COMPRESSIVE DEFORMATION AND YIELDING MECHANISMS IN CELLULAR AI ALLOYS DETERMINED USING X-RAY TOMOGRAPHY AND SURFACE STRAIN MAPPING

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ABSTRACT

The mechanisms of compressive deformation that occur in closed cell Al alloys have been established. This has been achieved by using x-ray computed tomography (CT) and surface strain mapping to determine the deformation modes and the cell morphologies that control the onset of yielding. The deformation is found to localize in narrow bands having width of order of a cell diameter. Outside the bands, the material remains elastic. The cells within the bands that experience large permanent strains are primarily elliptical. A group of cells work collectively to allow large localized deformation. Size does not appear to be the initiator of the deformation bands. Equiaxed cells remain elastic. The implications for manufacturing materials with superior mechanical properties are discussed. Visualization of internal deformation of a closed cell Al alloy core, as part of a sandwich panel construction, is also possible using x-ray tomography. Preliminary results for a punch indentation test are presented.

INTRODUCTION

Cellular metals have compressive stress/strain characteristics that enhance the mechanical performance of buckling or bending limited structures [1-3]. In order to attain these mechanical attributes, the cellular alloy must have stiffness and yield strength approaching theoretically achievable levels. The levels for closed cell solids with planar walls at low relative densities, (exemplified by the Kelvin solid) are expected to have stiffness represented by [4-8]:

\[ \frac{E}{E_r} = 0.35\rho \]  \hspace{1cm} (1a)

where \( E \) is the Young’s modulus, \( E_r \) the modulus of the cell wall material and \( \rho \) the relative density. A similar relationship exists for the yield strength, \( \sigma_y \), at low density [5,7,8]:

\[ \frac{\sigma_y}{\sigma_r} = 0.3\rho \]  \hspace{1cm} (1b)

where \( \sigma_r \) is the yield strength of the cell wall material.

The corresponding results for open cell solids are [8]:

\[ \frac{E}{E_r} = \rho^2 \]  \hspace{1cm} (2a)

and [10]:

\[ \frac{\sigma}{\sigma_r} = 0.3\rho^{5/2} \]  \hspace{1cm} (2b)
The difference between closed and open cell systems is that the deformations of the former are controlled by membrane stretching and the latter by beam bending [8].

Compression and tensile testing of various closed cell Al alloys [5,7,9,10] have revealed (Fig. 1) that their stiffnesses and yield strengths are in a range from a factor 2 to 100 lower than (1). This relatively inferior performance has been attributed to morphological defects, particularly non-planarities in the walls, such as curves and wiggles [4,6]. Numerical simulations [5-7] have affirmed the substantial influence of such defects on the properties. But, direct correlations between cell morphology and mechanical behavior have yet to be established. The purpose of this investigation is to observe the local deformations by methods that interconnect the properties with the cell morphologies. Both x-ray computed tomography (CT) [11-13] and optical methods are used. The former provides images of the interior cells and the latter of the surface features. These methods yield complementary information about the material deformations.

Fig. 1. The mechanical properties of cellular Al alloys compared with expected values for open and closed cell solids [7,9]: (a) Young's modulus, (b) yield strength.
MATERIALS

One material is focused upon for this study.

It is a closed cell material with relative density, $\rho = 0.07$, having the cell morphology described elsewhere [9]. It has the trade name ALPORAS® [14]. The cells are about 3–4 mm in diameter. The compressive stress/strain characteristics are illustrated on Fig. 2. In the plateau deformation domain there are distinct and quite regular stress oscillations, related to the number of deformation bands capable of forming. The compressive Young's modulus is: $E = 1\text{GPa}$. The nominal 'yield strength', designated as the first peak in the stress/strain curve is: $\sigma_y = 1.0 – 1.2\text{MPa}$ [5,7,9]. Local yielding occurs at much lower stresses, resulting in an initial loading modulus of only 200 MPa [6,7,9]. This material has about 1/3 the stiffness and yield strength expected from (1). But, it is stiffer than an open cell solid (2) at the equivalent density.

