Design and Fabrication of Ball Punch Deformation Test of Metallic Sheet Material

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Abstract. Predicting the behavior of sheet metal in forming process is very important to avoid material failure. The strain limit of sheet metals before tearing occurs is attainable in Forming Limit Diagram (FLD), which can be obtained experimentally or theoretically. Experimentally, FLD of a sheet metal can be achieved by performing ball punch deformation test. Unfortunately, commercially available ball punch deformation test apparatus is still very expensive. In this paper, the design, fabrication and testing process of more affordable ball punch deformation test apparatus is be presented. The ball punch apparatus has indenter's diameter of 22.4 mm, which capable to tear 0.2-2.0 mm thick specimen blanks with maximum capacity of 200 kN. The test results are then compared with other commercially available ball punch deformation test apparatus results in the literature, and show very good agreement.

Keywords: *Design; Fabrication; Ball punch deformation test; Forming Limit Diagram; Sheet metal forming.*

1 Introduction

Sheet metal forming is very common in several sectors of industries, thus it is important to understand the behavior of sheet metal in forming process. In the automotive industry, the general goal of its manufacturing development is to produce parts with shape conformance without cracking/tearing or wrinkling [1]. The conventional forming limit diagram (FLD) is a well-accepted tool for predicting formability and safety limit of sheet metal in forming process [2,3]. FLD can be determined using a procedure suggested by The American Society of Testing Material (ASTM) E643-15 (for evaluating the ductility of metallic sheet material) [4] and E2218-02 (for determining a forming limit curve) [5]. FLD presents a graphical description of material failure tests, such as a punched dome test. Although Gansamer in 1946, present a diagram similar to the typical FLD [6], the concept of forming limit was first developed by Keeler in 1965[7].

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Keeler realized the possibility to show an FLD for sheet metal in a coordinate system of two main strains, but only for $\varepsilon_2>0$ [8]. This idea was extended by Goodwin who completed the diagram for $\varepsilon_2<0$ [9], and since then it is called as the Keeler-Goodwin diagram.

Experimental determination of FLD is widely used, with the most recent was done by Nakazima and Marciniak [10,11] using ball punch deformation test. Unfortunately, commercially available ball punch deformation test apparatus is still very expensive. For instance, one of the commercially available integrated Sheet Metal Formability Testing System (SMFTS) with maximum capacity of 200 kN has a price tag of $29.500 [12]. Hence, the development of more affordable ball punch test apparatus is still needed. In this paper, the design, fabrication, and testing of an affordable modified ball punch test apparatus with capacity of 200 kN are presented. Additionally, comparison with other commercially available ball punch apparatus is also presented.

2 Development Process and Design Requirements and Objectives

In order to develop a ball punch apparatus with high accuracy and affordable price, the design as well as the fabrication processes must be done properly. The flowchart of the affordable ball punch apparatus development process conducted in this work is shown in Figure 1.

Prior to determining the design requirements and objectives (DR&O) of the ball punch apparatus, it is necessary to understand the requirement of a proper ball punch apparatus. According to ASTM E643-15 [4], there are several requirements need to be fulfilled in by a ball punch apparatus:

- Specimen holder shall be strong enough to hold the force of 12-120 KN which is given by ball punch to the specimen.
- The 22.4 mm diameter steel ball shall be hardened with hardness no less than 62 HRC.
- Load cell with the capacity of 20 tons shall be installed to measure the ball punch hold down force.
- Displacement sensor with accuracy of 0.001 mm to 0.01 mm shall be used to monitor the deformation of a specimen, with measurement point in the center of the specimen.

The requirements above are then expanded into design requirements and objectives (DR&O) as shown in Table 1.

