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Mechanical memory metal: a novel material for developing morphing engineering structures

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This paper describes a profiled metallic sheet with discrete, self-locking modes of deformation, which can be curved, flattened or asymmetrical. This behaviour is achieved by depressing dimples on its surface, and is completely reversible. The governing mechanism depends on the interaction between residual stresses and non-linear deformation coupled to the orientation of each dimple, resulting in complex distortions; we predict these changes in shape using a straightforward computational model, which will expedite the design of novel morphing structures.

Keywords: Ageing; Copper alloys; Buckling; Finite element analysis; Simulation

Reconfigurable structures offer reasonably large, securable and recoverable departures in shape, in order to meet changing environmental constraints or operational demands. They enable well-known deployable technologies, as found in household items such as umbrellas, and in foldable solar panels and antennae on spacecraft [1], and are being proposed for emergent technologies such as morphing aircraft [2]. Common examples achieve high displacements from structural mechanisms by a relative rigid-body motion between parts; rigidity must be imparted afterwards through pre-stressing elements, or by embedding actuators and/or lockable hinges, all of which increase the complexity and cost. Simpler examples are found in a class of continuously deformable elastic structures that offer a bi-stable reconfigurable action, whereby the interplay between geometrical change and stress-relief leads to a self-locking deformed state. It is well-known that spherical caps of the correct initial height can be turned inside-out [3], and, more recently, a range of cylindrical shells can be configured into a second cylindrical mode, either by pre-stressing [4], as in a child's "flick-bracelet", or by selecting favourable material properties [5]. These structures represent, however, exceptional solutions using a traditional form to which there have been no further developments that display the same simplicity and robustness of response.

In this paper, we introduce a novel shell structure with multiple self-equilibrating states, separated by repeatable and relatively large distortions, which is manufactured in a very straightforward way. This reconfigurability is achieved by first forming a regular pattern of bi-stable dimples in a thin, flat metallic sheet. Each dimple can be inverted and reverted by hand in a snap-through buckling fashion, effecting a particular but localised distortion. All dimples act cooperatively to produce a uniquely distorted sheet, depending on the combination of depressed dimples. Since each shape is exactly recoverable, the distortions are "remembered" and there is a digital memory-like response in the bending performance. Benefitting technologies are exciting diverse, and range from aircraft structures with adaptive aerodynamical capabilities under variable geometry jet-engine inlet nacelles and exit nozzles and/or shape-changing wings, to compliant low-impact shells that can be repaired remotely in hazardous conditions, to three-dimensional discrete manipulators.

The performance can be observed in Figure 1 for a square sheet made from age-hardened copper beryllium. The dimples are created by gently indenting the sheet in a successive manner, to yield a 5-by-5 regular square array. Two different, stand-alone configurations are shown. If all dimples are depressed in the same sense, the sheet becomes cylindrically curved about an axis parallel to either one of its diagonals, depending on

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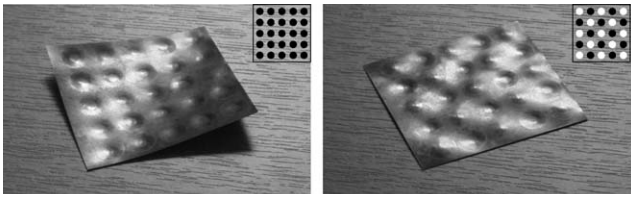

Figure 1. Two configurations of a dimpled 50 mm-by-50 mm copper-beryllium sheet. The top-right legend indicates the orientation of each dimple within the array, black (concave) or white (convex). Note the dimpled pattern is doubly symmetric, and the centre of dimples lie at the corners for repeating square cells. Left: all dimples are concave; right: adjacent dimples along any row and column are in opposite directions.

how the sheet is handled. When the direction of dimples alternates uniformly, the sheet is predominantly flat overall with the appearance of a chessboard. A better sense of reconfigurability is gleaned from a much longer strip-like specimen, indicated in Figure 2. Inverting a thin, central band of dimples produces a highly defined crease, connected on either side by straight, cylindrical parts. If all dimples are pushed through, the strip becomes cylindrically curved, as for the earlier square array, but in a helical mode. It is observed that the axis of curving is perpendicular to the lines of greatest distance between the dimple centres, or the so-called least-packing directions. On closer inspection, clusters of dimples in the long strip have been indented on the vertices of repeating hexagons around a central dimple, and hence, there are three least-packing directions here, of which one is parallel to the axis of helical curving. It can be verified for the square array that there are two such directions, aligned to either diagonal.