Surface strain measurements and x-ray studies were performed on ALPORAS®.

![Graph showing compressive stress/strain curve for ALPORAS.]

Fig. 2. Compressive stress/strain curve for ALPORAS.

MEASUREMENT PROTOCOL

Surface Strain Mapping

Commercial, digital speckle interferometry software [15] has been used for in situ surface deformation mapping. The method relies on comparison of pairs of images taken by optical microscopy during the deformation history sequence [16,17,23,24]. Two methods were implemented in order to define a continuum planar strain tensor on the surface, comprising cell walls, as well as cell cavities. (i) The surface was imaged directly. (ii) It was covered with a thin latex film epoxy-bonded to the surface with a substantial pre-stretch. In both cases, the specimen surface was sprayed with a krylon paint to enhance the speckle pattern.

The ALPORAS® specimens had dimensions, 30x30x50 mm, such that the cross section was no less than 8 cells wide. Each specimen was compressed in a servohydraulic testing machine (Instron 8501) under displacement control at 50 $\mu$m/s. Imaging was carried out with a CCD array of 640x480 pixels. Consecutive images were captured for later analysis. The principal in-plane incremental strains were obtained through post-processing of the displacement maps, employing a central difference scheme.
X-Ray Computed Tomography

Compression tests with x-ray computed tomography were performed on the ALPORAS® material in order to quantify the yielding and deformation mechanisms. Initial testing was carried out externally from the imaging system. It was determined that the first stress minimum, beyond the initial peak, occurred at a strain ~6%, (Fig. 2). In subsequent tests, the cell deformation was characterized by this level of strain.

Before straining, the internal structure was imaged using a Picker (Cleveland, OH) PQ-2000 CT Imaging System. The specimen was tested using an electromechanical test frame and then removed to the CT machine. Repeated scans were taken to match those of the unconstrained configuration.

In situ compression testing was performed using a specially designed loading stage. This was placed directly into the CT machine and the specimen compressed incrementally. After each strain increment an image was taken, yielding a two dimensional projection of the middle cross section of the specimen. Compression was carried out to ~15% strain.

Features within the cellular material which determine the deformation characteristics, were highlighted. These images capture the internal deformation fully constrained by all of the surrounding cells.

SURFACE STRAINS

Maps of the incremental principal strain, chosen to emphasize deformation banding, are displayed as a false color (Fig. 3), with the principal direction indicated by superimposed vectors. The ALPORAS® material deforms heterogeneously, by deformation banding, at loadings well below the peak stress (\(\sigma/\sigma_{\text{peak}} \approx 0.3\)). Typically, at these loads, a band having width about one-cell diameter (3mm) initiates. It then propagates across the specimen as the load increases. At the load peak, the band has extended across the entire specimen (with local densification) and, thereafter, the stress decreases upon further straining. The band normals are usually within ~20° of the loading axis. In some cases, several bands (two or more) may initiate within the gauge length. In others, the band initiates at one of the loading platens. This happens primarily in specimens with relatively high peak stresses.

In all cases, the principal strain directions are normal to the band plane (Fig. 3), indicative of a crushing mode of deformation. There is a large strain discontinuity across each of the bands. Outside the bands, the average strains are small and in the elastic range. Within the bands, strain increments exceed the average by a factor of 10, indicative of cell collapse and local densification. Such behavior is typical of that found in the transverse compression of honeycombs [8], bonded cylinders [18], etc.

These surface measurements provide a vivid visualization of the importance of band formation in plastic deformation. However, they do not identify the cells that initiate the bands and, therefore, are unable to provide a morphological explanation for the relatively low yield strength. The following x-ray measurements provide some of the missing information.