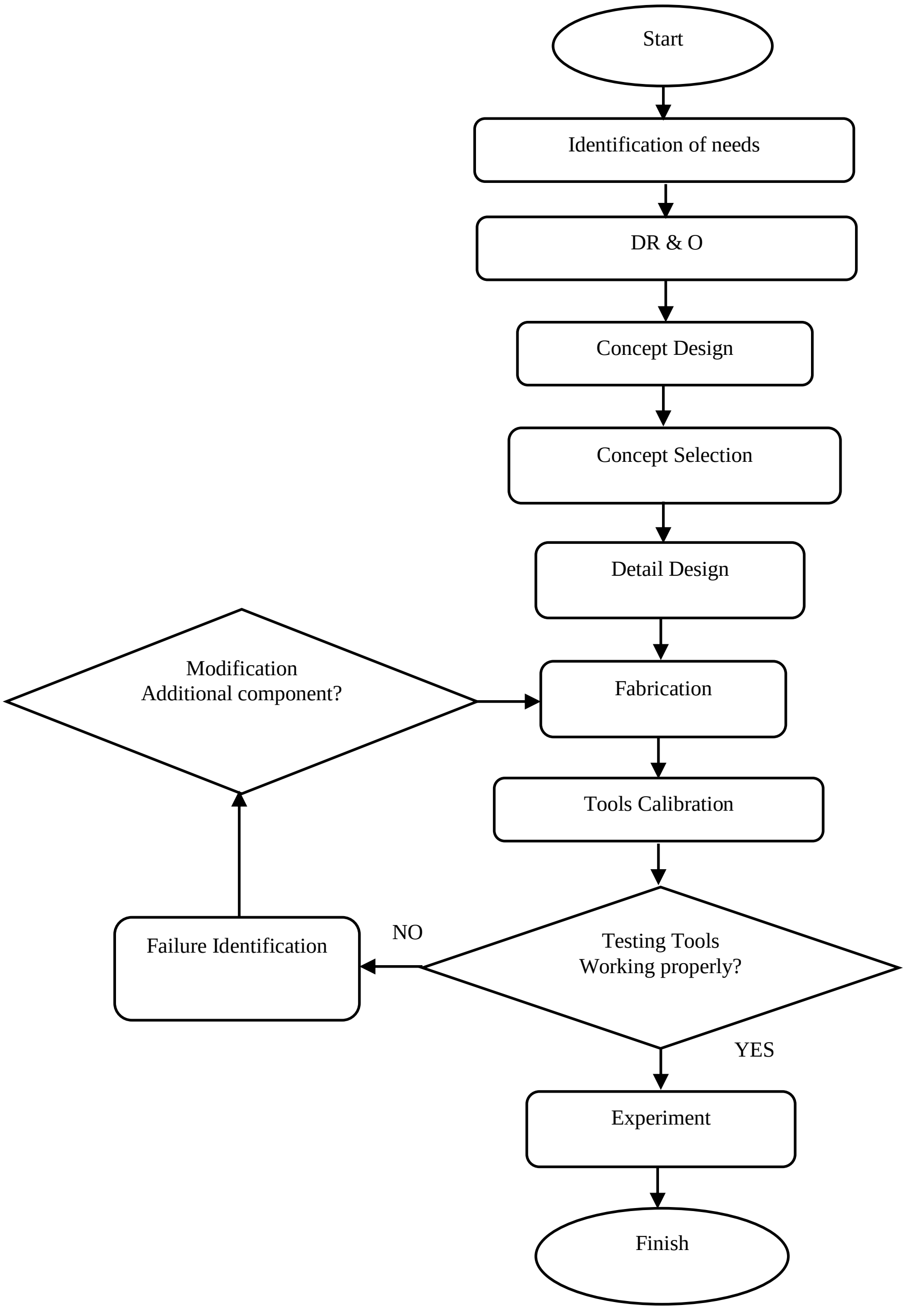


Figure 1 Design and fabrication flow diagram

Table 1 Design requirements and objectives (DR&O)

