A portable device for single point strain analysis in sheet metal forming processes

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Abstract

Strain measurement is one of the basic techniques in sheet metal forming for quantifying the deformation of a material under the effects of various loading conditions. The main components in the automatic strain measurement system are the image acquisition hardware and image processing software. This paper presents an automatic single point strain analysis system for sheet metal forming applications. The proposed system is very portable and consists of a USB microscope with different end caps for image acquisition. The software system was developed using Python – OpenCV library and provided with a graphical user interface (GUI).

Specifications table

| Hardware name            | Automatic single point strain measurement system |
|--------------------------|--------------------------------------------------|
| Subject area             | Engineering, Instrumentation                     |
| Hardware type            | Sheet metal surface strain measurement           |
|                          | Manufacturing and Mechanical engineering         |
| Cost of Hardware         | $58.9                                            |
| Open source license      | OSF: [https://doi.org/10.17605/OSF.IO/M85VBGitHub](https://doi.org/10.17605/OSF.IO/M85VBGitHub) |
| Source file repository   | [https://github.com/guru-narayana/GridAnalyser](https://github.com/guru-narayana/GridAnalyser) |
|                          | [https://osf.io/ad2gb](https://osf.io/ad2gb)     |

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Hardware in context

In sheet metal forming, the strain analysis is performed to understand the amount of deformation at different regions of the formed component and potential locations of failure. Two methods are generally used for strain measurement in sheet metal forming operations (i) Single point strain analysis and (ii) Multi-point strain analysis or full-field strain analysis [1]. In single-point strain analysis, a flat sheet is printed with a circular grid with a diameter ranging from 2 mm to 5 mm. When the flat sheet with a grid pattern is deformed to the required shape in the press, the circular grids will be deformed to ellipses of different sizes based on the amount of deformation. The major and minor axis of these ellipses is measured to evaluate the strains at different locations. Since only one grid element is measured at a time, this method is called the single point strain analysis method. Conventionally grid measurements are performed manually, using mylar tape, traveling microscope, or a stereo microscope, which are either time-consuming or of low accuracy (Fig. 1) [2–4]. In the recent past, the image processing technique is gaining much popularity because of its capability to measure gridded surfaces rapidly and accurately [5–9]. Grid Pattern Analyser (GPA) [5] and Forming Measurement Tool Innovations (FMTI) [6] are two commercially available automatic single-point strain analysis systems based on image processing. These systems use machine vision cameras and specialized lenses for image acquisition. The software automatically processes the acquired images, detects the edges of the ellipse, and evaluates the strain.

Multi-point strain measurement systems can measure large areas much faster than single-point strain analysis systems. These systems use the principles of Digital Image Correlation (DIC) for full field strain analysis. In this method, sequences of images are captured from non-deformed sheets with grids or speckle patterns (reference configuration) and deformed components (final configuration). The images of reference and final configurations are correlated to get the strain distribution [10,11]. Few of the organizations, namely, GOM (ARAMIS and ARGUS), Correlated Solutions Inc (VIC-2D and VIC-3D), Dantec Dynamics, and ICASOFT are commercially developing and supplying full field strain measuring systems [12–15]. In recent decades, substantial work has been done to improve the performance of DIC algorithms and define good practices for performing experiments and calibrations. This has led to the development of many open source software for full field strain analysis such as Ncorr [16], ALDIC [17], DICE [18], py2DIC [19], pyDIC [20], µDIC [21], YADIC [22], Multi-DIC [23]. The full-field strain analysis systems have been used extensively in sheet metal forming applications for the construction of forming limit curves [24], calibration of ductile damage models [25], evaluation of material anisotropic parameters [26], and to get the strain distribution in the different forming process [27–28]. Commercial DIC systems are still out of reach for many laboratories and small industries because of their high cost. Recently, some attempts have been made to develop the DIC systems using consumer-grade DSLR cameras [29–33] and raspberry pi single-board computers [23] instead of industrial-grade cameras.

