Cyclic Tension Compression Testing of AHSS Flat Specimens with Digital Image Correlation System

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Abstract. A cyclic tension-compression testing program was conducted on flat specimens of TPN-W®780 (Three Phase Nano) and DP980 (Dual Phase) Advanced High Strength Steels (AHSS). This experimental method was enabled utilizing an anti-buckling clamping device performed in a test machine, and the surface strains along the thickness edge are measured with a three-dimensional Digital Image Correlation (DIC) system. The in-plane pre-strain and reversed strain values, at specified strain rates, are investigated to observe the potential plastic flow and the nonlinear strain hardening behavior of the materials. The validity of the test results is established with the monotonic tension tests, to substantiate the true stress-strain curves corrected for the frictional and biaxial stresses induced by the clamping device. A process method for analyzing the correction using a macro script is shown to simplify the output of the true stress-strain results for material model calibration. An in progress study to validate the forming and spring-back predictive capabilities of a calibrated TPN-W®780 complex material model to an actual stamping of an automotive component will demonstrate the usefulness of the experimental cyclic test method. Suggestions to improve the testing, strain analysis and calibration of the model parameters are proposed for augmented use of this test method.

Keywords: AHSS, DIC, Tension Compression, Spring-back, Nonlinear Kinematic Hardening, Bauschinger Effect,
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INTRODUCTION

Cyclic tension compression testing of AHSS flat steel has exemplified the characteristic behavior of material tested under non-proportional loading. The nonlinear strain hardening behavior, stagnation and transient Bauschinger effect due to load reversal can be effectively verified with this test method. A comprehensive calibrated plasticity model that considers the hardening behavior and potential plastic flow rule in a multi-axial stress states, will advertently improve the numerical accuracies for spring-back and fracture predictions. This is preceded by a controlled experimental testing, starting with a properly formulated specimen design, development of an anti-buckling clamping device, and precise measurements of the test parameters. An investigative study of the tension compression tests for TPN-W®780 and DP980 sheet materials is conducted at specified strain levels and strain rates with the cyclic test program interfacing with the sensor controller of the Digital Image Correlation (DIC) System and the test machine. The force output signal from the load cell of the test machine is synchronized with the digital images recorded at the specified rate, taken at the thickness gauge length region of the test specimen. The data acquired are post processed to determine the stress-strain curves of two materials tested. Further analysis to correct the biaxial and frictional forces induced by the clamping device is performed to establish the validity of the test datasets with the unclamped monotonic tensile test. The corrected stress strain curves are then used to calibrate the complex plasticity model for numerical predictions using an optimization algorithm. Ways to improve the clamping device to allow a rapid change of test specimens and precise control in preventing buckling during compressive loading cycle are explored to support tension compression testing for wider industrial use.

CONTROLLED EXPERIMENTAL TESTING

Test Systems

The experiments are conducted in a load frame capable of exerting cyclic tensile and compressive loadings of ±100 kN to the clamped test specimen centered in an anti-buckling device. Both ends of the unclamped region of the specimen are gripped by jaws with maximum side forces of 20 kN. One set of the jaws and grips is mounted to a fixed lower gantry and the opposite pair to a movable crosshead that actuates vertically to a maximum stroke of 1000 mm. Variable speed of 0.0005mm/min to 750mm/min can be set to impose quasi-static or dynamic type test conditions. The load cell installed in the test machine provides a ± 10V signal to the sensor controller and data logger unit of the GOM ARAMIS DIC System through a BNC (Bayonet Neill-Concelman) connector and cable. The unit allows the interface of the test machine with the DIC System by synchronizing the control of the force measurements with the images recorded by the two CCD (Charged- Coupled -Device) cameras of up to 15 fps (frames per second) at full resolution. Real time analysis of the computed strain output from the ARAMIS software provides an analog signal at camera frame rate for feedback to the test machine for strain controlled reversal loading.

