Theoretical and experimental study of bistable symmetric shells built by locally nanostructuring an isotropic plate

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Abstract. A new bistable symmetric isotropic shell is proposed and studied by using nano-technique, surface mechanical attrition treatment (SMAT), to locally treat a rectangular region within a plate. Plastic deformations accumulate in the treated region with the impacts from randomly fast moving balls during the process. The impacts also induce nanotwins and mesh the grains of the material into nanoscales, which largely increase the elastic deformation ability of the processed plate. With sufficient plastic deformations accumulated and stretching the plate under the constraint from the untreated region, the induced residual stress field buckles the plate to hold two different stable configurations and, thus, the bistable characteristic is generated for the nanostructured plate. A numerical model is developed to predict the stable configurations with verification by experiments. The parameters to design the stable configurations of the bistable shells are systematically discussed experimentally and numerically.

1. Introduction

Bistable shells are promising for adaptive structures. The unique ability to hold a deformed configuration by inherent mechanical properties, instead of external input energies or support, has inspired various manufacturing methods to obtain bistable shells.

Two orthotropic moments, formed from thermal effect with the mismatch of the thermal expansion coefficients in two principal directions of unsymmetric composite plates, are likely to deform the plates to curve in two directions in the cooling process. However, the coupling between in-plane stretching and bending deformations constrains the composite plates to hold cylindrical configurations [1-5]. When the ratio of the energy stored in the nonlinear geometric deformation is large enough, which involves dimensions of the plates and the formed curvatures [6] or the stimulating stress [7], the manufactured shells hold two cylindrical stable configurations which curve in two orthotropic directions, instead of a saddle configuration curving in two directions simultaneously. Theoretically, the saddle configuration becomes an unstable equilibrium state for the bistable shells. Usually the stable configurations of bistable unsymmetric composite shells are uniformly curved except limited regions at edges [8], and the
curvatures are determined by the thermal strains. To modify the curvatures in the stable configurations, the unsymmetric composite plate is proposed to set on cylindrical molds in the curing process [9,10]. Furthermore, hybrid composite shells with metal plates embedded within the unsymmetric composite shells are proposed and manufactured [11]. To obtain bistable shells with non-uniform curvatures, bistable shells with a piecewise variation of lay-up in the planform are developed [12–15]. Even a tow-steering technique is used to weaken the sudden change of the in-plane lay-up [16]. As the composite materials are sensitive to temperature and moisture, the stable configurations of the developed unsymmetric composite shells are influenced by the environment [8,17,18].

Bistable shells with two stable configurations curving in one side are built by curing anti-symmetric composite plates in cylindrical molds slowly [19,20]. No thermal residual stress is left within the obtained shell in the initial state. A beam model by assuming cylindrical cross sections in stable configurations [21] and a shell model by further considering short boundary layers at edges [22] are used to predict the bistable behavior, which are quite complicated. Then a simple analytical model using two geometrical parameters is proposed and explicit results for the condition to obtain bistable cylindrical shells are provided, which can also be used to predict the second stable configuration [23]. The studies show that the made-up anti-symmetrical cylindrical shells can hold the second stable configuration when the coupling stiffness of the bending deformations in two directions and the twisting stiffness are large enough. And cylindrical isotropic bistable shells cannot be obtained through this manufacturing method.

Here, a new bistable shell with two symmetric stable configurations is proposed and theoretically investigated, which is obtained by locally treating isotropic plates with nanotechnology, SMAT. As the SMAT manufacturing process can be fully controlled, the stable configurations of the developed shells can be conveniently designed.

2. Bistable symmetric shells

SMAT uses small balls that randomly impact metallic material surface in high speed to induce nanotwins and mesh grains into nanoscales [24–27] with the setup schematically shown in figure 1. The processed material get nanocrystallized on surface [24]. Gradient plastic deformation is accumulated along the transverse direction and the size of the grains changes from a few nanometers on the surface to hundreds of nanometers in the sublayers. The changed microstructure largely increases the yield strength and elastic behaviour range of the material. To develop bistable shells, thin 304 stainless steel plates are locally treated with the SMAT process on both surfaces by turns in a rectangular region. Plastic deformation accumulates in the treated region little by little in-plane stretching the plate, but the untreated region constrains the in-plane expansion and the treated region goes into an impressive state. When the accumulated plastic deformation is large enough, compressive stresses within the processed region buckle the plate in two directions and enable the developed shell to hold two stable configurations.

