Grid Marking and Measurement Methods for Sheet Metal Formability

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Abstract
Several commercially available finite element programs are widely used for sheet metal forming analysis. However, programs may have a different result for the same case. It is essential to verify finite element results by experimental results. Grid marking and measurement is one of the common experimental methods for deformation measurements. In this study, grid marking and measurement methods were discussed in detail and evaluated in terms of measurement accuracy.

Keywords: Grid marking, Grid measurement, Deformation, Sheet Metal

1 INTRODUCTION

The sheet metal forming process is defined as a process of transforming sheet metal into a desired shape without fracture or excessive localized thinning. The process may be simple, such as a bending operation, or a sequence of very complex operations such as stamping [1]. In recent years, considerable effort has been dedicated to the numerical methods capable of modeling sheet metal forming processes. The aim of this effort is to assess die modifications, specify the process variables during production and reduce the die try-out period [2, 3]. Several finite-element software packages are commercially available for sheet metal forming analysis. However, each software program may give a different result for the same case. It is very important to verify finite element results by experimental results. The strain measurement in a deformed sheet metal is needed for measurement comparison. The sheet metal operation is usually considered a plane stress problem due to the thickness being much smaller with respect to other dimensions. For this reason, surface strain measurements are very important in the analysis of sheet metal forming processes. The Forming Limit Diagram (FLD) was also determined from surface strain measurement [3]. The FLD is a graph of the major strain (ε_1) at the onset of localized necking for all values of the minor strain (ε_2), as shown in Figure 1 [4]. Finite element software packages use FLD to evaluate deformation of sheet metal parts. It is quite possible to determine the limiting deformations such as necking and tearing [5].

The principal methods of measuring strain or deformation are grid marking, strain gages, mechanical and optical extensometers, ultrasound thickness and shape measurements. Grid marking is one of the commonly used strain measurement methods for strain analysis in sheet metal forming processes due to the relative simplicity [6]. It consists of a very small diameter circle or square grid pattern (approximately a range from 1 to 8 mm [7]). Grid marking is the process of printing line patterns in the area of interest on the sheet metal blank [8]. The utilized grid pattern should be very precise in order to obtain accurate results from the strain analysis [9]. Strain analysis by grid marking is a practical method, which has been utilized effectively to solve problems in metal forming [10]. This system was first proposed in 1965. For grid marking measurement different measuring techniques are used. These include both manual and automated measurement methods.

When sheet metal is formed, it is subjected to various stresses. These stresses produce non-uniform strains and might lead to wrinkling or fracturing in the formed part [10, 11]. The sheet metal is marked with line patterns such as circles and squares using various methods before the forming process are carried out [10]. The forming process

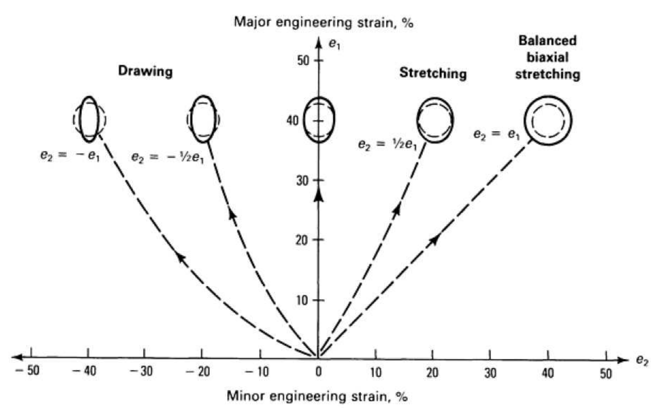


Figure 1: Schematic of several major strain/minor strain combinations in FLD [1]

causes the line patterns to deform by an amount which depends on the local deformation experienced by the sheet metal [5, 6]. After the sheet metal is formed, the circles will become an ellipse unless deformation is pure biaxial stretching as shown in Figure 2. The longest dimension of the ellipse is the major axis and the dimension perpendicular to the major axis is called as the minor axis.

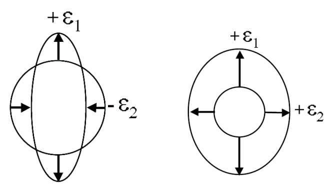


Figure 2: Circles becomes ellipse after deformation

Whereby grid measurements are carried out, strains can be calculated [10]. The grid analysis system supports the development of the Forming Limit Diagram (FLD), which may be used in studying the forming properties of sheets. The measured strains may be compared by a forming limit diagram with FEM to estimate whether a fracture occurs in sheet metal [12]. Figure 3 summarizes the grid marking and measurement procedures. This process is generally followed.

In this research, various grid marking and strain measurement methods were evaluated in terms of accuracy, durability, quality and cost.

