A NON-CONTACT OPTICAL UNIAXIAL TENSION-UNLOADING STRAIN MEASUREMENT

Dessie Jemal Ebrahim
PhD student, Institute of Materials Science and Materials Technology, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: dessie.jemal.ebrahim@student.uni-miskolc.hu

Zsolt Lukács
associate professor, Institute of Materials Science and Materials Technology, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: zsolt.lukacs@uni-miskolc.hu

Zoltán Kovács Péter
associate professor, Institute of Materials Science and Materials Technology, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: peter.kovacs@uni-miskolc.hu

Rahmato Abdulhakim Shukurea
PhD student, Institute of Materials Science and Materials Technology, University of Miskolc
3515 Miskolc-Egyetemváros, e-mail: abdulhakim.shukurea.rahmato@student.uni-miskolc.hu

Abstract
A tension-compression test is necessary to investigate the impact of the kinematic hardening model's parameters on the springback following sheet metal stamping processes. However, conventional cyclic testing using extensometers faces challenges due to buckling issues. Therefore, the implementing of Digital Image Correlation (DIC), a non-contact optical measurement system, becomes crucial. The present investigation involved the simultaneous use of an extensometer and an AutoGrid optical strain measurement system to perform a uniaxial tension-unloading test on aluminum alloy AA6082-T6. Both measurement systems were evaluated based on the comparison of the time-displacement, time-force, true stress-true strain, and reduction of Young's modulus due to deformation. The results show that the force, change in displacement, and stress-strain values obtained by the two measurement techniques are comparable and close. It demonstrates that the DIC method has high accuracy and moderate agreement with conventional extensometer.

Keywords: *AA6082-T6 Aluminum alloy, AutoGrid optical strain measurement, Digital Image Correlation, extensometer, tension-unloading test*

1. Introduction

A common optical measurement method in the contemporary metal industry is Digital Image Correlation (DIC), which is full-field, three-dimensional, and non-contact. DIC (Xie et al., 2009; Pan, 2011; Chen et al., 2016) is a potent optical method that is extensively employed in the field of experimental mechanics for full-field displacement and strain measurements. It is typically employed as a post-processing method that has a higher registration accuracy but a high computing cost. In the last few decades, a great deal of study has been conducted. The DIC method's basic idea is to use a correlation function to identify matched regions with exact locations across subsets in both the reference image and the target image, thereby enabling full-field deformation measurements. Numerous studies have been conducted in industry because of the benefits of whole field measuring and non-contact technology.