Category	Design Requirement Aspects
	Functional
M	Specimen holder shall be strong enough to hold the force of 12-120 KN given by ball punch to the specimen.
M	The 22.4mm diameter steel ball shall be hardened with hardness not less than 62 HRC
M	The direction of the load is perpendicular to the test specimen
M	Load cell installed must have a minimum capacity of 20 ton
M	Measuring instruments must be installed in ball punch apparatus to show the deformation rate of the specimen
M	Ball punch deformation test can be positioned vertically and horizontally
M	The top die area is expanded to make it easier to take a picture with the camera
W	Hydraulic pump as the source of the force
W	Test tool dimensions require minimum space
W	Displacement gauge sensors as the displacement measuring device
	Material
M	The main frame uses steel material
M	The specimen holder (top and bottom die) is made of think steel plate
M	The 22.4mm diameter steel ball must be hardened with hardness not less than 62 HRC
	Safety
M	Easy and safe to use
M	Strong structure and construction
M	Rigid to hold a force given by hydraulic ball punch
	Manufacturing
W	The fabrication process can be done using standard machines and tools
W	Ergonomics
W	Convenient when operating
W	The height of ball punch test equipment can be adjusted
	Economics
M	Using existing materials on the market (vendor available)
M	Using components that are already available in the market

Note: M=Must, W=Wishes

3 Design Selection and Fabrication

Three design concepts are then developed based on the previously determined DR&O. The detail explanations of each design concept are as follow:

– Design Concept A

In this concept, the test will be performed using a hydraulic tube connected to a ball punch to push the metal sheet specimen. The main frame consists of four supporting legs made of rectangular hollow steel to withstand the force given by the ball punch. The connections between the supporting legs, bottom plate and base plate are done by welding. The top holder and specimen are designed to be circular and are tightened using nuts and bolts for easy installation. The bottom specimen holder is designed to be square with six bolt holes. The bottom of the specimen is directly connected to the main frame. The illustration of Design Concept A is shown in Figure 2.

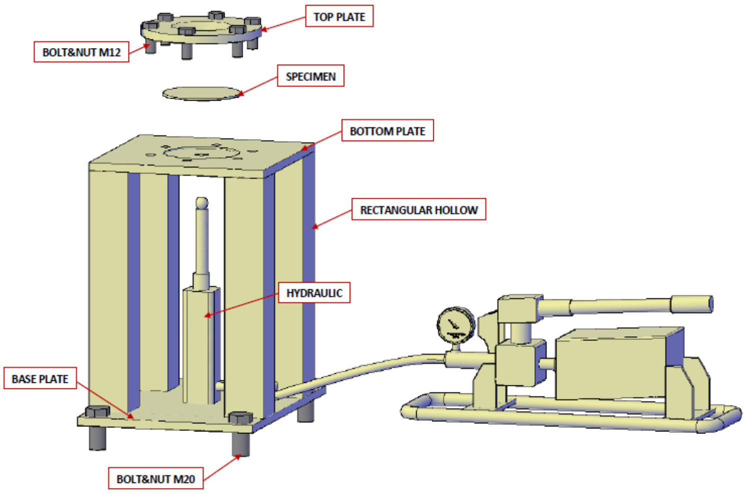


Figure 2 Ball punch deformation test Concept A

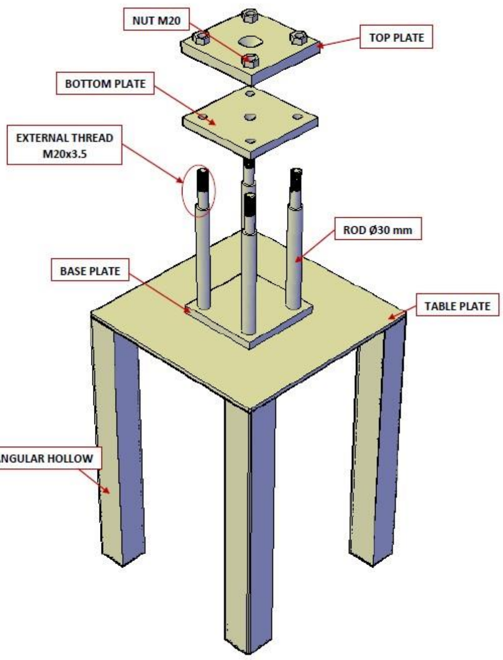


Figure 3 Ball punch deformation test Concept B

– Design Concept B

In Design Concept B, the welding system used in Design Concept A is replaced by four cylindrical rods with M20 thread size to facilitate apparatus dismantling. Furthermore, square specimen holder is used instead of circular specimen holder. Figure 3 shows the illustration of Design Concept B.