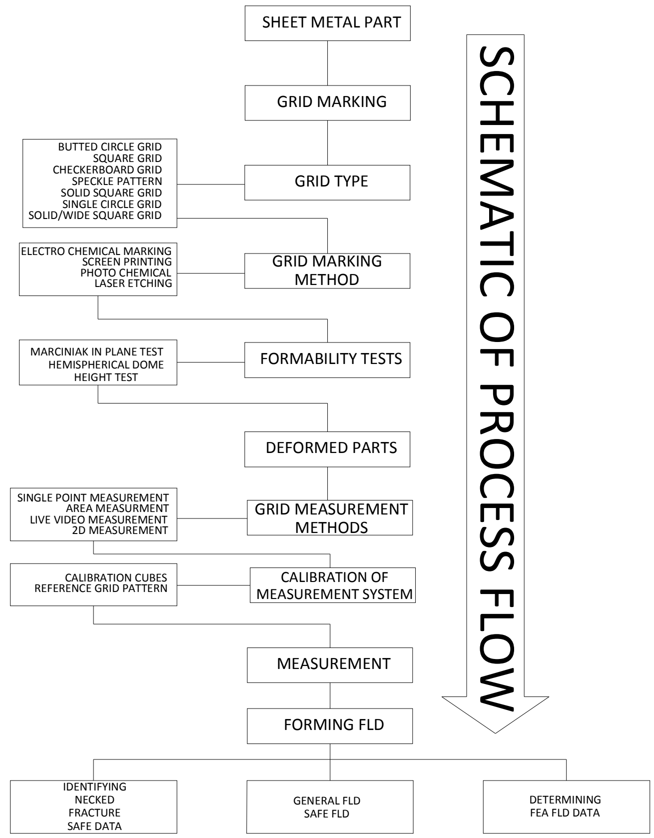


Figure 3: Grid marking and measurement procedures

2 GRID MARKING

2.1 Grid marking methods

Grid marking is the process of printing line patterns on the surface of the area of interest on the sheet metal blank. Some of the methods for marking line patterns on sheet specimens are screen printing, also referred to as serigraph or silk-screen printing, electrochemical etching, photochemical etching, and laser etching. All of these have particular advantages and disadvantages [10]. The applied grid pattern with a selected process must not affect the forming process and must also be able to resist the effects of forming process conditions, such as friction or lubricants. Moreover, it should be possible to apply the marking with as little effort as possible [5]. These methods differ from each other in terms of a pattern’s accuracy, resolution and contrast, durability, quality and cost [6]. Some applicable grid types are shown below in Figure 4 [13].

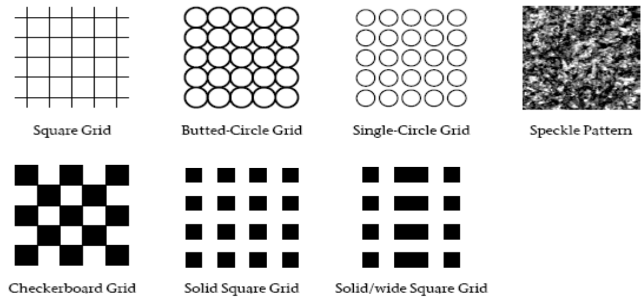


Figure 4: Different types of applicable grids [13]

2.1.1 Electrochemical etching method

Electrochemical etching method, first used to produce grids by R. H. Heyer [2], is one of the most popular methods for grid application to evaluate sheet metal formability because of its ease of application, no cause of distortion on the sheet metal [14], cost effectiveness [11] and durability during forming [12].

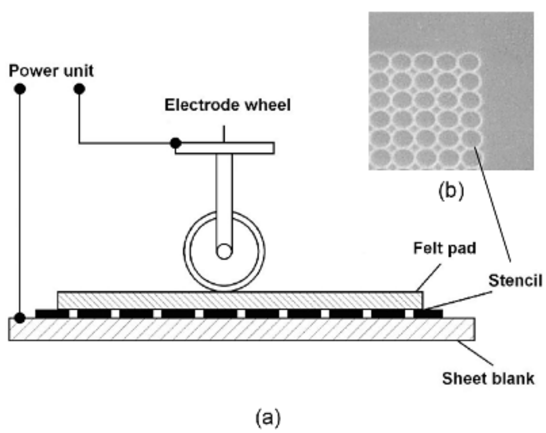


Figure 5: (a) The basic principle of electrochemical etching method [5], (b) example of a stencil

The basic principle of this method is shown in Figure 5. It requires a low voltage power source, stencil, felt pad, and etching solution. First, a power source is attached to the electrode and the blank. The power unit is equipped with an AC/DC switch, depending on the desired grid color. A desired pattern stencil is then carefully placed on the surface of the sheet. The surface of the sheet metal should be cleaned before the stencil is placed [7]. Only the circular ring or square areas of the stencil allow the etching solution to pass through. Afterward, a felt pad, saturated with the proper etching solution is carefully located on this stencil, avoiding wrinkling. There are several types of etching solutions for different materials. It is necessary to choose the correct solution for a particular type of material. The electric voltage is supplied for approximately a period of 5 seconds [15]. A flat or roller type electrode wheel with an attached power source is reciprocated on the felt pad and thus current is passed from the electrode to the blank. The etching solution is pressed out through the contours of the stencil and reaches the surface of the sheet by means of the pressure of the roller wheel. Current varies from 15-200 A depending on the stencil size and the line density. The required time for electrochemical etching is a function of blank material and the applied voltage [12]. The depth of etching is proportional to the time of application [2].

