Forming Limit Diagrams of Perforated St12 Steel Sheets

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Abstract

One of the unique characteristics of sheet metals is their formability, which is determined by the forming limit diagrams. These diagrams specify the maximum deformation limit before part's failure. For several applications of metal sheets, they have to be in the perforated format. Existence of holes in the perforated sheets may adversely deteriorate the forming limit of metal sheets. In this study, the effect of perforated sheets' hole size and hole layout on their formability are investigated. Several specimens of St12 steel with 0.6 mm thickness, different widths, two various hole sizes of 2 and 4 mm, and two layouts of triangular and square were prepared. The specimens were tested using Nakajima test (stretch with a hemispherical punch) to generate the forming limit diagrams. It was observed that both the diameter and layout of the punched holes have a significant effect on the formability of the perforated sheets. The perforated sheets with triangular hole layout showed higher forming limits due to their larger ligament ratios.

1. Introduction

Regardless of the advent of new additive manufacturing methods that uses different formats of material feedstock, such as powder, filament, or paste, the metal sheets have still kept their widespread use in different industries [1][2]. The formability of a metal sheet indicates its effective formability limit [3]. Each material's unique formability should be tested before designing the parts since there is a limit on metal sheet's formability. Such a formability limit inhibits the deployment of arbitrary dimensions in the parts' formed areas [4]. Therefore, it is necessary to use a metric to determine the safe range of deformation values, to the limit of which no failure would occur. The forming limit diagram (FLD), which contains the safe, critical, and failure zones, is such a metric that can be used to describe sheet metal's formability to prevent failure. The FLD is the most popular criterion utilized to forecast the formability of sheet metals and predict the feasibility of success or failure of sheet metal forming operations [5] [6]. The FLD could be determined both theoretically and experimentally using the modified approaches, including applying the ultrasonic vibration on the specimen in the forming process, as introduced in recent years [7] [8] [9]. The most well-known test to experimentally achieve the FLD is an out of plane test (e.g., Nakajima test), in which a sheet metal specimen is fixed between circular die rings and stretched by a hemispherical punch [10]. For a part under deformation, the FLD shows the critical combination of the major and minor strains as a curve, above which the local necking defect (unsafe zone) takes place. The FLD would be plotted according to different strain ratios, from uniaxial compression to equibiaxial tension.

One of the widespread use of metal sheets is in the form of perforated sheets. These sheets can be used in fabrication of beehives and silo ventilations in the food industries, production of metal filters and battery separator plates in the energy sectors, and manufacturing cooling pipes in the automotive industry, to name a few [11]. Preventing the occurrence of defects, such as necking, failure, and shrinkage in the perforated metal sheets is necessary since it keeps the parts' dimensional accuracy unchanged and aesthetically acceptable. Researchers have closely considered the behavior of defects when forming the perforated metal sheets. Chen et al. [12] examined the ductility of perforated sheets with circular holes

created in a triangular arrangement (hexagonal). In Chen's study, the equivalent chain method was implemented to develop a theoretical model, including the definition of a yield criterion and the corresponding rules as the apparent stresses and strains. Baik et al. [13] proposed a metric that could predict the strain limits of the perforated sheet; this metric was calculated based on a model that resulted in a more realistic value of lower formability limit. Their proposed yield criterion can be applied in all ranges of ligament ratios (unperforated gap between holes) and has been validated by finite element analysis. Li and Chen [14] investigated the plastic behavior of the perforated sheets with small values of the ligament ratio and presented a yield criterion which examined the apparent stresses. The efficiency of the proposed yield criterion is obtained by comparing the apparent stresses and strains with the results of finite element analysis. Although various studies have been performed to investigate the formability of perforated sheets, there still exists a lack of knowledge in forming behavior of the perforated metal sheets. Therefore, it is necessary to study the perforated sheets with different dimensions and geometry to determine the best possible formability outcome.

