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Materials science is based on an atomic understanding of material properties, but macroscopic structures are conventionally specified by a continuum description of a material's composition and morphology. Although atomic structure may appear in this description, it's typically with respect to a statistical ensemble rather than a unique configuration. Advances in fundamentally digital fabrication technologies are now leading to the possibility of explicitly specifying the internal configuration of a macroscopic material. We present analogs to atoms and bonds that allow individual elements to be placed in a physical structure much like the encoding of a data structure, and present experimental measurements to show how this control can be used to tune mechanical and electronic properties, and to assemble functional global structures with errors reduced relative to the placement of the local elements.

The frontiers of materials science in manufacturing, including nanomaterials,[1] composites,[2] net-shape production,[3] and 3D printing of functional systems,[4] are based on fundamentally analog processes – the composition and arrangement of the ingredients can be continuously varied. So-called "smart" materials[5] aren't all that smart; although they may sense and respond to external inputs, information is not explicitly encoded in them.

Metamaterials[6] do specify the local configuration of an engineered material, however they typically have been based on regular structures, and their study has concentrated on electromagnetic properties. Tour-de-force experiments have shown the feasibility of placing individual atoms,[7] but these approaches do not directly scale to making macroscopic structures.

An emerging alternative approach to fabrication is based on the assembly of fundamentally digital materials, which we define here to be materials with:

1. a discrete set of components

2. a discrete set of allowable relative positions and orientations of the components

3. explicit control of the placement of individual components

Together, these properties allow for the exact specification of the configuration of a material, and for the detection and correction or errors in that configuration. These are exactly the attributes that are assumed by the threshold theorems that underpin digital communications[8] and computation,[9] which provide an exponential reduction in error rates for a linear increase in system resources. Just as digital codes place symbols in a configuration space, the states of a digital material occupy sites in a physical space, with their microscopic configuration determining the macroscopic properties of the material

Atomic bonding has the first two attributes but usually not the third; NC machining and 3D printing start from digital descriptions, but that information is lost after it's represented in analog materials. The most familiar example of all three is a child's snap-together construction bricks, which allow a child to assemble a structure that's more accurate than their motor control. However, a child doesn't (usually) start from a digital description; emerging approaches to program the construction of digital materials include digital printing, coded folding, and algorithmic assembly.[10-12] Here we study the properties of digital materials that are common to all of these processes, rather than the differences in how they are designed and assembled.

We will investigate three-dimensional structures produced by the reversible press-fit assembly[13] of two-dimensional "GIK" tiles.[14] As shown in Figure 1, these structures can be assembled over a wide range of length scales, and the components can be produced from many materials. The GIK tiles have a chamfer that compresses the material when they are assembled; the resulting strain field produces an effective joint by increasing the tangential force required to overcome the coefficient of static friction. Figure 2 shows a finite-element calculation of the stress in a GIK joint, and its observation by optical birefringence imaging.

Figure 3a shows the stress-strain hysteresis of a press-fit joint, and its convergence under repeated cycling. The long-term stability of the force to disconnect the joint is plotted in Figure 3b. Together, these properties allow the joint to be considered as an effective bond that can be reversibly assembled and disassembled.

Figure 4a plots the force required to disconnect multiple parallel joints; because of the nonlinearity of the stress-strain curve this increases faster than linearly, analogous to the dependence of DNA melting on oligonucleotide length.[15] As GIK tiles are assembled, the chamfer corrects local misalignment errors, and Figure 4b shows that redundancy in the structure reduces global errors by elastic averaging.[16] Because GIK tiles must occupy regular lattice sites, accumulated assembly errors can be detected when the deviation becomes comparable to the lattice spacing.

The macroscopic properties of a GIK structure can be tuned by varying the microscopic structure. Figure 5a shows the linear dependence of the tension required to separate two tiles on slot size. Figure 5b shows how the compression modulus depends on the density of the GIK structure, removing 0-75% of the parts along one direction. To create an anisotropic compression modulus 1 out of 2 parts were removed along the x direction, 1 out of 3 in the y direction, and 1 out of 4 in z; these resulted in compression moduli of $E_z = 3.9$ MPa $E_y = 2.2$ MPa $E_x = 0.82$ MPa, shown in Figure 5c. The compression modulus was varied in Figure 5d by varying the ratio of plywood and aluminum parts, from 0 to 100%.