As a result of the voltage placed across the electrode wheel and sheet metal, the pattern of the stencil is etched on to the sheet surface. After etching, the sheet metal should be washed with a neutralizing solution. Thus patterns of different geometrical shapes such as squares or circles can be etched on the sheet rapidly and accurately by the electrochemical marking system [2, 5].

The main advantages of this method are that its application is simple and cost effective, the applied grid patterns are permanent, it does not cause distortion on the sheet metal [14], it does not introduce stress concentrations and the applied grid is durable during forming. In addition, accurate grid patterns can be obtained by using this method. However, this method can only be performed on conductive metals [16]. Nevertheless, it is widely used by the aircraft and defense industries. Required equipment and supplies for electrochemical etching are available commercially [12].

2.1.2 Screen printing method (Serigraphy)

Screen printing is one of the early methods of printing. The method was a technique first used by the Chinese almost 2000 years ago. This method is also known as serigraphy or silk-screening [17] and is one of the easiest and cost effective methods for grid marking [8]. In this method, the grid pattern is printed directly onto the metal sheet using a suitable ink which is resistant to the metal forming process [11]. The method is shown in Figure 6.

Firstly, the area of a screen is tightly stretched over an aluminum support frame that is blocked off with a non-permeable material to form a stencil. The screen material is traditionally made from silk, thus the process is commonly referred to as silk screening. Silk is a very durable material and can be cleaned and re-used. The stencil is negative of the image to be printed. There are a number of ways to prepare the screen to print an image. The basic principle is

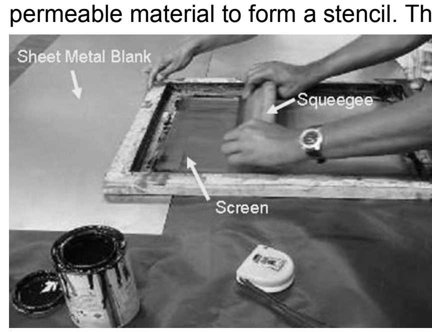


Figure 6: Screen printing process

to make a stencil on the screen which allows ink to be forced through its open areas to produce a design. One of these methods is photo-positive. In this process, the screen is covered on both sides with an emulsion that is sensitive to ultra-violet, UV, light and it is dried in a dark location. The screen is then placed over a desired stencil. Ultra violet light is allowed to react with the emulsion chemical on the screen. After a few minutes the lights are turned off. The UV lights will affect the photo emulsion areas of the screen but not the areas covered by the stencil. The areas that are covered by the photo-positives will remain soft, while the areas exposed to light will harden. The screen is washed out and thereby a desired stencil image is obtained [17]. After the desired image is obtained, the screen is placed over the cleaned surface of the blank. The ink is then poured on one side of the screen and forced through the stencil onto sheet metal with a rubber squeegee. Thus the ink fills in the stencil openings except the blocked-out sections and the desired image appears on the sheet metal [6, 8].

Selection of ink is important as the ink should not be wiped off during forming. In this case, black paint is used for screen printing.

The main advantages of screen printing methods are simplicity, ease of application, cost effectiveness and availability of resources in terms of materials, labor and expertise [8]. Moreover, sheet metals can be easily marked using suitable ink which is resistant to the metal forming process. The screen printed grids resist severe forming conditions. The accuracy of the process is related to the accuracy of the screen made. In general, grid patterns obtained from this method have high accuracy, resolution and contrast. With this method, the grid color can be chosen freely to maximize contrast.

2.1.3 Photochemical etching method

The photochemical etching method is an accurate method of grid marking. In this method, before a UV sensitive photo resist emulsion is applied to the blank, it must be perfectly cleaned. Then, the emulsion is covered with an image of the desired pattern and exposed to strong UV light. The image is developed and displays the desired pattern on the blank [18]. An etchant or paint is then applied to the uncovered metal surface. Different acid solutions can be used for etching according to sheet metal type. After etching the metal surface is cleaned with toluene or trichloroethylene [10]. Fine and sharp grid lines can be printed on the blank in this way. However, etching process must be carefully carried out in consideration of the coating thickness and the holding period in acid. In addition, both sides of the specimen must be coated with emulsion. The main disadvantages of this method are that the painting and cleaning process must be applied for each specimen, the required time to create one grid pattern can be greater than 30 minutes, and the method is applied to relatively small parts [2].