Test Preparation

In order to attain a large compressive strain range with this test method, preliminary preparation in determining the optimal specimen geometry and the clamping force to suppress the buckling modes have to be formulated. The modes associated are the L- buckling in the unclamped region, T and W buckling in the gauge area. The critical clamping force to mitigate T-buckling can be determined by adopting a formulation procedure given by Cao and Wang [1] to calculate blank holder force and an adaption of the plate buckling theory. The L and W buckling modes can be suppressed by designing an optimal specimen shape based on the secant formula and Euler method illustrated by Boger et al [2]. The flow curve expressed by the Swift model of a uniaxial tensile test can alternatively be framed in terms of maximum strain criterion, and in conjunction with the material's specific stress-strain relationship, the maximum attainable compressive strain for a predefined geometry can be determined before the onset of L or W buckling. Detailed formulations in deriving the specimen geometry and clamping force are given in the references cited above. The optimized specimen geometry for the two steel materials tested as depicted in Figure 1, should be machined to ±0.1mm tolerance limits in the straight edges and ±0.5mm in radii. All sharp edges should be removed and the specimen cleaned before applying the stochastic paint pattern on one side of the thickness edge.

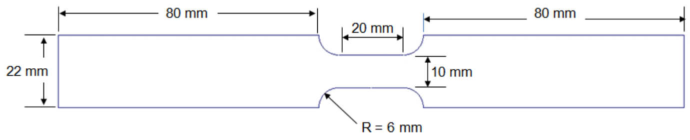


FIGURE 1. Test Specimen Geometry

An anti-buckling device deployed to prevent the T buckling, exerts a constant force to the test specimen sandwiched between two sets of plates held by spring loaded bolts. A similar type of clamping device was also investigated by Bae and Huh [3] at KAIST, and Marcadet and Mohr [4] at MIT. The amount of force per unit area applied onto the contact surfaces of the test specimen is distributed by fastening the bolts to equal specified distances between the holding end plates. The specified compression lengths of the springs were predetermined from the constant spring stiffness to loading forces. In order to minimize the friction between the specimen and the clamping plates, Teflon film of 0.3mm thickness is applied to the contact surfaces. The centering of the test specimen in the anti-buckling device is made with one side of the mating plates flushed with the geometry specimen at the gauge area. This configuration also allows the gauge section area to be more accessible to DIC measurements. Figure 2 shows the test specimen centered in the anti-buckling device with the configured clamping plates.

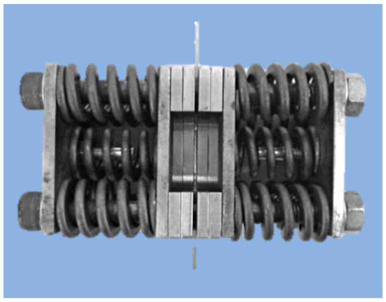
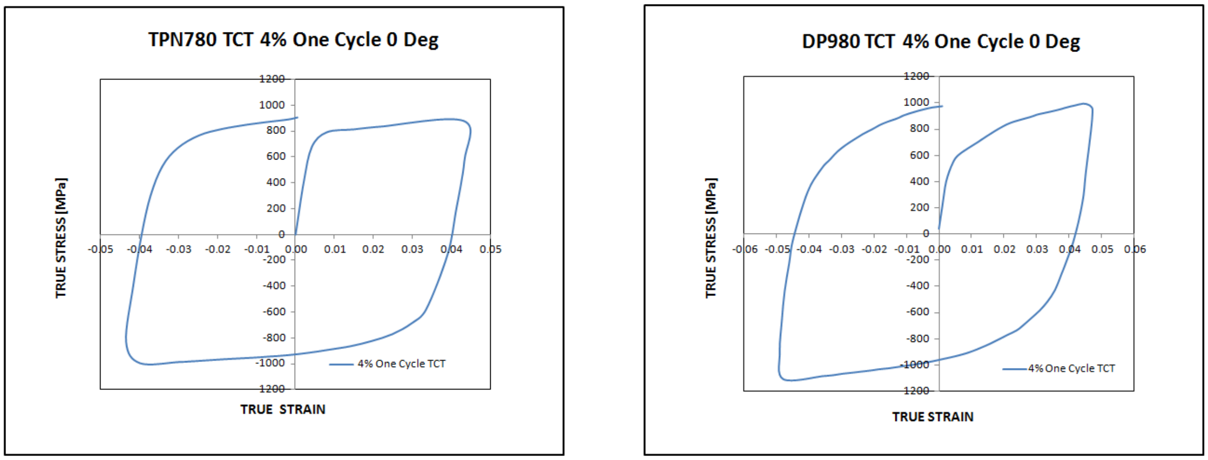