– Design Concept C

In Design Concept C, the top retaining plate is not connected to the threaded cylinder anymore. The table is scaled down to minimize the space required for the test equipment. The legs of the table are shortened as well according to the length of the hydraulic cylinder and the transverse structural boosts in the shape of L-bar are added. The hole area of the top plate is enlarged with additional 60° taper to make it easier to shoot using the camera. The illustration of Design Concept C is shown in Figure 4.

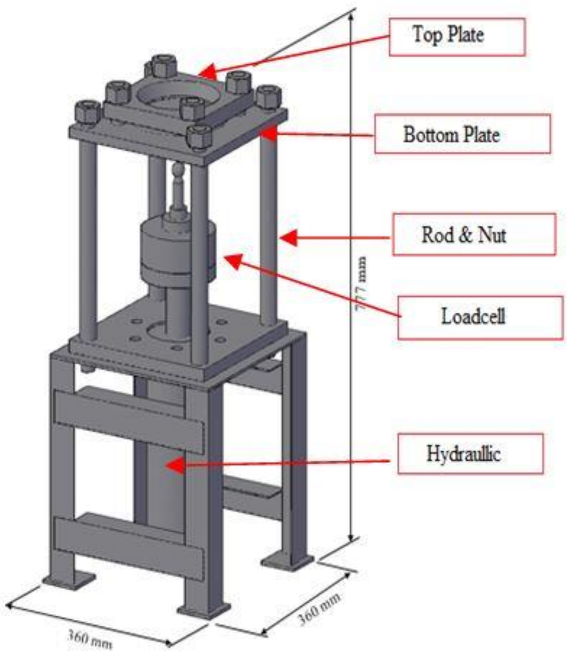
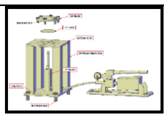
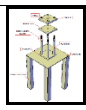
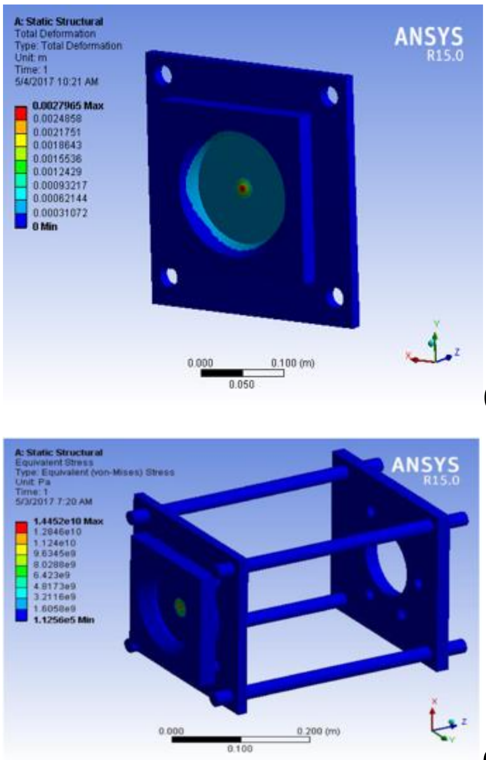


Figure 4 Ball punch deformation test Concept C

The next step is to choose the best design based on the product specifications as shown in Table 1. The detailed assessment of all design concepts is shown in Table 2. The portion of each criterion is determined based on the priority in the design requirements and objectives. It can be seen that concept C is chosen as the modified ball punch apparatus final design.

Table 2 The assessment of design concepts

No	Criteria	Percent (%)	Concept A	Concept B	Concept C
1	Design	-			
2	Functional	50%	30	20	50
3	Materials	10%	10	10	10
4	Safety	15%	8	7	12
5	Manufacturing	5%	5	5	4
6	Ergonomics	10%	8	7	10
7	Economic	10%	10	10	8
	TOTAL		71	59	94



(a)

(b)

Figure 5 Simulation test result of the structure with the force 200 kN

To ensure high measurement accuracy, the upper die deformation must be kept very small under loading, thus finite element analysis must be performed to check the deformation of final ball punch apparatus design. The finite element simulation is done at maximum possible load of 200 kN. The results, as can be seen in Figure 8a and 8b, show that only very small deformation happens at the base when the load is given to the specimen. As a result, it can be deduced that the final design of ball punch apparatus is capable to deliver high accuracy measurement result.