2.1.4 Laser etching method

The circle grid stencil is marked on the metal surface by means of a YAG laser. By using this method, it is possible to remove material in a controlled way. It has the best grid marking accuracy. However, the method can be an extremely slow, depending on the dimensions of the blank [11]. In addition, this method is very expensive and colored grids cannot be obtained by laser grid marking. The limitation of laser grid marking is that the grid is dark colored and thus it is impossible to obtain sufficient contrast between the grid and a dark colored surface without destroying at least the top coating [9].

2.2 Comparison of the grid marking methods

All of these grid marking methods do not change the intrinsic properties of the material and are widely used in different experiments related to surface strain analysis [11]. The grid marking methods have particular advantages and disadvantages and differ from each other in terms of pattern accuracy, resolution and contrast, durability, quality and cost. In selecting the most appropriate methods for a particular application, one must consider the advantages and disadvantages of each method as it may relate to the particular application. The selected grid marking method must not affect the forming process and the grids must not be affected by the forming conditions, such as friction or lubricants. As the strains can be determined by a computerized method, it is essential that grid line intersections are well-defined [9]. A comparative evaluation of the methods, considering the advantages of each, is given in Table 1.

Although the laser etching method is a very slow process depending on the dimensions of the blank, the method is more practical when creating grids on large sheets compared to etching. As the laser etching method is very expensive and colored grids cannot be obtained by this method, in some cases the serigraphy method may be preferred due to advantages such as choice of grid color to maximize contrast, and the availability of resources in terms of materials, labor and expertise. The grid pattern obtained by serigraphy is resistant to a temperature of about 150° C. Although the laser etching method has the best grid marking accuracy, the method is very expensive.

Table 1: Comparison of the grid marking methods

Grid marking method	Parameters								
	Accuracy	Quality, resolution and contrast	Durability	Resistance to friction/lubricants	Resistance to temperature	Applicability of different material	Cost effectiveness	Required time	Applicability of large parts
Electro chemical etching	A	B	A	A	A	D	C	A	C
Screen printing	B	A	A	B	C	A	A	A	C
Photochemical etching	B	B	C	B	C	A	D	D	D
Laser etching	A	A	A	A	A	C	D	D	A

A = Excellent, B = Good, C = Average, D = Poor

Compared to the chemical etching method, the laser etching method is a more accurate, faster and easier method on galvanized and cold rolled surfaces. The trace of the laser is half of the depth and width of that of the chemically etched grid. As such, the laser etched grid gives more reliable results in strain analysis, since the material thickness suffers less than with chemically etched grids. The use of the electro-chemical etching is unsuitable in coil coated materials. In this case, serigraphy method may be used [9].

3 STRAIN MEASUREMENT

Applied grids on the sheet metal should be measured before and after deformation in order to calculate strains. Thus forming limit diagrams can be constructed based on surface strain measurements. In addition, finite element analysis results can be verified by the way of measuring strains on the part which has been modeled in the finite element software [3]. Strain measurement should be within the tolerance of ±2.5 % according to ASTM E2218-02 [19].

3.1 Strain measurement methods

Many measuring techniques have been developed for assessment of surface strain on stamped parts. In many methods, the deformed grid pattern is measured and compared with its original size, and strains may be computed. The strain measurement may be performed manually or automatically.

3.1.1 Manual strain measurement methods

A ruler, divider or Mylar tapes with diverging lines, and traveling microscopes are used for manual strain measurement. An example of the most used manual strain measurement tool is a Mylar tape as shown in Figure 7. The Mylar tape's transparent scale is placed and aligned with an ellipse exactly, and this allows for direct measurement of relative strains. This method is the easiest way to obtain the strain values but its accuracy is not adequate in many cases and is reported to be approximately ± 5 % strain [11]. In addition, this method is slow, labor intensive, and it requires a skilled operator to avoid mistakes. Travelling microscopes are used to obtain better accuracy, but errors can be encountered, and the method is slow.

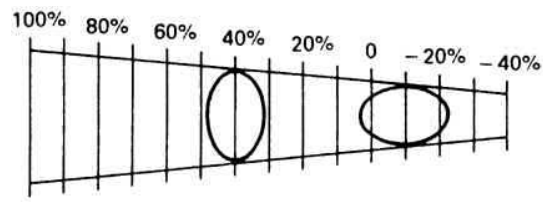


Figure 7: Mylar tape

3.1.2 Automated strain measurement methods

Automated strain measurement methods have been developed in response to the labor intensive and less accurate manual strain measurement methods. More precise and quick measurements can be carried out with the aid of an automated strain measurement method. Some of the commonly used systems are the Automated Strain Analysis and Measurement Environment (ASAME) by ASAME Technology LLC [13], GOM Industrial Measurement Systems by GOM Optical Measuring Techniques [20], FMTI Grid Analyzer by FMTI Systems, and ICASOFT by Digital Image Correlation Software.