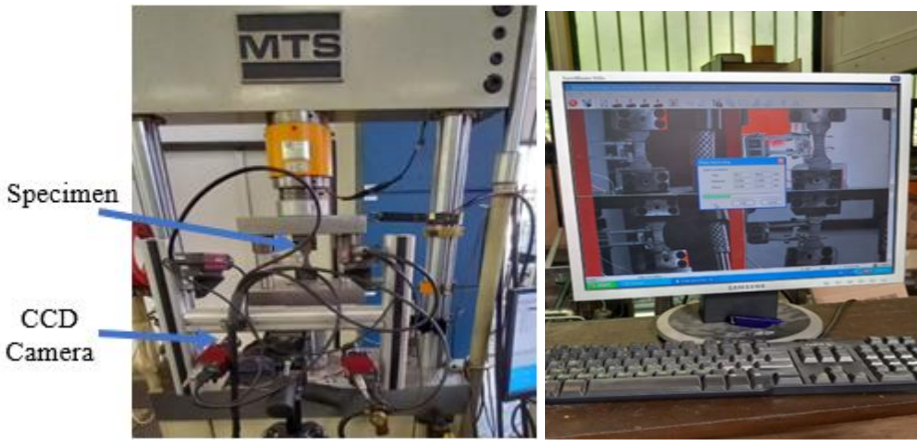
(Chevalier et al., 2001) used the DIC in rubber material testing and analyzing the material's uniaxial and biaxial tensile behavior. In crack growth studies, several researchers have also used the DIC to measure the crack tip open displacement (Sutton et al., 1992). In the cold expansion experiment, the DIC is used to record the variation in stress during the expanding process (Shi et al., 2017). In a cold expansion experiment, the stress surrounding the hole is attempted to be measured using the DIC method. First, a previous test was performed to assess the accuracy of the DIC method. A specimen subjected to a uniaxial tensile load was tested, and the strain was determined using both the DIC and an extensometer. In order to quantify the displacement field on all four surfaces of a tensile specimen with a rectangular cross-section, (Jordan et al., 2023) introduced surround DIC. DIC is a useful technique for measuring cross-sectional area changes in real-time uniaxial tension experiments on metals, and it seems to be especially useful for describing polymeric or foam materials that experience large volume changes. (Li et al., 2018) have proposed a method that enables the direct assessment of the genuine stress-strain curve in the post-necking range. Two stereo DIC systems, or four cameras, were used in the experiment to estimate the cross-sectional area of rectangular tensile specimens in real time. Through both virtual and real-world experiments, (Wang et al., 2015) show that their computational scheme yields accurate estimates of the stress-strain curve for strains up to 1. (Tian et al., 2016) proposes an advanced video extensometer that is real-time, non-contact, and highly accurate for measuring strain on a sample during mechanical testing. The two successive stages of the DIC measuring process image capture and displacement tracking algorithm are innovated to accomplish the goal of real-time, reliable, and high-precision strain measurement utilizing the video extensometer. An advanced video deflectometer for remote, real-time multipoint deflection measurement was created by (Song et al., 2016). DIC was used for measuring dynamic strain by (Wu et al., 2016). With the use of parallel computing, (Shao et al., 2016) were able to achieve real-time 3D deformation monitoring. Notwithstanding these developments, there hasn't yet been a report of a DIC-based video extensometer that measures longitudinal and transversal strains with the notable qualities of real-time, strong robustness, and extremely high precision. Understanding decrease of Young's modules under tension-unloading is important in the field of sheet metal forming operations, particularly with regard to springback phenomena (Dessie et al., 2024). However, the validation and calibration of subsequent kinematic hardening models related to the Bauschinger effect depend on the precise measurement of tension-compression testing. A typical phenomenon with metal materials is the Bauschinger effect, which causes anisotropy in the material's characteristics by reducing the yield strength of the material following pre-stretching and reverse loading (Wang et al., 2013). Extensometers are typically used to detect strain, although problems like buckling can affect how accurate they are, especially when loaded repeatedly. To overcome the limitations of using conventional extensometers during cyclic loading of sheet metal, uniaxial tension-unloading was conducted using AutoGrid non-contact optical measurement techniques simultaneously with extensometer. One cycle tension compression test also conducted with the attached newly developed anti-buckling fixture to MTS universal testing machine to confirm that AutoGrid non-contact optical measurement techniques could be used for cyclic tension compression testing (Ebrahim et al., 2022).

2. Experimental setup

In this study, we conducted a tension-unloading test on aluminum alloy AA6082-T6, a material commonly used in automotive industries. The experiment involved the simultaneous use of conventional extensometer and the AutoGrid optical strain measurement system produced by the ViaLux company. Using four charged-coupled device (CCD) cameras and movable measuring heads, the AutoGrid measuring system tracks the deformation of the grid that was printed using a unique method on the specimen's surface prior to testing. The cameras can measure the grid distortion very precisely because they have already been pre-calibrated. The software that comes with the device supports an automatic evaluation approach that can determine the strains from the measurement of distorted grid 3D coordinates.

A regular, quadratic net is utilized in the AutoGrid optical strain measurement system. The grid that was made prior to the forming process must be able to withstand significant deformation without breaking. There are several known ways to make this kind of grid. We utilized the so-called screen-printing technique, which is popular in the printing business, in our tests (Kovacs et al., 2008). Comprehensive picture presenting options, such as in-process measurement and analysis and multipurpose post-processing, are offered by the AutoGrid system. It's important to note that the software offers a simple way to fix inaccurate or missing measurement points. The post-processing application offers numerous options for evaluating three-dimensional deformation.