![Figure 1. Schematic illustration of SMAT setup](image)

In this study, commercial 304 stainless steel plates of 270×50×0.46 mm³ dimension are used in the experiment. Adhesive tapes are stuck onto two surfaces of the rectangular plates to form rectangular SMAT regions, as shown in figure 2. Then the plates are processed using the small balls moving in high
speed to impact both surfaces in random directions. The fast moving balls impacting outside the protected region are decelerated by the adhesive tapes and part of the kinematic energy is absorbed by the adhesive tapes. Limited part of the kinematic energy is transferred into the plate via an elastic deformation. No indentation is caused on the protected metallic surfaces. The impacts from the fast moving balls on the unprotected region transfer most of the kinematic energy into the plate, which is mainly absorbed via a plastic deformation. Due to the limited size of the SMAT chamber, the plates are processed with a segmented treatment. The plates are first processed on one surface separated into several segments and then treated on another surface, as shown in figure 2. The deflections along x-axis in the stable configuration of the developed shells are measured by using Form Talysurf PGI, which is designed to measure the roughness of the surface with an accuracy measurable in nanometers for deflections, with the probe passing the middle line of the plate, as shown in figure 3. As the stable configurations are symmetric, deflections of only one half of a shell are measured. The surface of the SMAT region becomes less smooth with the indentations left by the small balls, which is clearly shown in figure 3.

Figure 2. Bistable shells with a rectangular SMAT region in different sizes. (a) The initial plates with adhesive tapes on the untreated region; (b) Geometry of the SMAT region; (c) The developed bistable shells using SMAT.

Figure 3. Deflections along x-axis in stable configurations of the developed shells measured by Form Talysurf PGI.

3. Numerical model to predict stable configurations
Numerical simulation using commercial software, ABAQUS, is selected to predict the stable configurations. The SMAT process can be entirely numerically simulated with every impact using existing plastic constitutional models with the measured parameters, including velocities and moving directions of the balls, the height of the chamber and so on. Also the effect of the meshed grains to the
mechanical properties of the material can be considered by including related items in the constitutional model. However, this numerical simulation is cumbersome and time consuming as there are tens of thousands of random impacts in the SMAT process, which is not applicable to the design of the bistable shells from the proposed method.

As the plates are processed with SMAT on both sides by turns, the induced plastic deformation should be transversely symmetric, which can be replaced by an equivalent uniform one. The general solid and shell elements in ABAQUS can be used for the numerical model by simplifying the SMAT process via an equivalent uniform plastic strain field. Furthermore, as only an elastic deformation is involved in transitions between two stable configurations and the Young’s modulus of the material after the nanocrystallization process remain invariable, a simple elastic constitutional model rather than a complicated plastic constitutional model with many parameters is selected. The equivalent uniform plastic strain field is applied via a permanent uniform thermal strain field with

\[ \epsilon_p = \epsilon_t \] (1)

where \( \epsilon_t \) is the value of the applied isotropic thermal strain in the numerical simulation. With the above simplifications, the numerical simulation becomes applicable to predicting the stable configurations of the bistable shells from the proposed method.

In the numerical model, all displacements at the center of the plate are fixed except the transverse one, which is fixed at the four corners. The uniform thermal strain field is applied in the SMAT region via an increased temperature and S4R shell elements are used. The Poisson ratio of 304 stainless steel is \( \mu = 0.29 \) and the Young’s modulus is \( E = 192 \text{GPa} \). In fact, the Young’s modulus has no influence on the results from the numerical simulation. However, the Young’s modulus of the plate has a very important effect on the induced plastic deformations which is explained in the following section.