GOM optical measurement systems [13] are available for calculation of a deformation zone on sheet metal parts. There are several systems available through GOM: TRITOP (3D Coordinate Measuring Machine), ARAMIS (dynamic 3D strain Measurement), PONTOS (dynamic 3D analysis), and ARGUS (static 3D strain measurement and forming analysis).

When preparing the specimens to be measured using ARAMIS, instead of the circular or line mesh pattern, a stochastic (speckle) pattern is applied to the surface using a color spray (Figure 8).

FMTI's vision-based grid analyzer provides practical and advanced measurement methods for grid analysis. Stress, strain and thickness distribution can be calculated by using known grid patterns which are applied to the sheet surface. Measurement precision of 0.005 true strain or 0.5 % strain engineering units. It is possible to calculate springback, and failure, marginal, safe, index and date tags are stored with data collected by the FMTI Grid Analyzer. This grid analysis system is already in use in the automotive industry like the others [21] The FMTI Grid Analyzer is shown in Figure 9.

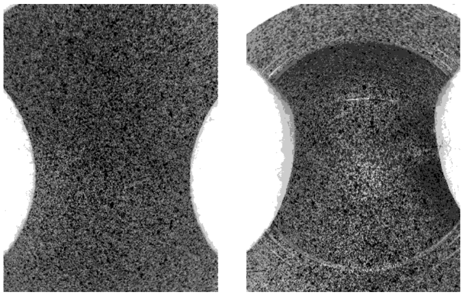
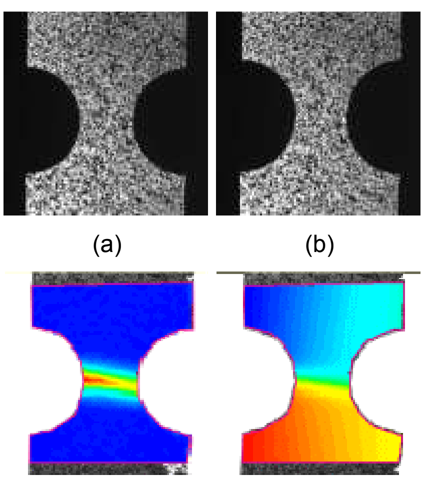


Figure 8: Before and after deformation stochastic pattern

Figure 9: FMTI Grid Analyzer

Icasoft software is designed for 2D measurements and calculations. The basic principle of this software is to compare differences between photos that are taken before deformation and photos that are taken after deformation. In order to measure strain using this method the surface of the object must appear as random as possible and the speckle aspect of the surface must remain the same in the initial and in the final photos. The Icasoft measurement system is shown in Figure 10.



(a) (b)

Strain (c) Displacement (d)

Figure 10: ICASOFT deformation measurement systems.

As shown in figure (a) and (b), the surface of the object was coated by a spray. This speckle pattern is used to compare the deformation zone between the photographs of the undeformed and deformed condition. An area is selected from the surface before deformation. And the software compares the reduction or expansion of this selected surface area. Only two grey level pictures are needed to measure the deformation zone and displacement. These pictures may be acquired using a videorecorder, digital camera, scanner, etc. [22].

ASAME Technology offers two main types of strain measurement systems. One of these is a single point strain analysis system, and the other is a multiple point strain and geometry analysis system [13]. The single point analysis system (GPA; Grid Pattern Analyzer) uses a video camera and software which measures one grid element, such as a circle or square, at a time and computes major and minor strains at the relevant grid (Figure 11).

