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Numerical analysis on the effect of thickness on biaxial tension limits☆

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Abstract

Forming limit curve is the plot between major and minor strain of a critical element during sheet metal forming. This curve provides the indication on how particular metal in a particular deformation mode can form safely. This knowledge further provides the input to design the tools which can form the safe product. As this method only follows the two principal strains it is mostly applicable to sheet metal forming. Sheet metal forming is one of the broad manufacturing processes which include many processes to trim, bend, draw, stretch, flare etc. Due to market light weighting demand the material needs to stretch uniformly to the limit to produce thinner and lighter but stronger parts. However, forming these lightweight parts needs to go through complex deformation paths, which brings the requirement to understand the material to extreme stretching. For this researcher devised the biaxial machine which is designed specifically to provide biaxial stress components using multiple and varying loading condition. In this paper the cruciform shape specimen which has 4 arms can be pulled in positive displacement to provide tension in the material. With changing the displacement or rate on individual axis multiple deformation paths can be created. In this paper the limits of material in a biaxial tension was investigated with varying the thickness of a specimen. The conventional route to create the equi-biaxial tension is hemispherical dome test which is also investigated for different thickness. It was found that the thickness has negligible influence on biaxial results but does changes the strains in arm. It was also found that due to pressure effect, the limit in hemispherical dome test is higher than in biaxial test.

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Keywords: Biaxial test, hemispherical dome test, numerical simulation, pressure effect, thickness effect

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1. Introduction

Across the board, investigators are struggling on how to provide efficient design which would meet the requirement for stricter environmental regulation. These environmental regulations and cost of fuel drives the need for lighter weighing, compactly designed vehicle parts. Due to light weight the mileage on the vehicle increases and can see a direct cost savings. This need has steadily increased due to recent economic changes and put automakers in the upmost position to think on efficient design which would lead for more savings by reducing the material waste, efficient use of material and energy. One of the ways on which many researcher are working is the efficient use of material i.e., either use higher density material with higher deformation or use lower density material which basically lacks deformation. In both cases the deformation is one of the challenges which need to address and understand properly for efficient design.

To understand the deformation closely in various modes, the forming limit diagram is one of the useful and powerful tools. This diagram is a plot between major and minor strain on a plane of sheet metal. This provides the indication on how, when and where the material will reach to failure and prevention technique to stop the deformation. Keeler [1] was the one who proposed the concept of forming limit curve on the major and minor axis of strain i.e., strain plane. This was further experimented on sheet metal during various stamping modes [2]. This forming limit curve provides a curve or envelope by joining limits in various tensioned modes. Basically this envelope floats from uniaxial to biaxial strain direction. Strain point above the envelope indicates the material failure by necking or tearing and point below refers to safety of a material [3]. It was identified in these literature [4-13] that this envelope is very sensitive to these parameters a) planar and normal anisotropy value "r-values", b) strain hardening exponent "n-value", c) strain rate "ε/sec-value", d) size of grain at start of deformation, e) prestrain, f) tool geometry, g) coefficient of friction between sheet metal and tool, and h) blank holding force. Traditionally hemispherical dome test were used to identify the limits of the material in various deformation modes. However in this method the punch was in contact with the sheet metal and deformation plane was also not remained on the plane. This contact condition can come in the form of either pressure or friction [14-15]. This friction becomes prevalent simply because the punch is in contact with the sample while manipulating it. This is an unwanted variable that can cause variations during testing and data collection [16-18]. Pressure is the other contact condition that can cause the sample to fail at higher forces or time because of how the pressure makes the material behave while under stress [19].

Due to these challenges a new testing method called biaxial test was devised, which can deform the material in various modes similar to traditional method with elimination of contact conditions. For this study the experimental testing previously performed on the Penn State Behrend's newly developed high-capacity biaxial machine. The sample used for this test rig is the cruciform shape samples which has 4 arms which can be displaced in positive direction to get various deformation modes. In this paper the material is simulated till its failure in the biaxial set-up with the variation of thickness. A traditional way i.e., hemispherical dome test was also performed to analyze the pressure effect. Different thicknesses of the specimen were tested to understand the variation of pressure due to thickness. The results between both tests were discussed and explained.