It is essential to look into the decline of the apparent elastic modulus in order to correctly forecast the springback in the numerical simulation. Uniaxial tension-unloading tests were selected to accomplish this issue. A tension-unloading test was carried out using a universal material testing machine (MTS 810.23) following the printing of the grid on the specimen and the calibration of CCD cameras. The experiment used a 25 mm extensometer to quantify conventional strain measurement. However, in optical strain measurement, a 20 mm initial length was chosen because all ten 2 × 2 mm square grids were visible during the test period. The experimental setup with CCD cameras and the frame or image capturing using ViaLux is shown in *Figure 1*.



(a) (b)

Figure 1. *Experimental setup: (a) MTS universal testing machine assembled with CCD cameras, (b) frame capturing using ViaLux*

3. Results and discussion

The accuracy of the optical strain measurement approach can be assessed by examining the stress-strain diagram during the tension-unloading test. It is crucial to compare the simultaneously recorded data from the conventional extensometer and the DIC system. A number of parameters, such as time-change in displacement (ΔL), time-force, true stress-true strain, and reduction in Young's modulus due to deformation, were used to evaluate conventional extensometer and optical measurement techniques as shown in *Figure 2*.

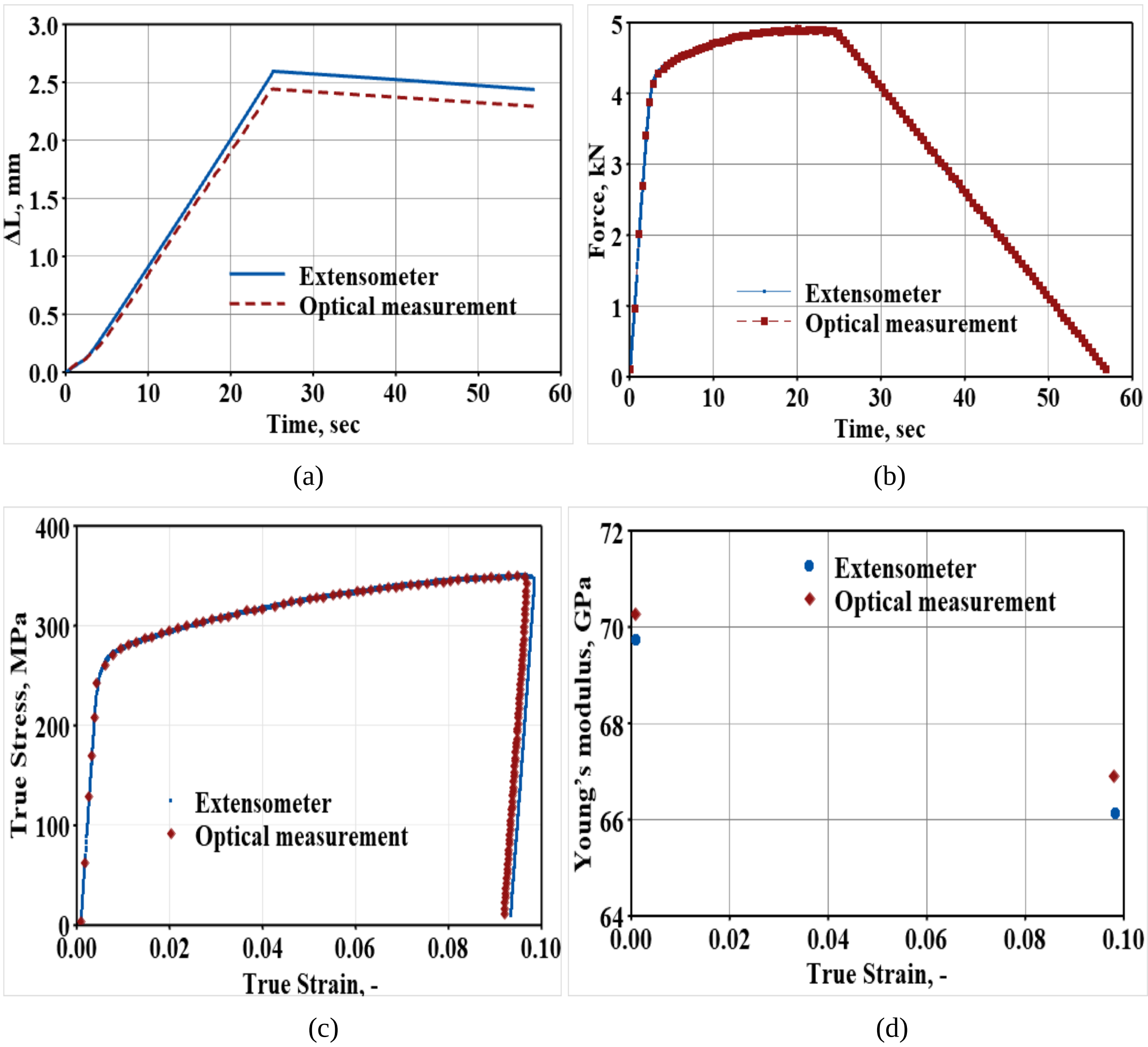
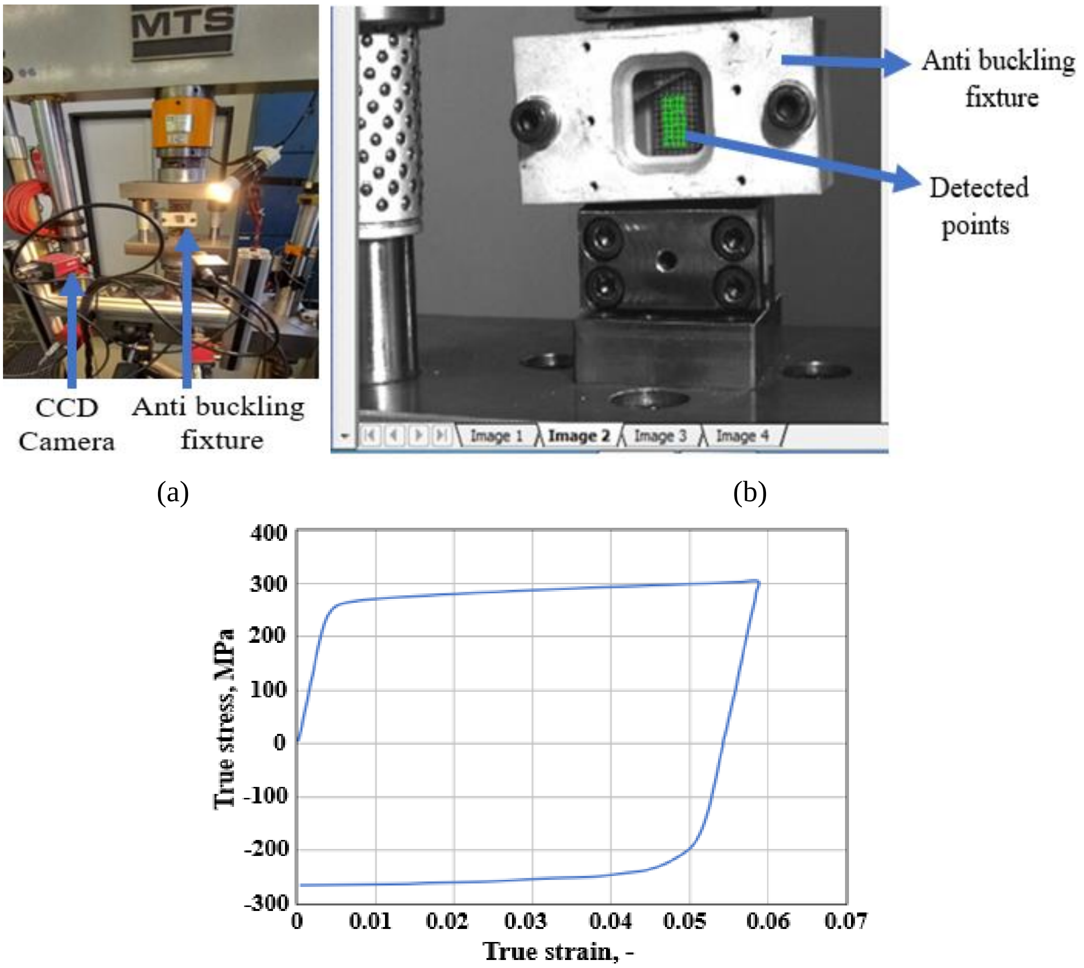