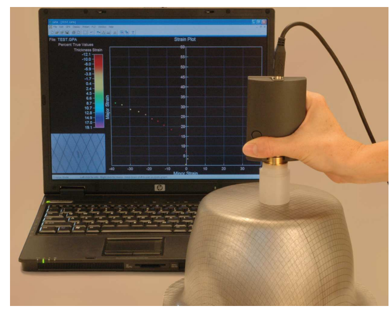


Figure 11: Single point analysis system

The multiple point analysis system measures both surface strains and surface geometry of a large area by the aid of two images which have a geometric relationship to one another. (Figure 12). Advanced image processing software is used to identify and compute the three-dimensional coordinates from two sets of coordinate pairs by establishing the correspondence of individual points in the two views by aid of intersecting points on the grid pattern [3]. There are two types of multiple point analysis systems. These are a position based system and a target based system (ASAME Target Model). The position based system consists of a CCD camera with positioning equipment, a computer and positioning encoders (Figure 13). The part to be measured is placed on a turntable, and then two or more photographs are taken from different angles. The photographs are then processed with ASAME image processing software in order to locate the 2-D grid coordinates. The 3-D coordinates are determined using the 2-D coordinates, camera position, and internal camera parameters such as lens focal length, rotations, and translations. However, the target based system does not require the measurement of the camera position, lens focal length and angle between images. All of these parameters are computed automatically by using a photogrammetric target cube, which is an object of known dimensions with easily identifiable markings. This target cube is placed next to the area to be measured, and photographs are then taken from two or more locations using a digital camera (Figure 14). Each photograph must include the target cube as well as the area to be measured. Then captured photographs are processed using the ASAME software in order to generate the surface geometry and compute major and minor strains [3]. The position based system is no longer used as it requires specially designed hardware and image processing boards which are increase the maintenance costs of such a system. Accuracies of the GPA and ASAME Target Model are denoted as 2 % and 1.5 % respectively [13]. The GPA makes a single measurement much faster than the ASAME Target Model, but the ASAME Target Model measures a large area much faster than the GPA.

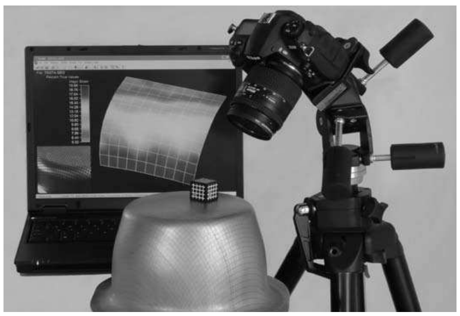


Figure 12: Area analysis system

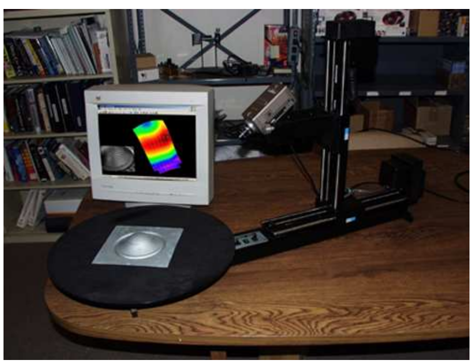


Figure 13: ASAME Table Model (no longer available)

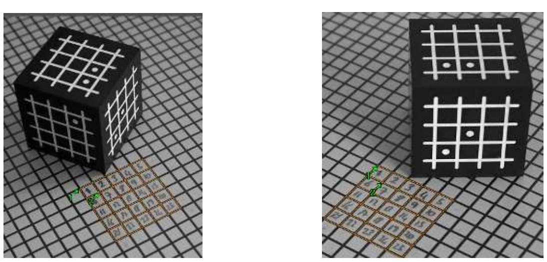


Figure 14: Photographs of 5x5 square grid region taken from two different angles

3.2 Strain measurement accuracy

In this research accuracy of the Mylar tape, the single point analysis system, and the multiple point analysis system measurements were investigated. For determining the accuracies of these measurement systems an undeformed flat sheet was measured, as it is assumed that the actual strains on the flat sheet are zero. Therefore, the deviation of the measured values from zero determines the accuracy of the measurement system. For determining the accuracy of the measurement systems under deformed conditions, a tensile test specimen has been used. The deformed and undeformed specimens were measured by the optical comparator, Mylar tape, GPA, and ASAME. The effect of parameters which influence the target model’s accuracy was also investigated. These parameters are target cube dimension, angle between two photographs, number of photographs, resolution of digital camera and closeness of measurement area to the target cube. In addition the effect of grid shapes to the measurement results was investigated by measuring circle and square grid shapes.

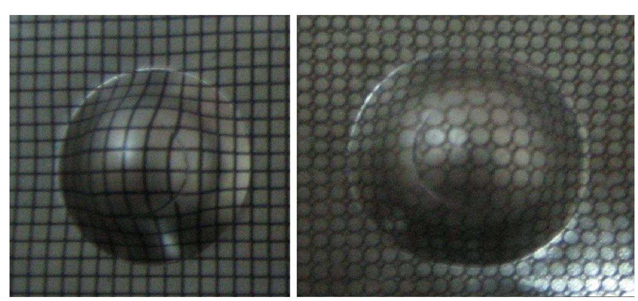
3.3 Durability of grids

Several sheet materials including pure Al, DKP and stainless steel, and titanium were investigated. Grids were applied to the surface of these sheet materials by serigraphy, and gridded samples were tested using the Erichsen test in order to see the durability of the grid on the material.