The literature review reveals that some alternative hardware and software options are developed for commercial DIC systems for full-field strain analysis [16,23,34,35]. However, such open-source hardware and software options for single-point strain measurement were not found in the literature [36–39]. Nowadays, researchers are focusing on developing low-cost alternatives to costly commercial systems for various measurements, such as detection of malignant tumor cells, yarn...
parameterization, and exposure measurement in the breathing zone [40–42]. Therefore, an attempt has been made to develop a portable device to acquire the deformed grid images for further processing using the developed in-house software for strain analysis. The developed system has been validated by measuring the elliptical grids of known dimensions.

Hardware description

Existing hardware systems

The commercially available systems use solid-state instrumentation cameras to capture the images. The captured images are then digitized and stored in the memory of a digital computer as a square array of light intensity values. The algorithm is programmed using the Fortran-IV and Macro-11 to determine a gradient-weighted average light intensity and then segmentation to differentiate the pattern from the background. The boundaries are extracted by considering the typical field of view followed by an ellipse fitting [43]. The other systems available for strain measurement include a portable video camera unit that produces an analog video image of one of the ellipse patterns. The hand-held camera unit includes a solid-state camera, light source, light diffuser ring, lens cover tube, nose corner, pistol handgrip, two-position trigger switch, and potentiometer. The external interface device converts the analog image to a binary image and then to a transition point image showing an edge of the pattern. Software available on a digital computer is then used to identify an ellipses inner and outer borders [44]. Finally, the inner and outer edge radii are used to calculate the average major and minor radii for the ellipse center [44]. The commercially available FMTI system used a customized portable camera with a lens and different diameter endcaps containing a lighting system [6]. The manufacturer did not reveal the internal features of the hardware. Similarly, the commercially available GPA system used the 3Com HomeConnect camera with variable diameter endcaps with brass lenses [5].

Design of the end caps

In the current work, a low-cost generic Universal Serial Bus (USB) microscope available online is used as preliminary hardware for image acquisition. This microscope is portable and handy in nature which is embedded with the high definition (HD) color complementary metal oxide semiconductor (CMOS) sensor, high-speed digital signal processing (DSP), 24bit DSP, Resolution 640 × 480, and 8 light emitting diodes (LED) illumination. The USB microscope’s having similarity to a traveling microscope in terms of optical magnification makes it an excellent choice for recording deformed grid images. Moreover, in the ready-made USB microscope, the magnification can be varied from 1X to 1000X using the roller provided on the microscope. The magnification roller consists of 50 divisions, thus making each division 20×. The microscope has a transparent end cap with dimensions of 23 mm in height and 20 mm in opening diameter. However, the given end cap creates significant noise while capturing the images of the grid printed on metal sheets. Hence, as an alternative solution, the overall design of the end cap was modified by changing the diameter, length, and material from transparent to opaque. The end caps were redesigned with modified diameters using the SOLIDWORKS Education 2022–2023 (Dassault Systemes SolidWorks Corporation, Waltham, US) software and pre-processed the output (.stl) file using Eiger 3D software available with Markforged (Mark TwoTM) printer. The printing parameters were kept as nozzle size = 0.2 mm, layer thickness = 0.1 mm, percentage infill = 37 % (line), support structure = line support (default), and print orientation = 0°. Then, the prototype of endcaps was printed with an opaque material, namely Onyx. Table 1 contains the design files of modified end caps. The end caps will maintain a constant distance from the object plane to a camera lens. This fixed distance will help to convert the pixel count into millimeters (mm) directly without repeated calibration for every measurement. The opaque endcaps could efficiently eliminate the noise created due to outside light. But, it was observed that still, considerable noise exists in the captured images due to the inbuilt 8 LED illumination system, which needs to be reduced. After several trials and errors, it was found that the LED system had to be changed. It was observed that when LED was placed at an angle to the object plane, it could reflect the light away from the camera lens, thus reducing the noise.