For obvious reasons of refinement, further development and practical application, we aim to understand this unique behaviour. The approach, however, is not trivial, for the deformation exhibits a clear hierarchical dependency involving each dimple, its interaction with other dimples, both adjacent and removed, and the free edges. This complex interaction coupled to the discrete nature of operation renders seemingly appropriate analytical methods, such as homogenisation techniques [6], not immediately useful. Alternatively, we resort to computational simulation for provisional insight but first, we review the behaviour of a single dimple.

A dimple is formed by punching a rod with a rounded end against a flat sheet using a hammer. For consistent dimple properties across the sheet, it is initially clamped between two thick steel plates with collocated holes conforming to the array pattern. Accordingly, the sheet can be indented from both sides by the rod, to remove any bias in residual forming stresses, so that each dimple has, roughly, the same bi-directional properties. The clamping plates are removed after dimpling, and the sheet becomes immediately curved in the manner described above.

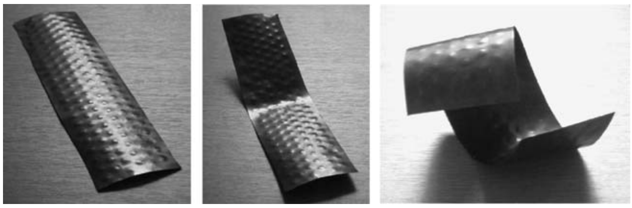

Figure 2. A long dimpled 65 mm-by-240 mm sheet in which the dimples repeat locally in a hexagonal manner. Left: all dimples point upwards, leading to a cylindrical curving about the long edges; middle: some dimples are pushed through in the centre, to render a creased intermediate configuration; right: all dimples are inverted, and the sheet coils around another imaginary cylinder.

In an earlier study [7], the author developed a finite element model of the manufacture and operation of a single dimple using the commercial software, ABAQUS [8]. Proper attention is paid to modelling the interaction between the punching rod and the sheet by means of a full contact algorithm with finite sliding and to capturing realistic residual stresses by defining a fully plastic material response with isotropic hardening. Axi-symmetry is employed to reduce the level of computational effort, and adequately captures the formation of a circular dimple but it is not sufficient when the interaction between dimples across the interstitial regions needs proper attention. An approximation is obtained by extending the sheet to form an annulus region around the dimple, which is perfectly restrained to model the effect of clamping. Parallel insight to the interaction between actual dimples after removal of the clamping plates is obtained if the boundary conditions are then properly arranged. Along lines, which bi-sect the interstices, the in-plane displacements must observe a periodic behaviour. For the finite element model, this represents a uniform contraction or expansion on the outermost edge; but since the sheet is very thin, transverse bending displacements are the dominant deformation, and thus, the radial displacements can be set to zero on the outermost edge, for convenience. Despite this crudeness, the model shows that subsequent dimple inversion attains a second, self-locking configuration only if the initial punching depth lies within certain limits as observed in practice [7]: if the dimple is too shallow, there is no lockable inversion; if too deep, the dimple crumples and collapses, with no repeatable behaviour. Therefore, we can be assured that the model reasonably predicts the general features of residual stresses left behind after punching; furthermore, this model usefully quantifies their effect upon the shape of dimple after removal of the clamping plates but before inversion is assessed, specifically:

- around the outermost edge, a normal compressive force persists, which tends to increase the height of the dimple;
- the annulus region beyond the dimple is held flat by a circumferential moment during clamping, which acts in the opposite sense to the dimple curvature and, when it disappears, the dimple undergoes further upwards curving;
- general levels of elastic radial and hoop-wise stresses decrease as the dimple relaxes but do not evaporate altogether due to residual plastic stresses.

Using this information, we may conjecture that, when a dimple is formed within an array and then the clamping plates are removed, it foists a localised, axi-symmetrical curving of the material around it, and in the same direction as the curvature of the dimple itself: any stress-relief following relaxation of all dimples is balanced by an uptake of strain energy in the now-curved interstitial regions. To verify matters for a truly three-dimensional structure would demand substantial sophistication and computational effort, if all dimples were indented and relieved by the same process; a single cell model might provide better insight with some computational savings, but the interaction with other dimples must be surmised. A quicker approach, however, is to render localised curving by another agency, for example, by direct heating. It is well known that bi-metallic structures curve when the ambient temperature increases, to ensure a compatibility of displacements between layers under differential expansion. Within a finite element analysis, curving is more simply obtained by prescribing a temperature difference through the thickness of an ordinary material. Therefore, spots of material are locally heated in the same manner, and repeatedly so over the entire sheet in the same pattern as the array whilst non-dimpled regions are not heated. In addition, reversing the temperature difference across a given spot is tantamount to inverting a dimple in practice, for it overturns the direction of heat-induced curvature. As a final embellishment, the interaction between in-plane stresses and bending is guaranteed by the finite element analysis solving for non-linear and large displacements.