4 RESULTS AND DISCUSSION

4.1 Accuracy of the applied grid patterns

Laser and photochemical etching methods have not been considered in this study, as these techniques present many disadvantages as mentioned earlier. The serigraphy and electrochemical etching methods were used to apply 2.5 mm square patterns and 2 mm circle grid patterns respectively, and the gridded sheets were formed. The grids obtained from both methods were not damaged. No fracture developed along the grids, which means that the grid did not change or weaken the material properties locally. As shown in Figure 15, it is clear that the grids obtained from serigraphy are more precise compared to the electrochemical etching method.

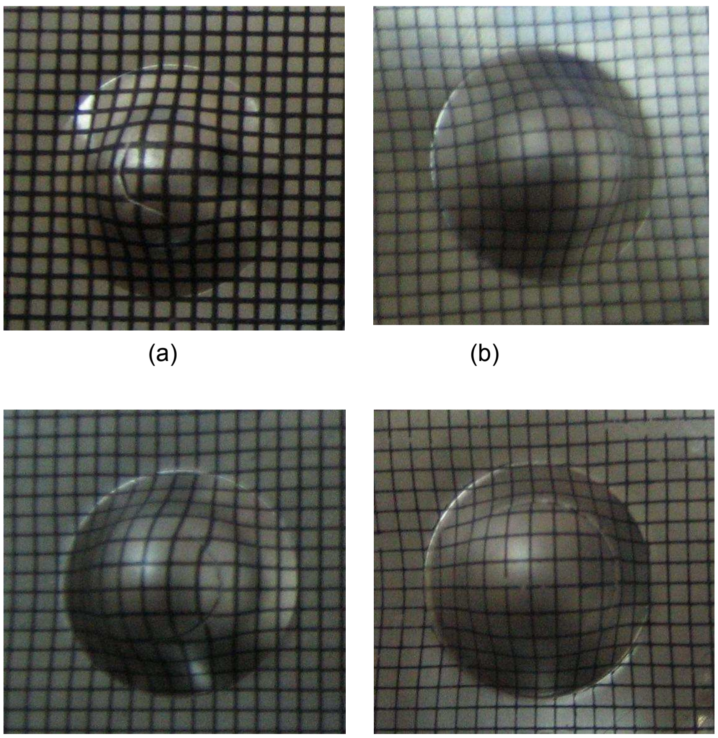


(a) (b)

Figure 15: Comparison of serigraph (a) and electrochemical etching (b)

In order to obtain accurate results from the strain analysis, the applied grid pattern should be very precise. To determine the accuracy of the grids, the dimensions of the obtained grids were measured with an optical comparator with a precision of 0.005 mm. Each measurement was repeated three times. The dimensions of the square grids and the circle grids are respectively 2.507±0.02 mm and 1.999±0.008 mm in the range with 95 % confidence [23].

Durability test results are summarized in Figure 16. Results clearly indicate serigraphy is a very suitable method in terms of durability.



(a) (b)

(c) (d)

Figure 16: Durability of Serigraphy grid by Erichsen test (a) AA 1050 (b) Titanium (c) DKP steel (d) Stainless steel

According to ASTM E2218-02 [19], the length of each side of the square pattern and the diameters of all circles shall be within ± 0.025 mm for 2.50 mm squares, or circle diameters gage length. In other words, the grid must be marked with error that is less than or equal to 1 % to obtain accurate strain measurement results. In the present case, the errors of the square grids and the circle grids are determined as respectively 0.8 % and 0.41 % and are within the acceptable tolerance limit.

In many cases, the serigraphy method is more suitable than chemical etching because it is cost effective and results in an applied grid with clean, sharp lines. However, it is resistant to a temperature of about 150° C. Therefore, the serigraphy method is not suitable in hot forming processes.

4.2 Accuracy of Strain Measurement

Measurement results on the undeformed flat sheets are given in Table 2 for comparison of the measurement systems and different parameters. All of the measurements with the ASAME Target Model were performed for an area of 5x5 grids for the square pattern and 6x6 for the circle pattern, where the area is located close to the target cube. The same regions were also measured with the GPA model. In Table 2, a typical measurement was made with the 25mm target cube and two photographs using an 8 MP resolution digital SLR camera. Each measurement was repeated three times and the confidence is 95 %.

As shown in Table 2, except in the case where the measurement area was located a distance of 80mm from the target cube, all measurements were within the specified tolerance of ±2% accuracy. Strain values may appear as relatively much different from each other. But it is normal in specified tolerances, since the maximum difference of the measured strain value is 1.57 % for the first column. In addition, the applied grids can already be marked with 0.8% error.