As it is known, the formed components may have different curvatures, which could be responsible for getting errors in the strain measurement. It can be compensated by using the variable diameter end caps which are designed according to the field of view and depth of field. Fig. 2 shows the principle adopted to set the field of view that corresponds to the magnification and end cap length. The length of the end cap is calculated on the basis of the field of view required (i.e., a diameter of the end cap) using Eq.1. where ‘H’ represents the diameter of the endcap, ‘H’ is the height of the image that fills the entire

| Design file name                          | File type   | Open source license | Location of the file |
|-------------------------------------------|-------------|---------------------|----------------------|
| 5 mm diameter end cap with side light     | .SLDPR,T,STEP | CC0 1.0 Universal   | https://doi.org/10.17605/OSF.IO/M85VB |
| 10 mm diameter end cap with side light    | .SLDPR,T,STEP | CC0 1.0 Universal   | https://doi.org/10.17605/OSF.IO/M85VB |
| 20 mm diameter end cap with side light    | .SLDPR,T,STEP | CC0 1.0 Universal   | https://doi.org/10.17605/OSF.IO/M85VB |
| End caps without side lighting            | .STEP       | CC0 1.0 Universal   | https://doi.org/10.17605/OSF.IO/M85VB |
| Image database                           | .STL        | CC0 1.0 Universal   | https://doi.org/10.17605/OSF.IO/M85VB |
| Demonstration video                      | .mp4        | CC0 1.0 Universal   | https://doi.org/10.17605/OSF.IO/M85VB |
camera’s field of view and is constant. ‘V’ is the distance from the lens to the image, which is 1 to 1000 times the endcap length (U). The distance from the camera to the lens is insignificant, i.e., $V \sim L$. With the help of the magnification ratio ($m$), the corresponding length of the end cap was evaluated.

$$m = \frac{H_2}{H_1} = \frac{V}{U} \Rightarrow U = \left(\frac{V}{H_2}\right)H_1$$

(1)

Fig. 3 shows the systematic flow of removing existing LED rings and assembling the 3D-printed end caps with side lighting. When the microscope is attached with plain end caps, the existing LED lights are used for illumination. In the case of end caps with side lighting, the existing LED ring in the microscope is replaced by a single LED connection attached at the tip of the end caps.

**Software description**

Two different graphical user interfaces (GUI) were developed using the MATLAB and Python platforms. The MATLAB platform was incorporated with two algorithms, namely, Arc support line segment and the Least square method, for fitting an ellipse automatically and semi-automatically, respectively [45,46]. This GUI would work only for the laser engraved grids. Screen-printed grids are detected with the help of GUI developed using Python platform, as shown in Fig. 4. This algorithm processed the image to remove the excess noise captured by hardware. The developed algorithm consists of the Otsu algorithm, Gaussian filtering, and thresholding to detect the edges of an ellipse.

In this work, the modified hardware was used with the python GUI to accurately fit an ellipse along the edges of the deformed circle (ellipse). GUI was provided with the calibration module, where the user needs to calibrate the known dimension circle to convert the pixel dimension into mm. Then the live camera images or saved images can be directly imported to process and fit the ellipse. It has been provided with the advanced settings tab to select the intersecting ellipse, square grid selection, threshold setting, and kernel selection. This tab will be helpful to fine-tune kernel parameters when the ellipse on the captured images does not fit properly. The GUI is provided with a separate noise adjustment slider varying from 1 to 22. By default, the material-specific noise adjustment is provided as an inbuilt feature. The user needs to adjust the noise level to fit the ellipse perfectly if a different material is used apart from standard materials such as steel, copper, and aluminum.
Design files summary

Table 1 contains the design files necessary to build the endcaps of USB microscope.

Bill of materials

The material required to build camera hardware for strain analysis is tabulated in Table 2.

Build instructions

- Take out the default endcap provided by the microscope manufacturer.
- Remove the ring light in the microscope using a soldering machine and desoldering wick.
- Use the multimeter to figure out the polarity of each pin.
- Solder the female jumper wires or 2pin JST cable to the connectors in the microscope.
- Solder the male jumper wires or 2pin JST cable to the 1 W 5 V led.
- Refer to the 1 W 5 V LED datasheet to figure out the Anode and Cathode of the Diode.
- In case the LED is overheating, use the current limiting resistor in series with the LED.
- Resistance in the range of 1 k to 10 k ohm is preferred; further increase in the resistance decreases the brightness significantly.
- Attach the LED to the 3D printed endcap using the epoxy-based transparent adhesive.