Figure 2. *(a) time-change in displacement curve, (b) time-force curve, (c) true stress-true strain curve, (d) Youngs modules reduction as a function of true strain*

As seen in the *Figure 2(a)*, the investigation revealed a notable discrepancy of 5% in the measurement of displacement change when comparing conventional strain measurement techniques to optical strain measures. This variation, however, was attributed to the changes in the initial length of the test specimen, as previously discussed. The initial length plays a crucial role in the accuracy of displacement measurements, and any alteration can lead to significant differences in the strain results obtained. By recognizing the impact of this factor, it becomes evident that the observed discrepancies were not due to inaccuracies in the optical strain method itself but rather to the variation in the starting conditions of the test setup.



(c)

Figure 3. *(a) Experimental setup with anti-buckling fixture, (b) grid point detection in ViaLux code, (c) single cyclic tension-compression of AA6082-T6 at 6% deformation*

There are also nonsignificant changes observed in the reduction of the Young's modulus as show *Figure 2(d)*. This can be attributed to the inherent complexity involved in accurately determining the Young's modulus, as it is highly sensitive to even the smallest variations or inaccuracies in the working environment. Factors such as temperature fluctuations, imperfections in material preparation, misalignment during testing, and even minor deviations in measurement equipment can all contribute to variations in the calculated values. These environmental and procedural influences make it challenging to precisely assess changes in the Young's modulus, often leading to results that fall within a nonsignificant range.

The comparison showed that the force, displacement change, and stress-strain values produced by the two measuring procedures were similar and showed good agreement. This shows that even under difficult loading circumstances like tension-unloading testing, the DIC approach provides excellent accuracy in measuring strain. Additionally, there were consistent patterns across the two measuring systems in the lowering of Young's modulus owing to deformation, a crucial parameter in the characterization of materials.

As seen in *Figure 3*, a single cycle tension-compression test was also carried out to assess the viability of the AutoGrid optical strain measurement system utilizing a unique anti-buckling fixture made of acrylic materials for transparency. The real stress-strain curve for 6% deformation of the single cyclic tension-compression of AA6082-T6 is displayed in the *Figure 3(c)*. These findings are significant because they enable a more in-depth analysis of the Bauschinger effect and its influence on the kinematic hardening model parameters. The Bauschinger effect, which describes the reduction in yield stress when a material is subjected to reverse loading, plays a critical role in the mechanical behavior of metals during cyclic loading. By analyzing the stress-strain data obtained from the test, researchers can gain deeper insights into the parameters related to the Bauschinger effect that are crucial for accurately modeling kinematic hardening. This includes factors such as the material's softening behavior during load reversals and other complex phenomena that influence the predictive capabilities of the kinematic hardening model. Several parameters in the kinematic hardening model are related to the Bauschinger effect such as transient softening, stagnation ratio, Young's reduction factor, and Young's reduction rate (Han et al., 2018).

4. Conclusion

This study shows that Digital Image Correlation is a reliable non-contact optical measurement method for strain analysis in tension-unloading experiments on aluminum alloy AA6082-T6. The findings show that DIC offers precise and trustworthy strain measurements, making it a competitive substitute for conventional extensometers, particularly in situations where contact-based measurements are difficult to perform. This development has great potential to improve our comprehension and forecast of material behavior in sheet metal forming operations. The AutoGrid optical strain measurement system provides a valuable tool for conducting more detailed examinations of cyclic tension-compression tests, particularly when assessing the behavior of high-strength aluminum alloys. This advanced system enables precise measurement of strain during cyclic loading. One of the key outcomes of this examination is that the optical strain measurement method can accurately determine the kinematic hardening model parameters of the material, which are critical for predicting springback after the stamping process. These parameters are directly connected to the Bauschinger effect, a phenomenon observed in metals where the material exhibits a reduction in Young's modulus when subjected to reverse loading after plastic deformation. Based on the findings of this study, researchers can more accurately predict springback during the stamping process of high-strength aluminum alloys by incorporating the kinematic hardening parameters into their numerical models. Ultimately, this research provides valuable insights that can be directly applied to optimize industrial stamping operations involving high-strength aluminum alloys.

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