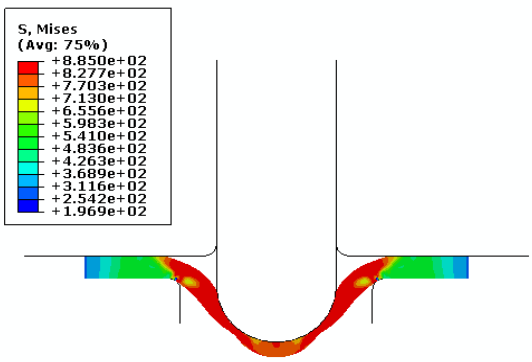
3.2 Stress Distribution

Figure 7 illustrates the stress distribution under small punch load for four different cases. Specifically, these images (in Figure 7) are taken at a 20% drop in maximum force which represents the fracture point of the material. Moreover, the displacement distribution as shown in Figure 8 is also taken at similar point. From Figure 7, it is evident that the stress distribution in the specimen is not uniform over the entire specimen. The highest stress concentrations occur near the contact region between the punch and the specimen. This implies the punch exerts a concentrated force on a small area of the specimen, leading to significant deformation near the punch. This force is transmitted through a small contact area, resulting in high localized stresses. The stress gradually decreases away from the contact area. These findings are further supported by the results reported in [6].

Since the friction between punch and specimen is accounted in the simulation, additional resistance to deformation occurs in the meridional direction in the contact regions of the punch and specimen. Due to the interaction of various forces, the highest stress concentration occurs at a specific angle relative to the centre of the specimen. Figure 7(a) and (b) denote the stress distribution for case-1 for thickness non-uniformity at lower and upper surface, respectively. Furthermore, the stress distribution for case-4 and case-7 for both upper and lower surface non-uniformity is also analyzed as given in Figure (c) to (f). It is observed that all the stress distributions patterns are almost identical to each other. From that observation, it can be said that the changes in the parameter value 'a' and 'b' do not have significant effect on stress distribution patterns.



(a)