INTERNAL DEFORMATIONS

Images of interior cells before and after axial straining (Fig. 4) elucidate the cell morphologies that yield prematurely, as well as those that resist yielding. These images comprise two dimensional sections through the foam, each ~0.5mm thick. The displacements of locations within the cell walls obtained from comparisons before and after straining (Figs. 5a-c), provide an explicit visualization. The cells outside the deformation bands deform elastically and retain their original shape (Fig. 5c). Conversely, the cells exhibiting permanent deformations within the bands
Fig. 3. Surface maps of the incremental principal strain. Principal directions are indicated by superimposed vectors. Stress-strain curves are also indicated.
Fig. 4. X-ray tomographic images of a plane through the center of the test specimen before and after straining by 6%, highlighting a critical cell. Because of the image depth (1mm) there is apparent overlap of the cell walls. The schematic of the deformed and undeformed gives a clearer indication of the associated cell geometries.
comprise one of the two morphologies indicated on Fig. 5a,b. (i) Ellipsoidal cells with T-shaped cell wall intersections. These wall intersections are approximately parallel with the load direction. (ii) Non-planar walls with appreciable curvature. It is clear that an interaction between cells is necessary for deformation to take place within narrow bands. This cooperation is emphasized when critical cells of the types described are present. Further inspection of these images reveals that there is no obvious preference for the larger cells to be more susceptible to permanent deformations. That is, large cells remain elastic provided that they have an "equiaxed" morphology with minimal ellipticity. The implication is that shape is more important than size in determining the yielding susceptibility of the cells. Examination of cells within the deformation band shows more ellipticity than those outside.

Comparison between two consecutive images, produced from the in situ compression testing, pinpoints the location where a deformation band starts, (Fig. 6). The increment in strain between the two images is ~1.3%. These cells show the ellipticity expected, combined with the necessary cell wall interactions. What is clear is that the deformation band is instigated at more than one location and that these "hot-spots" meet as straining is increased.

Fig. 5. Schematics of three typical cells indicating their shapes before and after testing to 6% strain: (a) and (b) represents cells within the deformation bands that experience appreciable permanent deformations, (c) represents a cell that experiences minimal change.
PUNCH INDENTATION OF SANDWICH PANEL WITH CLOSED CELL POROUS AL CORE

X-ray imaging has been used to analyze internal deformations of a sandwich panel. The panel is constructed using Al alloy 6061-T6 face sheets separated by a closed cell porous Al core, ALPORAS. The 5"*5" panel has faces which are 0.03" thick and the core is 0.4" thick. Bonding between the core and face is achieved using a standard industrial epoxy adhesive.

After imaging the internal cell configuration, the panel was indented using a half inch diameter circular punch indenter. The indenter was displaced 3mm and the stress-displacement curve is presented, (Fig. 7). CT images were captured after deformation. Fig. 8 examines the internal structure of the core before and after indenting. Comparing these results with the compressive response of the core material alone, [9], it is clear that the face sheets have a significant influence on the mechanical response to straining.
Fig. 7. Stress/displacement curve for punch indentation test of sandwich panel

Fig. 8. X-ray images showing internal deformation of a sandwich panel subjected punch indentation: (a) before indentation, (b) after indentation.
CONCLUDING REMARKS

The cell morphologies that dictate yielding appear to be shape dominated. That is, elliptical with cell wall junctions that experience bending initiate band formation and have an imp influence on the yield strength. Highly curved cell walls also have a detrimental influence. Former finding is consistent with calculations that demonstrate a diminished strength upon ren of cell walls [22,23], which serves to convert equiaxed cells into elliptical morphologies. Presence of large cells, provided that they are relatively equiaxed, appears to be of secor performance.

Given the role of cell shape, improvement of the mechanical properties through contr the cells during manufacture appears to be particularly challenging. That is, while the eliminatic large cells is tractable, approaches for avoiding elliptical cells are less clear. One contributio ellipticity derives from gravitational effects at high temperature, which cause distortions of cells. Addressing these issues may be an avenue for controlling cell shape and enhan performance.

It is now possible to track the internal deformation of sandwich panels. Fur investigation is to be carried out to examine the effects of the face/core interface. The influen face sheet thickness must also be quantified.

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