2. Material

To perform this study aluminum alloy 5083 was considered. The as-received material was brittle in nature and thus annealing operation at 500^{o}C for 5 minutes was performed to increase the ductility [20]. The tensile true stress strain for this annealed material is shown in Fig. 1. The tensile behavior was further fitted with power law and parameters were used for numerical simulation with isotropic hardening. However initial part of the yielding was directly included for the actual test. The mechanical properties of this annealed material are given in Table 1.

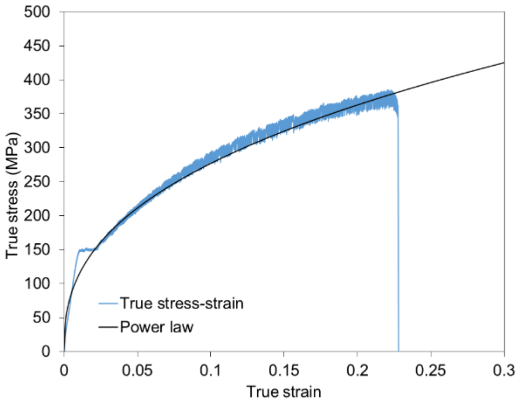

Fig. 1. True stress strain curve along with fitted power law [20]

Table 1. Mechanical properties of annealed AA5083 as determined by testing [20]

Yield Stress (MPa)	Tensile Stress (MPa)	Elongation (%)	K (MPa)	n
150	290	26	680	0.39

3. Numerical Methodology

To analyze the effect of thickness on forming limits two test method were applied a) Biaxial test, and b) Hemispherical dome test. Both were set such that to provide the equi-biaxial deformation mode. Cruciform specimen with diamond center was used in both tests for simulation [20]. Two material thicknesses were considered for this study i.e., 2 mm with 0.762 mm at diamond region and 4 mm with 1.572 mm at diamond region. ABAQUS/Explicit 6.13-2 was used to model both tests. The material tensile data as mentioned above was fed in the numerical model with isotropic hardening law.

3.1. Biaxial test model

To create the equi-biaxial deformation mode each armed were pulled in the positive displacement to provide the tension in all direction. Both horizontal and vertical arms were set to move at the same rate. For this purpose a three dimensional model was created as shown in Fig. 2a. The specimen was model as a deformable body with S4R (4-node quadrilateral, reduced integration) shell elements. To accurately capture the strain evolution finer mesh was created at the center with 0.5 mm element size and in the arm was set for 2 mm size (Fig. 2b). Again to accurately capture the thinning and the instability five integration points through the thickness direction were used.

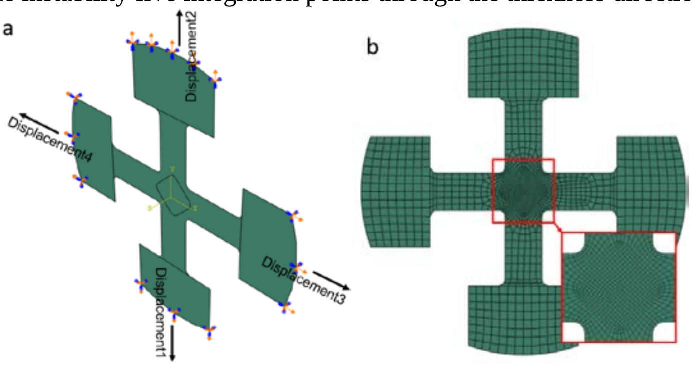

Fig. 2. Biaxial Model a) 3D model and b) Meshed samples

3.2. Hemispherical dome test model

Unlike to biaxial test model, the tooling's like die and punch were required to deform the cruciform specimen. Even though specimen was model as a deformable body, the tools were considered as rigid surfaces. Again a three dimensional model approach was applied to simulate this test [20]. S4R shell element i.e., 4-node quadrilateral with reduced integration was used to mesh the specimen. Same meshing was applied in this model as used in biaxial test model. Due to usage of lock beads in the blankholder during the experiments [20], the specimen were properly trimmed at the lock bead position and those edges were restricted in all degree of freedom during simulation. With the help of this method the modeling of blankholder was eliminated. Note: Lock bead was used to prevent the material feed during forming. The contact interaction between tooling's and specimen was set with surface to surface. The friction coefficient between the tools and specimen was determined through trial and error method to match experimental results and came out to be 0.12. This constant coefficient of friction was used in all simulations.