Operational instructions

The grid measurement system is specifically developed for research laboratories and small industries working in the field of sheet metal forming. The developed system is user-friendly and affordable. Initially, the user has to screen print the circular grid on the sheet undergoing deformation in any forming process. Care has to be taken that the grid should not be damaged while performing forming operations. The user has to select the proper end cap corresponding to the grid’s maximum deformation and the part’s curvature. For example, if the grid of 3 mm diameter is printed on the aluminum sheet and if it is deformed to an ellipse with a major axis length, say 14 mm, then a 20 mm end cap is the best possible solution for the user to use.

Similarly, the user has to ensure that the endcaps periphery should make full contact with the measured component, i.e., there should not be any gap for accurate measurement. Initially, the user has to open the advanced tab in the software to set the grid type, whether it is intersecting or not. Next, calibration has to be performed by capturing the circle grid of the known dimension using the proposed hardware with the selected end cap attachment and assigning the known dimension to the
The software is provided with two options for image capturing, namely, *live video* and *saved images*. Then, the deformed circle (ellipses) images need to be uploaded and checked for an ellipse fitting. If the edges of the ellipse are not detected automatically, then the user has to change the kernel value, canny threshold range, and noise level till the automatic edge detection is achieved. It will help in converting the pixel dimension of subsequent ellipse measurements into *mm*.

![Fig. 4. Software interface for automatic strain analysis a) Main window b) Advance setting window.](image)

**Table 2**

| Designator               | Number | Cost per unit currency | Total cost | Source of materials | Material type                  |
|--------------------------|--------|------------------------|------------|---------------------|-------------------------------|
| End cap                  | 3      | $4.22                  | $12.66     | 3D printed          | onyx                          |
| LED light                | 1      | $12.80                 | $12.80     | Amazon              | Non-specific                  |
| USB Microscope           | 1      | $24.99                 | $24.99     | Amazon              | Non-specific                  |
| Snap Connectors          | 3      | $2.67                  | $7.99      | Amazon              | Non-specific                  |
| 100 O 1/4 W resistor     | 3      | $0.013                 | $0.038     | Amazon              | Non-specific                  |
| Fevikwik                 | 1      | $0.35                  | $0.35      | Amazon              | epoxy-based transparent adhesive |
detection of the ellipse. By default, the software provided three noise levels corresponding to the three different sheet materials. The software automatically detects the major axis and minor axis dimensions and is capable of converting them into strains. The required data can be saved in the given table by clicking *Add data* button followed by pushing the button *save data* to save the available data in .xls format.

**Validation**

The developed strain measurement system was validated by printing the known dimension ellipses in different orientations on a flat steel sheet. Two types of ellipses were considered i.e. open and filled to inspect the algorithm accuracy of fitting a mean ellipse. Fig. 5 shows the sheet printed with the known dimension ellipses.

The images were captured using the modified hardware and then processed through the developed software. The generated data is tabulated in Table 3.

![Open Ellipses and Filled Ellipses](image)

**Table 3**

| Actual Dimension | Measured Dimension | Deviation in Measured Dimension | Actual Strain | Measured Strain | Deviation in Measured Strain |
|------------------|--------------------|---------------------------------|---------------|-----------------|----------------------------|
| Major axis       | Minor axis         | Major axis                      | Minor axis    | Major           | Minor                       |
| Major axis       | Minor axis         | Major axis                      | Minor axis    | Major           | Minor                       |
| Actual Dimension | Measured Dimension | Deviation in Measured Dimension | Actual Strain | Measured Strain | Deviation in Measured Strain |
| Major axis       | Minor axis         | Major axis                      | Minor axis    | Major           | Minor                       |
| Major axis       | Minor axis         | Major axis                      | Minor axis    | Major           | Minor                       |
| Maximum deviation| 0.4055             | 0.2877                          | 0.1542        | 0.1455          | 0.0089                      |
| Minimum deviation| 0.1542             | 0.1455                          | 0.0089        | 0.0050          |                             |
| Mean deviation   | 0.2877             | 0.1542                          | 0.1455        | 0.0089          |                             |
| Standard deviation| 0.025              | 0.025                           | 0.0050        | 0.0050          |                             |

Fig. 5. Screen printed ellipses with known dimensions for validation.
It was observed that the maximum deviation in strain measurement is in the order of ± 0.01. It can be reduced to a further extent through proper calibration and by using more accurate printing methods such as laser engraving. In the screen printing method, one of the possible reasons for deviation is that the paint spreads along the boundary and makes the contour wavy.