4. Results and discussions

4.1. Equivalent uniform plastic strain and stable configurations

Currently there is no method that can be applied to determine the accumulated plastic strains induced in the SMAT process along the transverse direction. Theoretically, the accumulated plastic strains increase with the treatment time. The equivalent average plastic strain value \( \epsilon_p \) is determined by comparing the maximum deflections of a plate from the experiments with the theoretical results. To determine \( \epsilon_p \) for the equivalent uniform plastic strain field induced in the SMAT process on both surfaces of the plate with \( t = 0.46 \text{mm} \) for 420s, the deflection at the center of the plate with a SMAT region of the dimensions 80\( \times \)20 mm\(^2\) is recorded with the applied \( \epsilon_p \) from the numerical simulation, as shown in figure 4. The deflections in two stable configurations at the center of the developed bistable are 16.85 mm and 16.59 mm. The corresponding uniform plastic strain is \( \epsilon_p = 2450 \times 10^{-6} \) as shown in figure 4. The stable configurations and their deflections along x-axis of the developed shell from the experiment and numerical model are compared in figures. 5 and 6. As the two stable configurations are symmetric to each other, the two deflections from the numerical simulation are the same and the results for one stable configuration are shown in figure 6. The numerical simulation gives good predictions for the shape of the stable configurations of the developed bistable shell. Owing to the segment treatment, the plastic deformation induced in the process is not very in-plane uniform, so the deflections of the developed bistable shell are not smooth in the nanostructured region.
Figure 4. Deflections at shell center with respect to applied equivalent uniform plastic strain $\varepsilon_p$ in the numerical simulation.

Figure 5. Two stable configurations of the developed shell. (a) The manufactured shell with SMAT process for 420s; (b) The predicted stable configurations from the numerical simulations.

Figure 6. Experimental and numerical deflections along x-axis in two stable configurations of the developed bistable shell.
4.2. SMAT region
The processed region has a significant effect on the stable configurations of the developed shells. When the nanostructured region is too small, the processed plate may still hold a monostable flat configuration. On the other hand, when the processed region is too large, such as the plate is fully nanostructured, the processed plate may also hold a monostable flat configuration. The bistability of the developed shell is caused by the accumulated plastic deformation stretching the plate under the constraint from the untreated region. A too small processed region does not offer enough stimulation and a too small untreated region does not offer enough constraint. The deflections along x-axis in stable configurations of the developed bistable shells with different processed regions are shown in figure 7 with results from the numerical simulation. The deflections first increase with the increase of the SMAT region and then decrease with further increasing. The deflections of the developed bistable shells are influenced by the segment treatment and are quite sensitive to the processed region when most of the plate surface is nanostructured. The deflections of the developed bistable shell in figure 7(d) are considerably smaller than the predicted values. In fact, it is found that the half width $L_y$ of the actual processed region in the shell is about 0.4 mm larger than the designed one which decreases the deflections. The above results indicate that the stable configurations can be controlled by the nanostructured region.

5. Conclusion
Nanotechnology, SMAT, is used to develop bistable shells by treating flat plates locally. The accumulated plastic deformation stretches the plate in the treated region under the constraint from the untreated region, which results in compressive stresses and leads to buckling of the plate in two directions, and enables the developed shell to hold two stable configurations. A simple numerical model is developed to predict the stable configurations and study different parameters related to the stable configurations. The results indicate that the deflections in the stable configurations do not always increase with the increase of the ratio of the SMAT region. A proper SMAT region can lead to maximum deflections in stable configurations. An equivalent uniform strain field is utilized to replace the theoretically transversely symmetric plastic strain field. And the average plastic strain value is determined by comparing the maximum deflections from the experiments with the numerical results. The developed numerical model can be used to guide the design of the bistable shells.

![Figure 7](image)

**Figure 7.** Deflections along x-axis in the stable configurations of the bistable shells with the SMAT region with $L_y$=0.02m and (a) $L_x$=0.06m; (b) $L_x$=0.10m; (c) $L_x$=0.12m and (d) $L_x$=0.135m.
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