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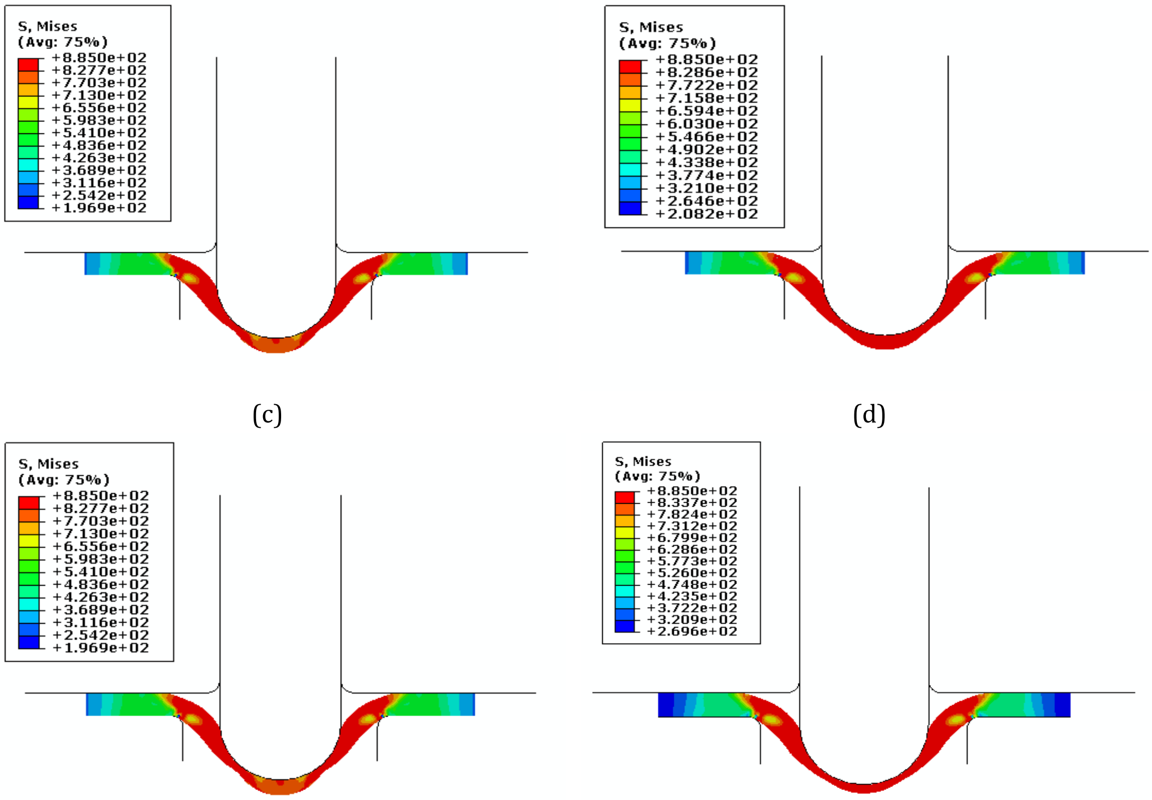
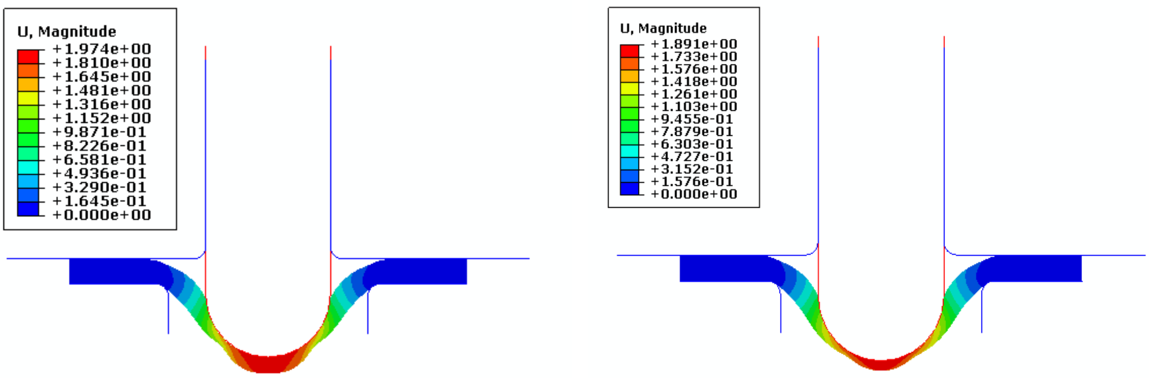


(e) (f)

Figure 7. von-Mises stress distribution (a) Case-1 (lower surface), (b) Case-1 (upper surface), (c) Case-4 (lower surface), (d) Case-4 (upper surface), (e) Case-7 (lower surface) and (d) Case-7 (upper surface).

Figure 8 shows the displacement distribution for case-1 and case-7 with non-uniformity at lower and upper surfaces, respectively. Both images in this figure show that the maximum displacement occurred at the center of the sample. The sample mostly deformed at the contact area between specimen and the puncher. For case-7, it is observed that significant reduction in specimens thickness occurred at the contact area compared to case-1. This contributes to the lower maximum force as discussed earlier in section 3.1.



(a) (b)

Figure 8. Distribution of deformation for (a) Case-1 (lower surface) and (b) Case-7 (upper surface).

4. Conclusions

This study investigates the effect of non-uniformity of specimen thickness on the mechanical behavior during small punch loading. The non-uniformity is denoted by the two parameters: a' and 'b'. Mechanical quantitative parameters like force, deflection, and stress are evaluated. The conclusion can be drawn as follows:

- With the increase of 'a' parameter, the value of maximum force and displacement at maximum force drops. Notably, this phenomenon becomes more pronounced for the case with nonuniformity at upper surface. Conversely, there is no significant effect of 'b' in force and displacement values.
- There is no notable effect of 'a' and 'b' parameters on the stress distribution for both the upper and lower surfaces nonuniformity.
- If the analysis is conducted solely to analyze stress and strain distribution, it is generally acceptable to have some nonuniformity of specimen thickness. However, if the focus is on the force-displacement value and mechanical properties, then nonuniformity can severely compromise the reliability of data obtained from the Small punch test.
- Future research could explore asymmetrical thickness variation by changing the thickness profiles on each surface differently, such as using different curves or step heights on each side. This would create an uneven stress field, providing insights into how asymmetry affects stress concentration.

5. Acknowledgements

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