In this study, after preparing samples with different hole sizes as well as various arrangement of holes (made through the specimens), stretching tests were performed with the spherical head punch. The purpose of these experiments is to obtain the FLD for different combinations of hole geometry and hole arrangement. Through investigation of the maximum formability per hole size and hole arrangement on the specimens, the best set of parameters (among the performed tests in this work) for obtaining the best possible formability outcome is determined.

2. Experimental Procedure

2.1. Material and Methods

Following ISO 12004-1 [15], to obtain the FLD, grids with precise dimensions are engraved on the surface of the test specimens and are formed under different strain conditions. After forming operation, the engraved circles turned into ellipses and by measuring the large and small diameters of the ellipses, the major and minor strains were computed. The diameters were measured (with 50 μm accuracy) by image analysis on the taken optical microscope images. The FLD were plotted so that the horizontal axis represents the minor strain values and the vertical axis shows the major strain values.

In this study, the Nakajima test was utilized to determine the FLD. In the Nakajima test, different strain paths can be obtained by pulling specimens with different widths using a hemispherical punch. The forming setup used for performing the experiments is composed of a punch, a matrix, and a sheet holder which is shown in Figure 1 (in the closed state before starting the test). Also, the dimensions of the forming setup are shown in Figure 2. The experiments were performed on a 400 ton universal testing machine at a speed of 10 mm/min [16]. The tests were stopped right after specimens cracking, i.e., when a fall was observed on the force-extension diagram displayed on the machine's screen [17]. The tested samples are made of St12 steel with 0.6 mm thickness due to their widespread use in fabrication of automotive bodies. The mechanical properties of St12 are 170 MPa, 305 MPa, and 30%, for yield

strength, ultimate tensile strength, and elongation, respectively. The holes were made through the sheets by a CNC punching machine.

2.2. Design of Experiments and Sample Preparation

For design of experiments, two factors were considered. One factor was the hole diameter with two levels of 2 and 4 mm. The other factor was the layout of hole locations on the specimens, which has two levels of square and triangular arrangements. As required for the FLD determination, five sample widths were considered for each hole layout. Three replications per sample was also considered for evaluating the results' reproducibility. Therefore, 60 (20x3) samples of rectangular pieces with circular holes of diameter size 2 and 4 mm in square and triangular arrangements were prepared. The length of all samples was constant 80 mm while their width was various at 20, 36, 52, 64, and 80 mm for specimens with 2 mm hole size and 26, 38, 50, 62, and 80 mm for samples with 4 mm hole size. The widths of samples with 2 mm hole size were different than those of 4 mm hole size since a constant margin length from the most corner hole to the sample's edge was considered during the designing step of sample geometries. On the surface of the samples, circular grids with a diameter of 2.5 mm were electrochemically etched so that the deformation of the grids could be traced after formability tests to measure the strains. Figure 3(a) and (b), shows the dimensions of the holes in the square and triangular layouts, respectively. The engraved grid on a sample with a hole diameter of 4 mm is shown in Figure 3(c). Figure 4 shows an instance of a set of prepared specimens to represent the factors of hole diameter and layouts used in this study.

Following the standard instructions, to provide the required lubrication conditions, three pieces of Teflon sheet (with grease in between layers) were applied between the punch and the surface of specimens for each experiment. Figure 5 shows an example of a deformed sheet in the cavity of the used forming setup with the lubricant Teflon layer.

To determine the surface strains, the large and small diameters of ellipses on the surface of the specimens were obtained by measuring the dimensions of the grid ellipses, located beside the cracking area. Then, the strain values were calculated using the equations

$$\varepsilon_1 = \ln \left(1 + \frac{d_1 - d_0}{d_0} \right)$$

1

$$\varepsilon_2 = \ln \left(1 + \frac{d_2 - d_0}{d_0} \right)$$

2

where ε_1 and ε_2 are the major and minor strains, respectively; also, d_1 and d_2 are the large and small diameters of the elliptical grids after deformation; d_0 is the initial diameter of the grid circles before

deformation, which is 2.5 mm.

3. Results And Discussion

3.1. Minor and major strains

Figure 6 illustrates a qualitative comparison for deformed specimens with a hole diameter of 2 mm in both square and triangular layouts, and a comparison for specimens with a diameter of 4 mm in square and triangular layouts is shown in Figure 7.