Some results are presented in Figure 3 for a number of configurations of the same 5-by-5 array from before. The sheet is a 30-by-30 element mesh of quadratic shell elements, each with eight nodes and five degrees-of-freedom per node. The heated spots are comprised of square patches of nine elements rather than being circular, for it leads to a simpler mesh detail when the temperature can only be specified on the element nodes, and it appears not have a detrimental effect on the response. Since we are interested only in capturing the profile of displaced shapes, the temperature gradient through the sheet is increased from zero -or decreased for inverted dimples- up to a nominal value at which displacements are found to be similar to experiments. The initial geometry is slightly skewed, as in the actual specimen, although the side-lengths differ from each other by less than 1%. Importantly, one of the patches always has slightly less thermal activation, to reflect any slight deviation in dimple geometry and effectiveness in practice.

Six cases are shown in Figure 3 and are exceptionally similar to the actual shapes. First, all dimples are set to be unidirectional, leading to a cylindrical mode. Even though it has been noted that bending about either diagonal is preferred, the underlying physical reasons for this preference are not known. Without any form of imperfection, however, spherical rather cylindrical bending occurs; thus, the presence of imperfections initiates a switch into a different curving mode at some thermal gradient, and is similar to the bifurcation in modes experienced by circular and elliptical disks [9,10] heated over their entire surfaces where, interestingly, the axis of curving is proven to be indeterminate. It has been found in a separate study here that curving about either of the diagonal directions is always adopted, for any small perturbation of the peripheral shape or thermal profile across the sheet.

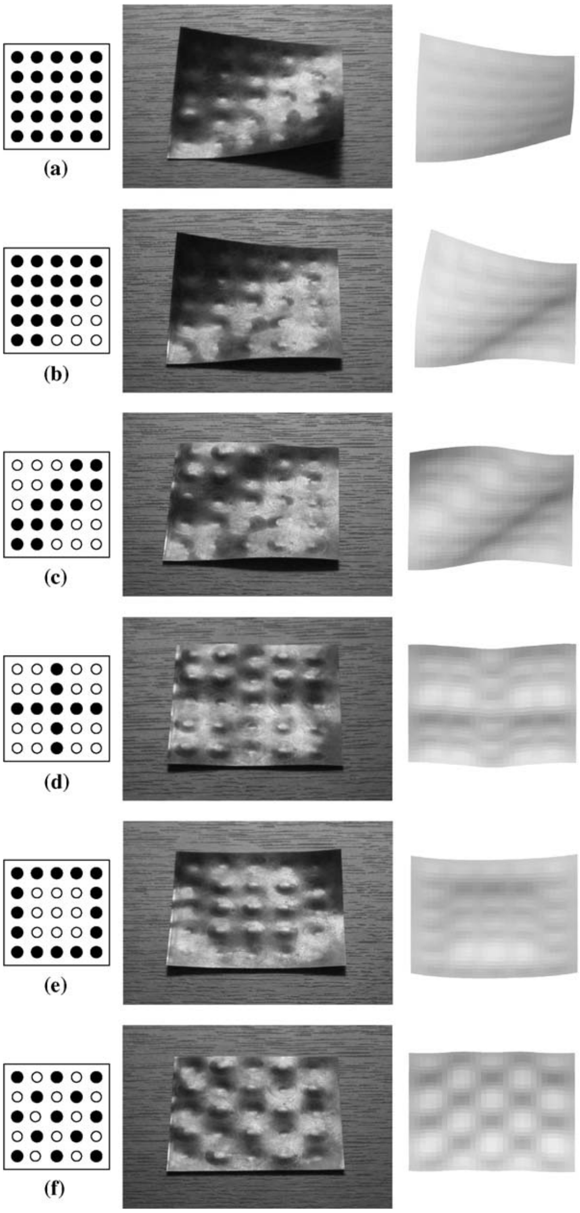

Figure 3. Distortions of the original square sheet of Figure 1 formally compared to a finite element analysis, which simulates the effects of dimpling and inversion by localised heating in a flat sheet. Each row of sub-figures pertains to a unique orientation, and displays in columns, first, the schematic dimpled orientation (black, concave; white, convex), second, the actual sheet, third, the same view from a finite element analysis. Note the excellent correlation between figures for overall distortion and local detail, including the edge profiles. For the second and third columns, note also that the light source directions are different; for the finite element analysis, a lighter surface is higher than the surrounding material. Shadows are deliberately retained in the experiments, for a greater contrast.