FIGURE 2. Anti-buckling device with centered test specimen

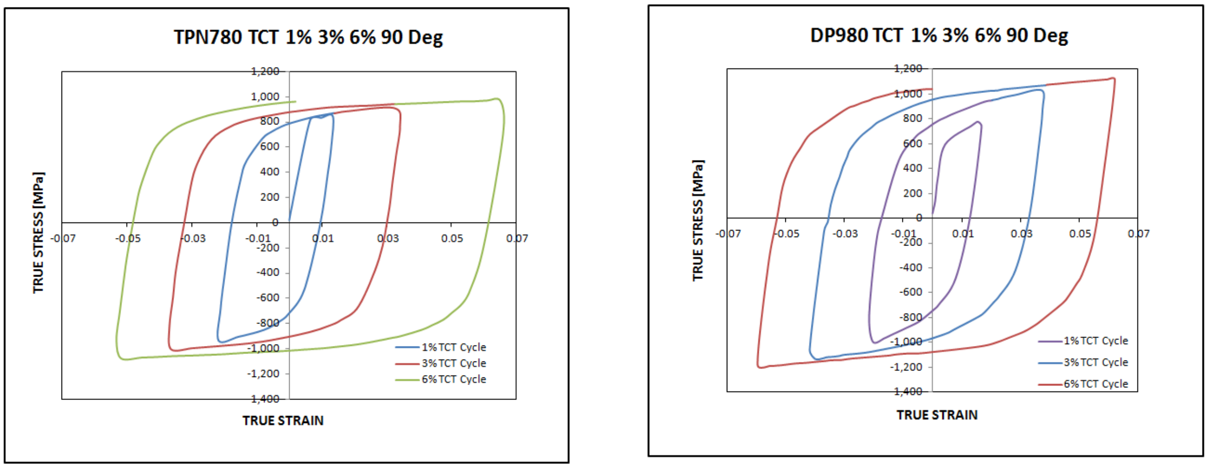
Cyclic Tension Compression Testing

The setup parameters established in a test program define the phase cycles for a given test run. The point of load application to reversal and removal can be conditioned to strain or displacement control at specified speed or strain rate. The test program when invoked initiates the displacement of the crosshead in the test frame. The interface of the load cell with the sensor controller of the DIC system synchronizes the force signal with the computed strain recordings for reverse loadings when specified strain thresholds are reached. Test termination can be auto set to completion of phase cycles with crosshead travel back to initial state. A full one cycle Tension-Compression-Tension (TCT) test , set at ±4% strain levels to load, unload and load again are shown below in Figures 3(a) and (b) for the TPN-W®780 and DP980 in 0 degree or rolling direction test specimens at strain rate of 0.001/s. At similar strain rate, multi-cycles were conducted to predefine strain levels of 1%, 3% and 6% indicated in Figures 4(a) and (b) for the materials tested in the transverse direction.



(a) (b)

FIGURE 3. TCT one cycle test run at 0.001/s to 4% strain (a) TPN780; (b) DP980



(a) (b)

FIGURE 4. TCT multi-cycles test run at 0.001/s to 1%, 3%, 6% strains (a) TPN780; (b) DP980

Process for Force Corrections

The constraining of the test specimen with an anti-buckling device to suppress T-buckling, requires all raw stress-strain data acquired from the cyclic tension compression tests to correct for the frictional and biaxial forces induced by the clamping plates. The measured force recorded by the load cell is the resultant of the frictional and deformation forces accumulated by the test specimen. In order to correct the effects of friction, a monotonic tensile test with and without the clamping device will need to be conducted for each material tested and the curves utilized for comparison study. The actual deformation force of the test specimen is the total force from the load cell minus the frictional force as;

$$\mathbf{F_{deform} = F_{total} - F_{friction}}$$

Where $F_{friction} = \mu F_2$ as represented by Coulomb frictional law. Work done by Balakrishnan [5] estimated the magnitude of the friction coefficient μ, to be in the range of 0.06 -0.09 by measuring the yielding force of identical specimens as a function of the side force, F_2. The friction coefficient will also vary with the surface condition and pressure maintained by the side force acting on the contact surfaces of the test specimen. The deformation stress $\boldsymbol{\sigma_d}$, is derived from the measured total force per specimen cross sectional area subtracted from the frictional stress exerted by the clamping force. The biaxial effect, though small, can be accounted for by calculating the through thickness stress $\boldsymbol{\sigma_t}$ and the von Mises effective stress yield function $\boldsymbol{\bar{\sigma}}$ as;

$$\boldsymbol{\sigma_t = S_t(1 + e_t)} \qquad \boldsymbol{S_t};\ \boldsymbol{e_t} = \text{Engineering Stress \& Strain in thickness}$$

$$\boldsymbol{\bar{\sigma} = \sqrt{\frac{1}{2}[(\sigma_d - \sigma_t)^2 + (\sigma_d)^2 + (\sigma_t)^2]}}$$