After obtaining the minor and major strains, the data points per each test should be correspondingly placed on a diagram where the horizontal and vertical axes represent the minor and major strain values, respectively. To obtain an FLD, a curve must be fit through the points to indicate the boundary between the safe and failure zones.

3.2. Obtained FLDs

The resulted FLDs are shown in Figure 8 and 9 for parts with 2 mm holes with square and triangular arrangements, respectively. Also, Figure 10 and 11 shows the FLD of parts with 4 mm hole with square and triangular layouts, respectively. In FLDs, generally, the major strain corresponding to the minor strain of zero (the y-intercept) represents the least amount of formability. Therefore, to compare the formability of specimens with different hole size or layout, the value of y-intercept of FLDs can be looked at. According to Figures 8 and 9, for parts with a diameter of 2 mm, the minimum formability for the triangular layout with major true strain of 0.27 is greater than that of a square layout with major true strain of 0.22, indicating the greater formability of the triangular arrangement.

Also, for parts with 4 mm diameter holes according to Figures 10 and 11, the minimum formability for the triangular arrangement with major true strain of 0.26 is greater than that of a square arrangement with major true strain of 0.12, which follows the results obtained for parts with hole size of 2 mm. Therefore, it can be concluded that the formability of the perforated sheets in triangular layout of holes is higher; this is because the ligament ratio between the holes in triangular layout is larger than that of the square layout.

To compare the effect of diameter size on formability, according to the FLD of square arrangement shown in Figures 8 and 10, the 0.22 minimum strain for a diameter of 2 mm is greater than that of a 4 mm diameter with minimum strain of 0.12. Similarly, for a triangular layout according to Figures 9 and 11, the minimum strain for a diameter of 2 mm (0.27) is greater than the corresponding value for a diameter of 4 mm (0.26). The mentioned cases show more formability of the sheet with a triangular layout and holes with diameter size of 2 mm since the combination of triangular layout and smaller holes created larger ligament ratios.

3.3. Part's Extension at Failure

Another criterion for investigating the formability of samples is by measuring the depth of deformed specimens at the moment of failure (appearance of cracking around the holes), which is commonly referred to as the dome height. The formability of perforated sheets with a diameter of 2 mm was found to be higher than that of perforated specimens with a diameter of 4 mm due to existence of greater amount of bulk material between the 2 mm holes. To avoid interaction of specimens' dimensions when comparing the dome height for different hole diameters and layouts, the specimens' dimensions were kept constant at 80x80 mm, and the force-displacement diagrams of experiments (three replications per sample) were compared as shown in Figure 12; the dome height (extension depth) of the specimen with 4 mm hole in square layout is 6.3 mm and can withstand a force of 110 N at failure while the same specimen with a triangular layout has a dome height of 6.7 mm and endures a force of 130 N at failure. Therefore, the triangular arrangement resulted in higher formability. Also, the sample with a hole diameter of 2 mm in a square layout after formability test shows a dome height of 7.7 mm and can bear a force of 220 N at failure while the same model with a triangular layout has a dome height of 9.5 mm and tolerates a force of 320 N at failure. The jaw of tensile test machine moves a longer distance in the case of triangular layout. Also, by keeping all variables constant, the formability of sheets with 2 mm holes is higher than the sheets with 4 mm holes.

3.4. Analysis of Variance

To evaluate whether the observed formability results are statistically significant different, an ANOVA was run on the results with significance level of 0.05 [18]. As mentioned before, the hole size (2 and 4 mm) and hole layout (square and triangular) were considered as factors and response variables are the observed major strains, the ultimate tensile force at failure, and the extension (dome height) of parts.

Considering the major strains as the response variable, the results were found to be statistically significant different since the P value of ANOVA was found to be less than 0.05 (<0.0001). Also, no interaction was found between the hole size and hole layout although both were found to be significant main effects. Figure 13(a) and (b) shows the least square means plot for hole size and hole layout, respectively, and evaluation of interaction between hole size and hole layout is illustrated in Figure 13(c) where no interaction can be observed (the lines do not intersect). As can be seen in Table 1, a Tukey test was also performed on the results, indicating that all the parameter sets are significantly different where 2 mm hole in triangular layout and 4 mm hole in square layout resulted in the highest and lowest major strain values, respectively. For Tukey test it should be noted that the levels that are not connected by the same letter are significantly different.