4. Results and discussion

The experimental set-up for biaxial test is a Penn State Behrend's newly developed high-capacity biaxial machine which was funded by National Science Foundation. This machine is capable of providing different deformation modes using both horizontal and vertical axis on the cruciform specimen. Previous experiments were performed on the same material with same annealing condition. The strain evolution was captured using a digital image correlation and discussed in more detail in this literature [20]. The comparison of the horizontal arm nominal stress strain curve from both experiment and simulation can be referred in [20] and was noticed that the curve lie on top of each other with only difference in failure strain. With this close agreement all biaxial simulation were conducted in ABAQUS with same set up.

Similarly, the experimental set-up for hemispherical dome test was considered which was used in the previous study [20]. This process was modeled in ABAQUS as explained in methodology and results on force displacement curve were compared. To bring the model to the close relation the friction coefficient was trialed and found to be 0.12 for good match. It was found that numerical results is in very good co-relation with experiments and thus the same model was used in this study with same constant friction coefficient [20].

4.1. Biaxial test data

Figure 3a shows the equivalent plastic strain distribution on the specimen with 2 mm thickness near to failure. It can be seen that the strain are concentrated at the radius region between the horizontal and vertical arms. Figure 3b shows the separation of the material during pull. Further the engineering (nominal) stress-strain was plotted for both horizontal and vertical arm for both 2 mm and 4 mm specimen thickness (Fig. 3c). It can be noticed that the stress-strain behavior neglects the thickness difference and fall one on top of each other. This ruled out any differences in their failure limits for this test.

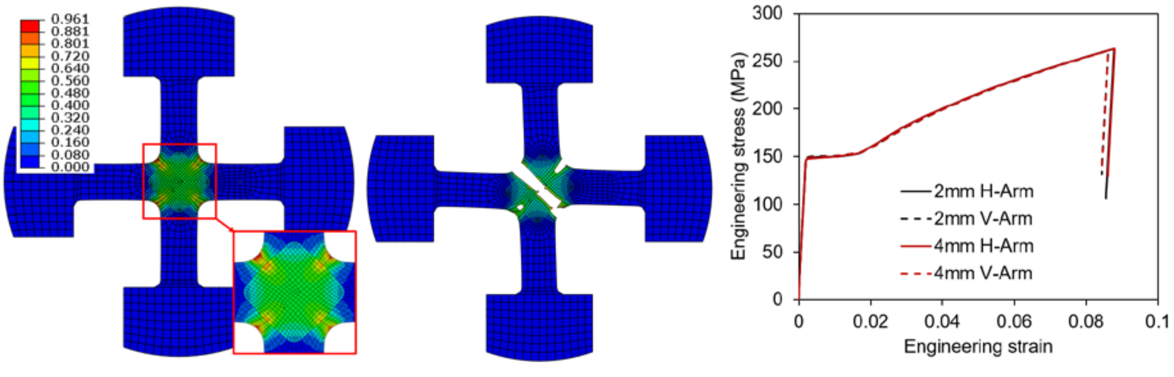

Fig. 3. Left-Equivalent plastic strain pattern on simulated biaxial specimen (2mm thickness) a) Near to failure and b) Separation and Right-Horizontal and vertical arm stress-strain curve in biaxial simulation with different thickness

4.2. Hemispherical dome test data

The equivalent plastic strain distribution for cruciform specimen with 2 mm thickness deformed with hemispherical punch is shown in Fig. 4a. Again it was found the strain gets concentrated at the radius between horizontal and vertical arm which provides the region for crack initiation. Figure 4b provides the separation of elements with further pull.

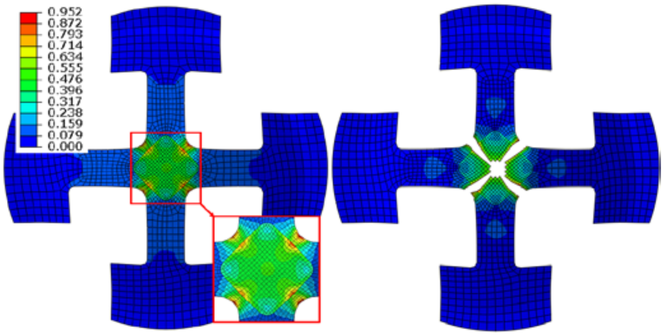

Fig. 4. Equivalent plastic strain pattern on simulated hemispherical dome specimen (2mm thickness) a) Near to failure and b) Separation