The ball punch apparatus is then fabricated based on the final design. The final product after assembly process is shown in Figure 6.

Figure 6 Final product of ball punch apparatus

4 Results and Discussion

To check the functionality of the newly developed apparatus, ball punch deformation test is then performed against several sheet metal specimens made of ASTM A36 mild steel. The picture of the tested ASTM A36 sheet metal specimen which display the overall deformation is shown in Figure 7. Finite element analysis is then performed to validate the experimental results. The deformation result of the finite element analysis that has been performed is shown in Figure 8. It can be seen that the deformed shape of the specimen as well as the failure location of the finite element result match very well with the result from the experiment. Both results show that a peak in radial strain develops during the punch indentation which concentrated and caused circumferential crack at the contact between sheet metal plate and the ball punch.

Figure 7 ASTM A36 sheet metal specimen after ball punch deformation test

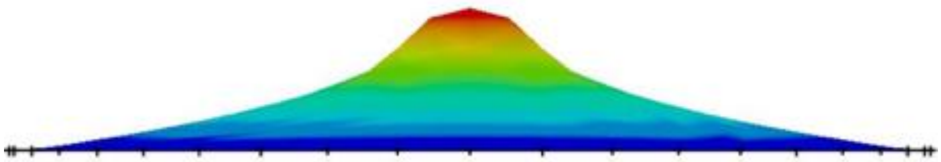
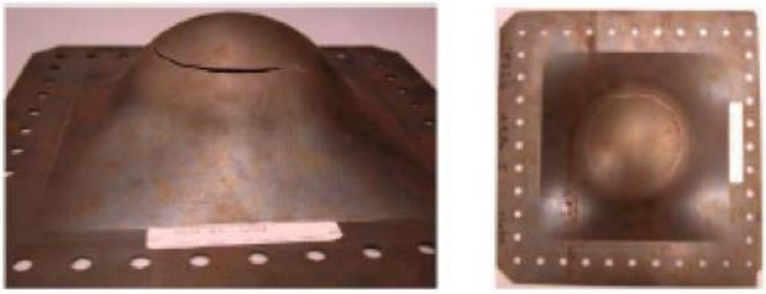
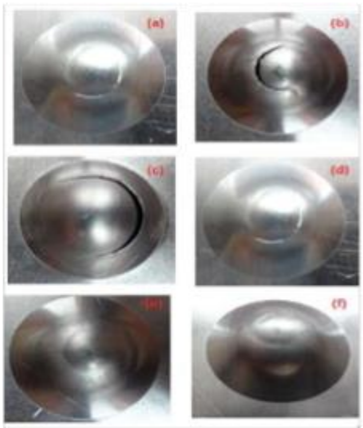


Figure 8 Finite element deformation result of ASTM A36 Mild steel

Further validation is done by comparing the current result with the results available in the literature. Figure 9a shows the experimental results conducted by Y.W. Lee et al [13], which shows similar deformed specimen shape as the current result. Additionally, Chandini et al [14] have performed tests to obtain FLD utilizing commercially available Erichsen cupping test machine and the result as can be seen in Figure 9b shows that the circumferential crack happens at the contact between sheet metal plate and ball punch which is similar to the current result.



(a)



(b)

Figure 9 (a) Experimental & simulation result of punch force [13]& (b) Cups drawn on Erichsen cupping test [14]

5 Conclusions and Future Works

More affordable ball punch deformation test apparatus has successfully been developed. The result achieved from the newly developed apparatus is consistent with the finite element results and the experimental results from another commercially available machine. At present, large deformation digital image correlation (DIC) system is still under development and in the near future will be used to provide real-time and full-field strain measurement in the ball punch deformation test. Up until now, strain measurement on ball punch and cupping tests were done using either displacement gauge, which can only provide real-time measurement at one point, or by manually measure marking on the specimen blank which can only be done by halting the test.

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