Applications of materials for printing electronic circuits have been limited by interconnect conductivity and semiconductor carrier mobility.[4] Because digital materials are assembled rather than deposited, conventional processes can be used to produce and optimize the properties of the components. Figure 6 shows a Schottky diode constructed from copper, n-type silicon, and lead tiles. The copper/silicon interface creates a Schottky junction with a barrier height of 0.35 eV; the silicon/lead interface makes an ohmic contact (barrier height -0.05 eV) for measuring the diode's characteristics. The I-V curve is comparable to that of an LED;[17] this is less sharp than that of a commercial Schottky diode because of the lower Cu-Si barrier and the larger contact resistance. Because universal logic can be built with diodes and resistors,[18] this device demonstrates that active electronic circuits can be assembled from functional digital materials.

The mechanical properties assumed here will hold over a wide range of length scales; as an alternative to additive or subtractive manufacturing processes, high-throughout assemblers[10] can construct macroscopic objects from microscopic elements. Beyond offering tunable, functional material properties, the ultimate implication of this use of digital materials lies in their lifecycle. Trash is defined by materials that are disposed because they can not be economically separated, and the purpose of recycling is to reprocess waste into a form that can be reused. These are essentially analog concepts, reflecting the lack of information within the materials. Because digital materials, on the other hand, are reversibly assembled from a discrete set of components, they can be deconstructed as well as constructed. Just as the most efficient computers operate reversibly,[19] rearranging rather than erasing bits, the most efficient manufacturing is likely to be based on digital materials that can be added, subtracted, and sorted with equal ease.

Methods

For the mechanical measurements, plywood (white birch, 95 ±5 mils) and Delrin (64 ±1 mil) parts were cut on a lasercutter (Universal, CO2, 100W); aluminum parts (2024, 101 ±2 mils) were cut with a waterjet cutter (Omax). Materials testing was done with an Instron 4411 (time resolution 5ms, force resolution 0.01 N, position resolution 01 mm).

Strain imaging was performed on lasercut transparent acrylic parts, 1cm thick, compressed with a force of 500N on the Instron. White light illumination was photographed through orthogonal polarizing lenses by a Nikon 995 digital camera.

GIK parts were made and compressed using the Instron material testing machine with a force of 500N. The acrylic parts were illuminated with white light through a polarizing lens. The resulting interior stress pattern was photographed using a Nikon 995 digital camera through an orthogonal polarizing lens. The resulting photograph was compared to the simulated stress pattern obtained using FEMLAB version 3.1 finite element simulation software.

The N-doped silicon GIK used for the Schottky diode presented in this paper was cut from a N/ Phos dopes wafer of Resistivity 1-20 ohm-cm and thickness 525 micrometers +/- 25 micrometers using a Bueheler diamond wafering blade on a commercial ISOMET 1000 wafer cutting machine. The copper GIK used for the Schottky diode was also cut on the same machine in the same conditions from 0.047" thick stock copper. The lead GIK used for the Schottky diode was also cut on the same machine using 0.085" thick lead sheet purchased from McMaster-Carr.

Acknowledgments

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Figure Captions

Figure 1: Dimensional scaling of a press-fit structure

Figure 2: Calculated and observed stress in a press-fit joint

Figure 3: **a)** Hysteresis of a press-fit joint (plywood). **b)** Repeatability of a press-fit joint (plywood and Delrin).

Figure 4: **a)** Nonlinear scaling of parallel press-fit joint strength (plywood**)**. **b)** Maximum lateral displacement as a function of the number of parallel rows (Delrin).

Figure 5 :Tunability of a digital material. **a)** Force to separate a joint as a function of the slot size (plywood). **b)** Compression strain as a function of the occupied sites in a 3x3 unit cell cube (plywood). **c)**, Anisotropic compression strain (Delrin). **d)** Compression strain as a function of the fraction of aluminum and plywood tiles, from 0 to 100%.