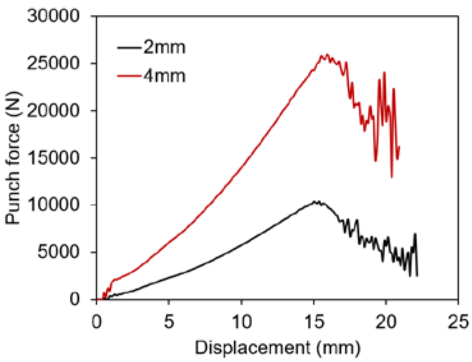

Fig. 5 Punch force displacement comparison during simulation of hemispherical dome test for different thickness

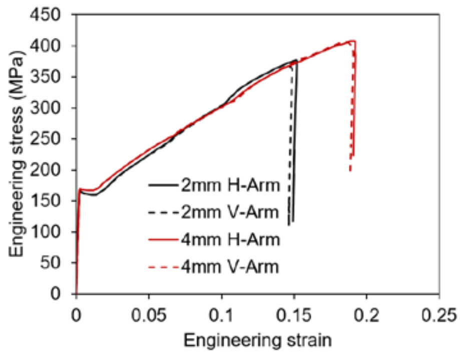

Fig. 6. Horizontal and vertical arm stress-strain curve in hemispherical dome simulation with different thickness

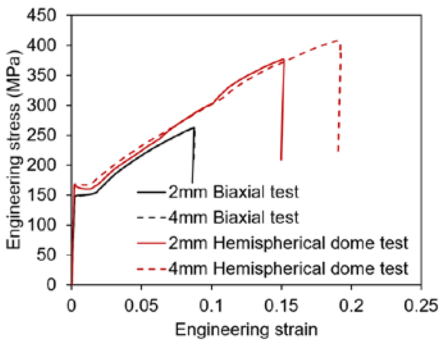

Fig. 7. Horizontal arm stress-strain curve during biaxial and hemispherical dome simulation with different thickness

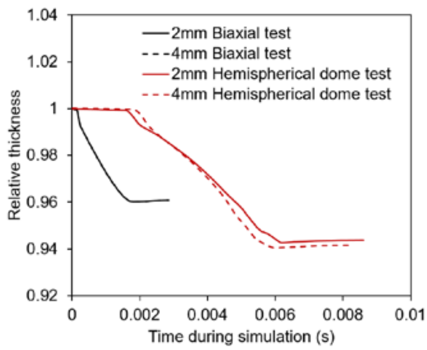

Fig. 8. Relative thickness distribution during biaxial and hemispherical dome simulation with different thickness

The force-displacement curve during hemispherical dome test for 2 mm and 4 mm specimen thickness is shown in Fig. 5. It can be seen that the maximum force required to form for 4 mm thickness specimen to dome is approximately 2.5 times (i.e., 25839 N) than the 2 mm thickness specimen (Maximum force = 10480 N). Similarly the failure displacement for 4mm thickness specimen is little higher i.e., 15.5 mm as compared to 15mm for 2mm thickness specimen. Further the engineering stress strain data from horizontal and vertical arm were acquired and plotted and shows in Fig. 6. To be consistent in comparison between biaxial and hemispherical dome test data the name of the arm kept same i.e., horizontal and vertical. Even though the specimen failed at same displacement the strain at the arm is higher for 4 mm thickness specimen than 2 mm thickness one by approximately 5%. When comparing Fig. 5 with 6 it can be found that a very little influence of thickness on the formability but it does have higher effect on the strain in the arm. The comparison between the biaxial and hemispherical test are given in next section.

4.3. Comparison of failure limits

Figure 7 provides the horizontal arm stress strain curve during the process. It can be noticed that with same specimen thickness the strain for failure is higher (i.e., by 7%) in hemispherical dome test than in biaxial. And further the 4 mm thickness specimen is having additional 5% increase in strain before failure within hemispherical dome test. To see how the third direction i.e., thickness gradient looks during the process the plot of relative thickness was created. Relative thickness is the ratio of achieved thickness to the original thickness. Relative thickness was chosen was a good way to present for different specimen thickness results. From Fig. 8 it can be observed that the thickness drops steeply in biaxial test than hemispherical test and saturates earlier. Due to lower slope of thickness gradient during hemispherical dome test the formability increases as well as failure delayed. Within hemispherical test the 2 mm thickness specimen fails first than the 4 mm thickness one. As explained earlier that the thickness has very less effect on the formability which may results to have similar effect of the forming limits.