In the second case, a triangular portion of dimples is inverted, forming oppositely disposed cylindrical surfaces with parallel axes. These features, along with the narrow transition region, are clearly visible in the simulated shape. When another cluster of dimples is inverted towards the opposite corner, in the third case, three alternating cylindrical regions are formed, despite their small widths, to render a wave-like shape. The shapes

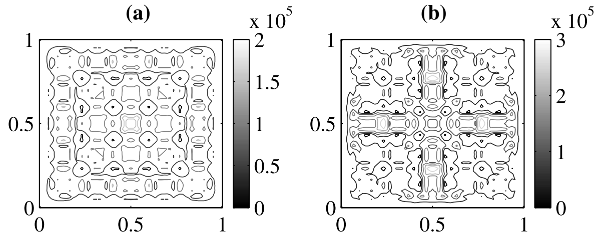

Figure 4. Contours of strain energy density per unit volume of sheet [Pa/m^3] for two cases from Figure 3. The left-hand sub-figure simulates unidirectional dimples and the right equates to the fourth case where a "cruciform" of inverted dimples appears within the contour pattern. The maximum thermal gradient in both cases is set to be the same at 2×10^6 K/m, and the axes of both plots refer to normalised horizontal and vertical coordinates within each sheet.

in both cases can be achieved without imperfections since the thermal (dimpled) profile is naturally asymmetric.

The fourth and fifth cases attest to symmetrical but localised clusters of dimples bounded by lines of inverted dimples parallel to the edges. Again, the results are not imperfection sensitive, so long as the imperfections remain small, and the prediction of displacements is very good everywhere. In the final case of alternating dimples, any curving effects tend to be nullified in an overall sense, as might be expected from elementary averaging of the symmetrical and doubly-periodic thermal profile.

We may conclude that the finite element analysis is effective in predicting the general form of displaced shapes, although the demonstration here has been largely qualitative. The efficacy of the thermal analogue depends on its ability to capture well the performance of a single dimple and, above all, the interaction between dimples, for this determines the deformed profile and, commensurately, the structural characteristics of overall stiffness and stability. For example, the two sub-figures in Figure 4 illustrate the variations of strain energy density (per unit volume) in two of the previous cases for the same degree of heating, where the simulated dimple arrays are respectively unidirectional and an inverted cruciform. In both cases, the interaction between heated (dimpled) and unheated (flat) portions manifests as rapidly changing contours in close proximity between them; but the absolute levels are amplified in the second case, where there are neighbouring regions of sheet heated in opposite senses – for inverted dimples side-by-side. While the dimple patterns and orientations are evident within the contours, the correlation with displaced shape and stiffness is not so obvious, and will form an essential part of future study. It is clear that co-operative same-sense dimples afford the greatest overall displacements, for they offer the least elastic resistance to the natural curving induced by heating. Conversely, neighbouring opposite-sense dimples introduce displacement constraints due to antagonistic curving, thereby elevating stored energy levels. These conjectures are complemented generally by the data in Table 1, which computes the total strain energy stored in each of the six previous cases under isothermal conditions: and as the number of antagonistic dimples rises, so do the overall levels of stored energy.

Table 1. Comparison between the total strain energies stored in each of the cases in Figure 3 in order from top (a) to bottom (f)

Case from Figure 3	(a)	(b)	(c)	(d)	(e)	(f)
Specific stored energy	1	1.065	1.037	1.173	1.234	1.222

The unidirectional case has a total energy of approximately 0.074 Pa but it is set to be the standard case with a specific stored energy of unity; all other cases are measured relative to this case for the same thermal gradient (= 2×10^6 K/m).

This paper set out to present the unique performance of a multi-stable, reconfigurable metallic sheet with embedded dimples and to develop a credible method for elucidating individual shapes. In doing so, we have reviewed an earlier computational model for the operation of a single dimple. Its manufacture produces residual stresses that force extra curving, and in the surrounding interstices – and in the opposite sense if the dimple is inverted. The displaced shape overall derives from the interaction of the potential for curving of each dimple and the need for a compatibility of displacements with neighbouring dimples. Another computational model simulates these competing outcomes by heating a flat sheet according to the array pattern and bi-directionality of dimples, to give localised curving. As a result, very favourable predictions of shape and detail are obtained compared to experiments. This work will continue with further quantification of performance, in order to predict the degree and variability of displacements, for use in the design of practicable structures.

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