Table 1
Results of a Tukey test performed on the major strain values

Level		Least Sq Mean
Triangle,2	A	0.389
Triangle,4	B	0.336
Square,2	C	0.285
Square,4	D	0.191

Considering the specimens' ability to withstand the ultimate tensile force at failure, different samples showed a statistically significant difference in the ANOVA results (P value less than 0.05). No interaction was found between variables (the hole size and the hole layout) as shown in the least square means plot in Figure 14(c) although both variables were found to have significant main effects (Figure 14(a) and (b)). Table 2 shows the results of the Tukey test where the 2 mm hole in triangular layout was found to withstand the highest tensile force at failure (294.7 N) while the 4 mm hole in square layout endures the least force (67.6 N), among other parameter sets. The endurance forces at failure for 2 mm hole in square layout (179.9 N) and 4 mm hole in triangular layout (152.2) were not found to be statistically significant different based on the Tukey test (the same letter B for both parameter sets), meaning that the plastic behavior of these two types of perforated sheets is similar since the 2 mm hole in square layout results in similar ligament ratio as the 4 mm hole in triangular layout. Thus, if the sample preparation cost for these two specimen types (2 mm hole in square layout and 4 mm hole in triangular layout) is different, the cheaper method of part fabrication could be used.

As mentioned earlier, the dome height can be a good metric for assessing the specimen's formability. Running an ANOVA on the dome height of formed parts shows that the results are significantly different (P value=0.0002). As the least squares means plots in Figure 15 show, no interaction was found between the hole size and hole layout, but both were significant main effects. Performing a Tukey test on the dome height (see Table 3) shows similar results to that of the ultimate tensile force at failure, i.e., the 2 mm hole in triangular layout has the highest dome height (12.6 mm) while the 4 mm hole in square layout has the least dome height (5.8 mm), among the rest parameter sets. The dome heights for 2 mm hole in square layout (8.7 mm) and 4 mm hole in triangular layout (9.2) were not found to be statistically significant different based on the Tukey test.

Table 2
Results of a Tukey test performed on the
tensile force at failure

Level		Least Sq Mean
Triangle,2	A	294.772
Square,2	B	179.974
Triangle,4	B	152.269
Square,4	C	67.611

Table 3
Results of a Tukey test performed on the
dome heights

Level		Least Sq Mean
Triangle,2	A	12.678
Triangle,4	B	9.292
Square,2	B	8.709
Square,4	C	5.825

3.4. Investigation of Failure Fractographs

The ruptured surface of the specimens was observed using scanning electron microscopy (SEM). Since the specimen with 2 mm hole in triangular pattern led to the highest formability, the fracture surface at failure of one of its replications is shown as an instance in Figure 16. During the formability test of specimens, the micro-voids would merge to each other and lead to the progress of ductile fracture through crack propagation, creating surface fracture patterns. Having a closer look at the surface patterns in Figure 16, several dimples in various shapes and sizes can be observed. These dimples are features of a ductile fracture; each dimple is attributed to a crack location during the plastic deformation process. By advances of void propagation, the unfractured material is strained until the ultimate fracture occurs [19]. The variation of dimple size is affected by the void's stress threshold and growth rate, which are influenced by the physical characteristics of the microstructural features [20].

4. Conclusion

In this study, the formability of St12 perforated sheets was experimentally investigated. Several specimens with 2 and 4 mm holes in square and triangular layouts were prepared and evaluated using Nakajima test to obtain the FLDs. Using the provided force-displacement diagrams from the tensile testing machine, the dome height (extension depth) of different specimens was examined as another measure of formability. Based on the obtained result, the following conclusion can be made:

1- The perforated sheets in triangular layout showed higher formability than the sheets in square layout due to their larger ligament ratios. of the samples showed that.