It has been a challenging task to measure the strains near the edges or curved areas. This requires circle diameters in the range of 1 mm or less. Hence, the proposed system was validated for an ellipse dimension ranging from 1 mm to 4 mm. Table 4 shows the deviation in the measured dimension and strains. The average deviation in the measured strain was found

Table 4
Measured dimensions and calculated deviation in screen printed ellipses on a flat sheet with dimensions in the range of 1 mm to 4 mm.

| Actual Dimension | Measured Dimension | Deviation in Measured Dimension | Actual strain | Measured strain | Deviation in Measured Strain |
|------------------|--------------------|---------------------------------|--------------|----------------|-----------------------------|
| Major            | Minor              | Major                           | Minor        | Major          | Minor                       |
| 2.00             | 1.50               | 2.04                            | 1.55         | -0.04          | -0.05                       |
| 1.50             | 1.00               | 1.54                            | 1.05         | -0.04          | -0.05                       |
| 2.50             | 1.50               | 2.49                            | 1.55         | 0.01           | -0.05                       |
| 2.00             | 1.00               | 2.00                            | 1.04         | 0.00           | -0.04                       |
| 2.50             | 2.00               | 2.51                            | 2.01         | -0.01          | -0.01                       |
| 3.50             | 1.50               | 3.47                            | 1.51         | 0.03           | -0.01                       |
| 3.50             | 2.50               | 3.48                            | 2.51         | 0.02           | -0.01                       |
| 3.50             | 3.00               | 3.44                            | 2.96         | 0.06           | 0.04                        |
| 3.00             | 1.00               | 2.93                            | 1.04         | 0.07           | -0.04                       |
| 3.00             | 2.50               | 2.94                            | 2.50         | 0.06           | 0.00                        |
| 3.00             | 2.00               | 3.00                            | 2.01         | 0.00           | -0.01                       |
| 4.00             | 2.00               | 3.99                            | 2.00         | 0.01           | 0.00                        |
| 4.00             | 3.00               | 3.98                            | 2.98         | 0.02           | 0.02                        |

Maximum deviation 0.07 0.04 Maximum deviation 0.24 0.01
Minimum deviation -0.04 -0.05 Minimum deviation -0.026 -0.049
Mean deviation 0.01 -0.02 Mean deviation 0.003 -0.015
Standard deviation 0.03 0.03 Standard deviation 0.014 0.021

Fig. 6. a) Flat sheet with 1 mm diameter screen printed grids and formed component b) Comparison of strain distribution with 3 mm and 1 mm diameter grids.
to be 0.003 and –0.015 for major and minor strains, respectively. Further, the extra deep drawing (EDD) flat sheet was printed with a 1 mm and 3 mm circle grid pattern and deformed into a hemispherical dome shape. The incremental forming experiment was performed on an EDD sheet to form the hemispherical dome. The strains on the formed components with 1 mm grid are compared with those obtained from a 3 mm printed grid pattern as shown in Fig. 6. It was observed that the results obtained from the 1 mm grid and 3 mm grid pattern were identical apart from the number of data points. Hence, it can be concluded that the sheet printed with a 1 mm grid can be used for strain measurement in sheet metal forming, which will give an advantage in measuring the accurate strains in the bending region.

Conclusion

The automatic single-point strain measurement system was developed by modifying the hardware of a low-cost and generic USB microscope camera and user-friendly in-house software. The modified hardware can reduce the unwanted noise generated due to the luster of the metal sheet. The proposed system is capable of measuring the strain according to guidelines provided by the ASTM E2218–02 standard. Similarly, the system is capable of measuring the strains by printing the grid of dimension 1 mm. The system was validated by printing the known dimensions of filled and open ellipses, and the mean absolute deviation in the strain measurement was found to be in the order of ±0.009.

Declaration of Competing Interest

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.

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