When comparing the ASAME Target Model and GPA measurements, the ASAME Target Model is usually more accurate and gives a better repeatability. The accuracy of the measured strains can be defined as the summing of the mean strain and its uncertainty. It is assumed that for the undeformed specimen the true value of strain must be zero. Therefore, the accuracy of strain measurement data obtained were within the range of 0.42 % to 2.22 % for the GPA and within the range of 0.14 % to 0.60 % for the ASAME Target Model. In addition, measurement with the ASAME Target Model is much faster than that with the GPA. Making measurements with the 15 mm target cube instead of the 25 mm did not significantly affect the results. For accurate results, the area to be measured and the target cube should fill the photographs as much as possible. If the target cube and measurement area occupy only a small portion of the photograph, the computation for the position of the target in the photograph will be less accurate. In the ASAME software manual it is noted that using more than two photographs may increase measurement accuracy. But in this work, measurement with three photographs did not significantly affect results. Decreasing photograph resolution from 8 MP to 3.1 MP also did not significantly affect the results. When a measurement performed from an area where there was 80 mm distance to the target cube, the results exceeded the tolerance value.

Table 2: Comparison of measurement results for undeformed flat sheet

		Square Grid		Circle Grid	
		Major Strain (%)	Minor Strain (%)	Major Strain (%)	Minor Strain (%)
Measurement with Mylar tape		Commonly not used		3.3 ± 0.9	
Measurement with GPA		0.42±0.97	0.16±0.26	0.36±0.65	-0.97±1.25
Measurement with ASAME Target Model	typical parameters	0.10±0.16	0.38±0.13	-0.18±0.39	-0.89±0.17
Measurement with ASAME Target Model	15 mm target cube	0.24±0.12	-0.22±0.15	0.23±0.55	-0.38±0.73
Measurement with ASAME Target Model	Lower angle between two photographs	0.65±0.78	-1.28±0.73	-0.35±0.38	-0.69±0.46
Measurement with ASAME Target Model	with three photographs	-0.02±0.12	-0.30±0.29	-0.17±0.29	-0.38±0.22
Measurement with ASAME Target Model	3.1 MP resolution	0.07±0.25	-0.30±0.48	0.45±0.30	-0.40±0.71
Measurement with ASAME Target Model	80 mm distance to target cube	3.55±0.37	-0.39±0.30	4.59±0.31	1.73±0.49

Table 3: Comparison of measurement results for deformed sheet

ASAME		GPA		Mylar Tape		Optic Comparator	
Major Strain (%)	Minor Strain (%)	Major Strain (%)	Minor Strain (%)	Major Strain (%)	Minor Strain (%)	Major Strain (%)	Minor Strain (%)
5.38 ± 0.40	-2.34 ± 0.36	5.91 ± 0.16	-2.15 ± 0.07	4.8 ± 5	-2.4 ± 5	5.37 ± 0.41	-2.13 ± 0.2

Measurements which were performed on a tensile test specimen are presented in Table 3. A single circle grid was measured using ASAME Target Model, GPA, Mylar tape and optic comparator. Each measurement was repeated three times and the confidence is 95 %. The most sensitive measurements can be performed with the optic comparator. For this, other measurement systems results were compared with it. If we assume that the results from the optic comparator are equal to the real value, then when ASAME Target Model and GPA are compared in terms of major strain, the difference between real value with the GPA and the ASAME Target Model results was 0.54% and 0.01% strain respectively. Results of the minor strain measurement are not in the same direction. For the minor strain, the difference between results of the GPA and the ASAME Target Model with real value was 0.02 % and 0.21 % respectively. If the mean values of differences are computed, the ASAME Target Model has 0.11 % and the GPA has 0.28 % strain values as compared to the real value. In this case, the ASAME Target Model has better accuracy than the GPA. The difference of the results from the Mylar tape and the real value was 0.57 % and 0.27 % for major and minor strain respectively. Considering that the Mylar tape method has an uncertainty of 5 %, these results are good.

5 CONCLUSIONS

Grid marking and strain measurement methods used for determination of sheet metal formability were investigated and compared in terms of their usability and accuracy. Electrochemical etching and serigraphy methods for grid marking, and manual and automated strain measurement methods for measuring strain were dealt with and the following results were obtained.

- For grid marking, the serigraphy method is the most convenient because of its ease of application, cost effectiveness, high accuracy, resolution and contrast. The applied grids also resist severe forming conditions.
- However, in the condition where manufacturing temperatures are higher than 150 ºC, such as warm forming, electrochemical etching is more suitable.
- The applied grid patterns were 0.8 % and 0.4 % within error tolerance respectively using these methods. These values are within specified tolerances in ASTM E2218-02.
- Manual strain measurement methods are not convenient because of low accuracy and/or time consumption.
- The ASAME Target Model is a more suitable measurement system from the point of accuracy.
- When measuring a large area, the ASAME Target Model is more convenient, but measuring a single grid is carried out more quickly and easily with the GPA. In addition, the GPA is less expensive than the ASAME Target Model.
- A strain measurement accuracy within the range of 0.42 % to 2.22 % for the GPA and 0.14 % to 0.60 % for the ASAME Target Model was obtained. These values are within specified tolerances in ASTM E2218-02.

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