2- Based on the values for major strains, the amount of formability of perforated sheets with 2 mm holes is higher than that of sheets with 4 mm holes.

3- In square samples with edge lengths of 80 mm, the sheet with 4 mm holes in triangular layout has a dome height of 6.7 mm, which shows a 6% increase compared to the sheet with a square layout (dome height of 6.3 mm). In the 2 mm diameter perforated sheet, this improvement is around 23% (increase in the dome height from 7.7 mm to 9.5 mm). A similar conclusion can be made for the type of layout (triangular or square).

4- Based on ANOVA results for all considered response variables, it was found that the 2 mm hole in triangular layout has the highest formability due to the largest ligament ratios while the 4 mm hole in square layout has the least formability due to the smallest ligament ratios; no significant difference was found for the rest parameter sets.

Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of data and material

Not applicable

Code availability

Not applicable

References

1. M.H. Sehhat, · Ali Mahdianikhotbesara, Powder spreading in laser-powder bed fusion process, 23 (2021) 89. <https://doi.org/10.1007/s10035-021-01162-x>.
2. B. Behdani, M. Senter, L. Mason, M. Leu, J. Park, Numerical Study on the Temperature-Dependent Viscosity Effect on the Strand Shape in Extrusion-Based Additive Manufacturing, J. Manuf. Mater. Process. 4 (2020) 46. <https://doi.org/10.3390/jmmp4020046>.

3. E.A. Alisaraei, R. Hashemi, D. Rahmatabadi, C. Sommitsch, Experimental study of forming limit diagram and mechanical properties of aluminum foils processed by the accumulative roll bonding, *Mater. Res. Express.* 7 (2020). <https://doi.org/10.1088/2053-1591/abced9>.
4. M.H. Sehhat, A. Mahdianikhotbesara, M. Hadad, Formability Investigation for Perforated Steel Sheets, *SAE MobilityRxiv*, (2021). <https://doi.org/10.47953/SAE-PP-00182>.
5. D. Rahmatabadi, R. Hashemi, Experimental evaluation of forming limit diagram and mechanical properties of nano/ultra-fine grained aluminum strips fabricated by accumulative roll bonding, *Int. J. Mater. Res.* 108 (2017) 1036–1044. <https://doi.org/10.3139/146.111566>.
6. N. Najafizadeh, M. Rajabi, R. Hashemi, S. Amini, A method and apparatus for determination of the ultrasonic-assisted forming limit diagram, *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* (2021) 095440622110115. <https://doi.org/10.1177/09544062211011509>.
7. N. Najafizadeh, M. Rajabi, R. Hashemi, S. Amini, Improved microstructure and mechanical properties of sheet metals in ultrasonic vibration enhanced biaxial stretch forming, 5 (2019) 1–10. <https://doi.org/10.22064/tava.2019.102421.1124>.
8. N. Najafizadeh, M. Rajabi, R. Hashemi, S. Amini, Studying the Effects of Ultrasonic Vibration on Microstructure and Hardness of St14 Steel Sheet, 2018.
9. D. Rahmatabadi, M. Tayyebi, N. Najafizadeh, R. Hashemi, M. Rajabi, The influence of post-annealing and ultrasonic vibration on the formability of multilayered Al5052/MgAZ31B composite, *Mater. Sci. Technol.* (2021) 1–8. <https://doi.org/10.1080/02670836.2020.1867784>.
10. D. Rahmatabadi, R. Hashemi, M. Tayyebi, A. Bayati, Investigation of mechanical properties, formability, and anisotropy of dual phase Mg-7Li-1Zn, *Mater. Res. Express.* 6 (2019). <https://doi.org/10.1088/2053-1591/ab2de6>.
11. Perforated Metal | Custom Perforated Metal | Metalex, (n.d.). <https://metlx.com/products/perforated-metal/> (accessed January 8, 2021).
12. F.K. Chen, Analysis of plastic deformation for sheet metals with circular perforations, *J. Mater. Process. Tech.* 37 (1993) 175–188. [https://doi.org/10.1016/0924-0136\(93\)90089-O](https://doi.org/10.1016/0924-0136(93)90089-O).
13. S.C. Baik, K.H. Oh, D.N. Lee, Forming limit diagram of perforated sheet, *Scr. Metall. Mater.* 33 (1995) 1201–1207. [https://doi.org/10.1016/0956-716X\(95\)00349-Z](https://doi.org/10.1016/0956-716X(95)00349-Z).
14. Y.-C. Lee, F.-K. Chen, Yield criterion for a perforated sheet with a uniform triangular pattern of round holes and a low ligament ratio, n.d.
15. ISO - ISO 12004-2:2008 - Metallic materials – Sheet and strip – Determination of forming-limit curves – Part 2: Determination of forming-limit curves in the laboratory, (n.d.). <https://www.iso.org/standard/43621.html> (accessed March 31, 2021).
16. A. Mahdianikhotbesara, M.H. Sehhat, M. Hadad, Experimental Study on Micro-Friction Stir Welding of Dissimilar Butt Joints Between Al 1050 and Pure Copper, *Metallogr. Microstruct. Anal.* 2021. (2021) 1–16. <https://doi.org/10.1007/S13632-021-00771-5>.
17. M. Soltaninejad, M. Soltaninejad, F.S. K, M.K. Moshizi, V. Sadeghi, P. Jahanbakhsh, Environmental-friendly mortar produced with treated and untreated coal wastes as cement replacement materials,