A scripted macro [6] to analyze the images and load collected in the DIC software can be modified to correct the frictional and the biaxial effects to output the normalized flow curve of the material tested. The flow curves in Figure 5 compare the supported and unsupported tension test of the DP980 test specimen with the normalized curve after frictional and biaxial force corrections.

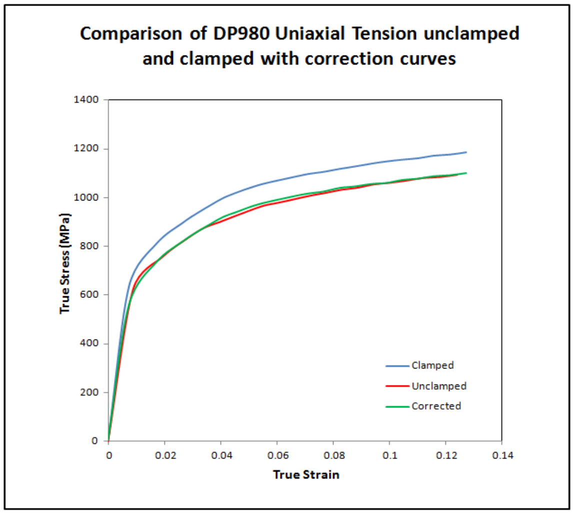


FIGURE 5. Tensile test curves of DP980 with supported, unsupported and corrected for frictional/biaxial forces

Complex Plasticity Models

The true stress-strain curves obtained from the Tension Compression test are further evaluated to calibrate the complex hardening behavior of advanced plasticity models that consider nonlinear kinematic hardening, transient Bauschinger effect with load reversal and permanent softening or stagnation. Models that can closely describe the phenomenological sheet material behavior under multi-axial stresses and take account its history, will advertently improve the numerical accuracies for forming, spring-back and fracture predictions. However, the significant numbers of material parameters in the constitutive models to be determined from experimental mechanisms have considerable drawbacks without a procedural method to calibrate them. The application of a scripted analysis algorithm in MATLAB or an optimization module, coupled with a Finite Element (FE) code, can be automated to calibrate the model parameters in an iterative and repeatable manner. The procedural calibration process can be performed in three main steps:

1) Experimental data input of stress-strain curves from uniaxial tensile and tension compression cyclic tests
2) Perform a series of single element simulations to optimize the chosen plasticity model parameters that minimize the error between experimental results and simulated responses
3) Deliver the identified material parameter results in the format of the selected FE material input card.

This process can be repeated for any number of materials in a way that ensures consistent and systematic calibration.

A structural validation study is in progress to correlate the actual stamping of the TPN-W®780 automotive part with the forming and spring-back predictions using the complex hardening rule of the Yoshida-Uemori advanced plasticity model. The reported results will account for the accuracy of the cyclic tension compression test method to calibrate this advanced complex material model and its predictive capability.

DISCUSSION AND CONCLUSIONS

The cyclic testing of flat AHSS specimens was accomplished with an optimal designed test specimen geometry and clamping device to prevent buckling during compressive loading. The feasibility of this test method to characterize the material behavior was illustrated with good alignment of the corrected constrained and unconstrained flow curves in the monotonic tests. The measuring scheme utilizing 3D DIC system to compute the in-plane surface strains in the thickness gauge section is robust in acquiring two directional strains, and provides synchronization for load reversal to preset strain thresholds. The scripted macro running in the DIC software to post process the experimental data is configured to generate the required flow curves for model calibration. A procedural method to perform the calibration process is proposed to deliver systematic and consistent results. An improvement of this testing technique to enable rapid change of test specimens would be to apply piezoelectric hydraulic clamps that can regulate the biaxial forces to suppress buckling, and mechanism for auto alignment to the central axis of the test frame. The wider acceptance of the cyclic tension compression test method to enhance material characterization for Advanced High Strength Steels will ultimately lead to an industry standard for formability testing.

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