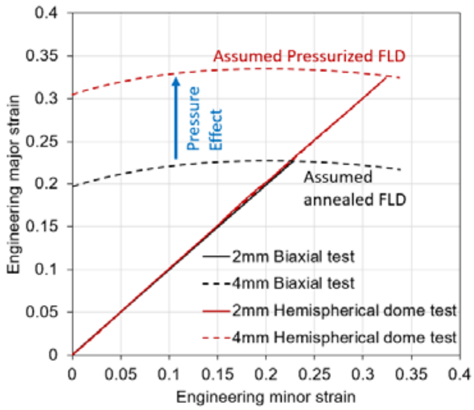

Fig. 9. Biaxial strain path during biaxial and hemispherical dome simulation along with as received material FLD with thickness difference

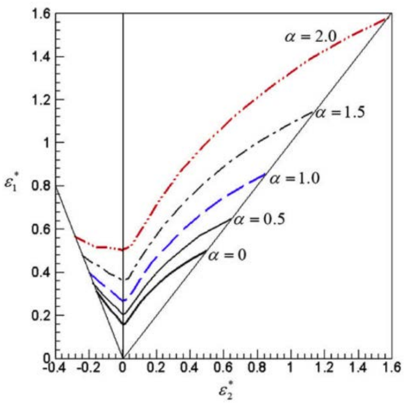

Fig. 10. Forming limit diagram under hydrostatic pressure [19]

To understand the forming limits, the strain path of the center element at the diamond was plotted and is shown in Fig. 9. It can be observed that the strain for failure for both 2 mm and 4 mm thickness specimens in biaxial tests is same and similar observation made for hemispherical test. The strain for failure was predicted through a point when the engineering stress drops with respect to strain and that frame was considered to analyze the failure. It is worth noting that the strain for failure in hemispherical test is higher than the biaxial one. Been set both experiments for the equi-biaixal test why the hemispherical test would provide higher strain for failure. The answer is hidden in Fig. 10 which was taken from this literature [19]. It shows that as the pressure through the thickness increase the forming limit increases. After close observation it can be noted that in the biaxial test the specimen is not in contact with any of the tool but it does in hemispherical dome test. This rigid body (hemispherical punch) is providing the pressure on the specimen which increases its forming limits. Thus in Fig. 9 provides the forming limit curve which was taken from [20] and further shift for annealed material which was considered for this study. This curve later shifted to realize the failure in hemispherical dome test and can be considered as the pressure effect. This phenomenon was not realized earlier because the reference forming limits were considered from the dome test which involves the pressure effect from the solid punch and failure captured in industry was through pressure effect such as solid punch or fluid pressure (in case of hydroforming). Due to the new biaxial test rig this difference needs to investigate to prevent the faulty calculation during die design.

5. Conclusion

In this work to analyze the effect of thickness on the forming limit strain the biaxial test and hemispherical dome test were modeled in ABAQUS simulation software. Two thickness specimens were considered for forming/stretching. The cruciform specimen with diamond thinner section was used for the test. Through both tests the equi-biaxial deformation mode was created and results were analyzed. From the results it was observed that thickness has no effect on the biaxial results, but it does have on the hemispherical dome test. The strain for failure on the arm gets higher with increase in thickness. By comparing biaxial and hemispherical dome test it was found that the stresses on the arm were inline but biaxial samples failed earlier irrespective of specimen thickness, then 2 mm thickness hemispherical specimen and then 4 mm specimen. It is also concluded that the formability of a material is higher as compared to biaxial samples. The reason found was the pressure effect. Due to rigid contact with the specimen in hemispherical dome test the forming limits raised. Thus it is recommended that while performing the forming limit experiment through the biaxial test, the forming limits needs to analyze and applied properly to the process. It is also recommended to analyze the pressure effect in the process and raise the forming limit based on the process. This analysis will provide the best calculation of the process parameter to maximum and efficient use of the material.

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