- Clean Technol. Environ. Policy 2021. 1 (2021) 1–18. <https://doi.org/10.1007/S10098-021-02204-X>.
18. C.H. Hung, W.T. Chen, M.H. Sehhat, M.C. Leu, The effect of laser welding modes on mechanical properties and microstructure of 304L stainless steel parts fabricated by laser-foil-printing additive manufacturing, Int. J. Adv. Manuf. Technol. (2020) 1–11. <https://doi.org/10.1007/s00170-020-06402-7>.
19. A.P. Jirandehi, T.N. Chakherlou, A fatigue crack initiation and growth life estimation method in single-bolted connections, J. Strain Anal. Eng. Des. 54 (2019) 79–94. <https://doi.org/10.1177/0309324719829274>.
20. Fractography: observing, measuring and interpreting fracture structure topography, n.d.

Figures

Figure 1

Used Nakajima forming setup in the closed status before starting the forming operation.

Figure 2

Illustration of the dimensions of the used Nakajima forming setup.

Figure 3

(a) Dimensions of the holes in the square arrangement, (b) Dimensions of the holes in the triangular arrangement, (c) An example of the engraved grid on a specimen with a 4 mm hole.

Figure 4

A set of perforated sheets: (a) 4 mm diameter with triangular layout, (b) 4 mm diameter with square layout, (c) 2 mm diameter with triangular layout, (d) 2 mm diameter with square layout.

Figure 5

The hemispherical punch and lubrication Teflon layer after performing the test (the formed part can be seen in the matrix cavity).

(a)

(b)

Figure 6

A qualitative comparison of formability for samples with a diameter of 2 mm in (a) Square layout, and (b) Triangular layout.

(a)

(b)

Figure 7

A qualitative comparison of formability for samples with a diameter of 4 mm in (a) Square layout, and (b) Triangular layout

Figure 8

FLD of parts with 2 mm hole in square layout

Figure 9

FLD of parts with 2 mm hole in triangular layout

Figure 10

FLD of parts with 4 mm hole in the square layout

Figure 11

FLD of parts with 4 mm hole in the triangular layout

Figure 12

Sample with dimensions of 80 × 80 mm; dome heights for a= 6.3 mm; b=6.7 mm; c=7.7 mm; d=9.5 mm

(a)

(b)

(c)

Figure 13

The results of ANOVA on the major strain values

(a)

(b)

(c)

Figure 14

The results of ANOVA on the ultimate tensile force

(a)

(b)

(c)

Figure 15

The results of ANOVA on the dome heights

Figure 16

The SEM of specimen's fracture surface (2 mm hole in triangular pattern)