Figure 6: Nonlinear electronic properties in a press-fit structure

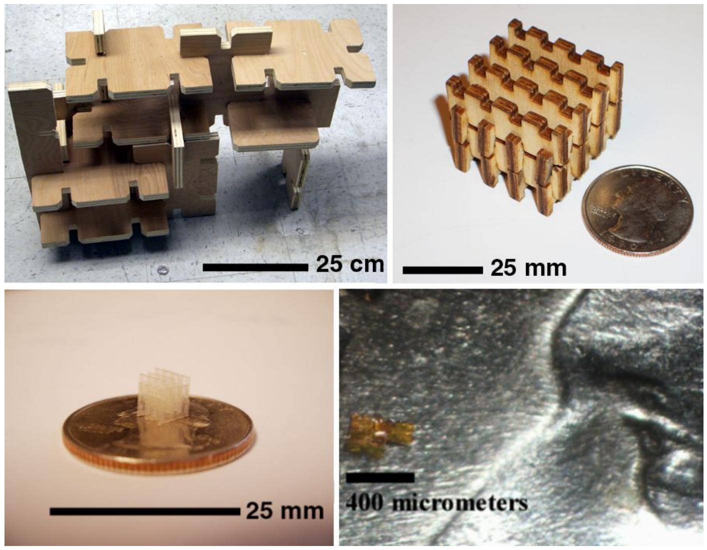

Figure 1

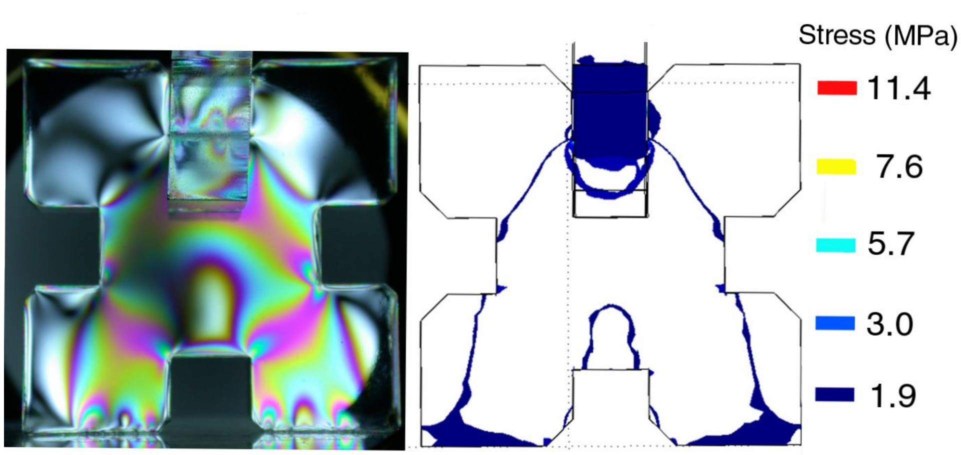

Figure 2

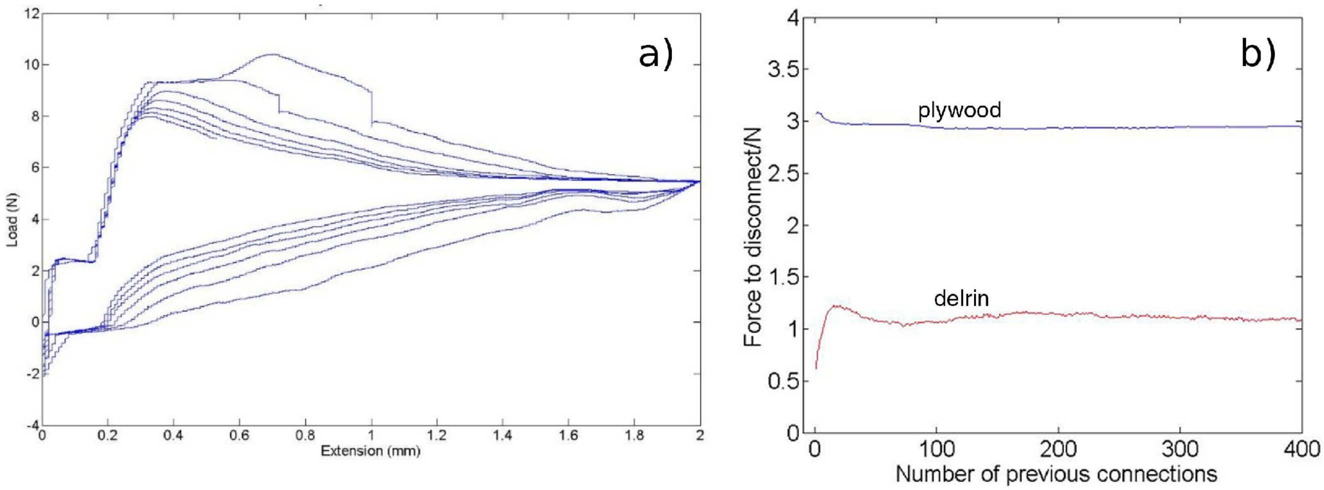

Figure 3

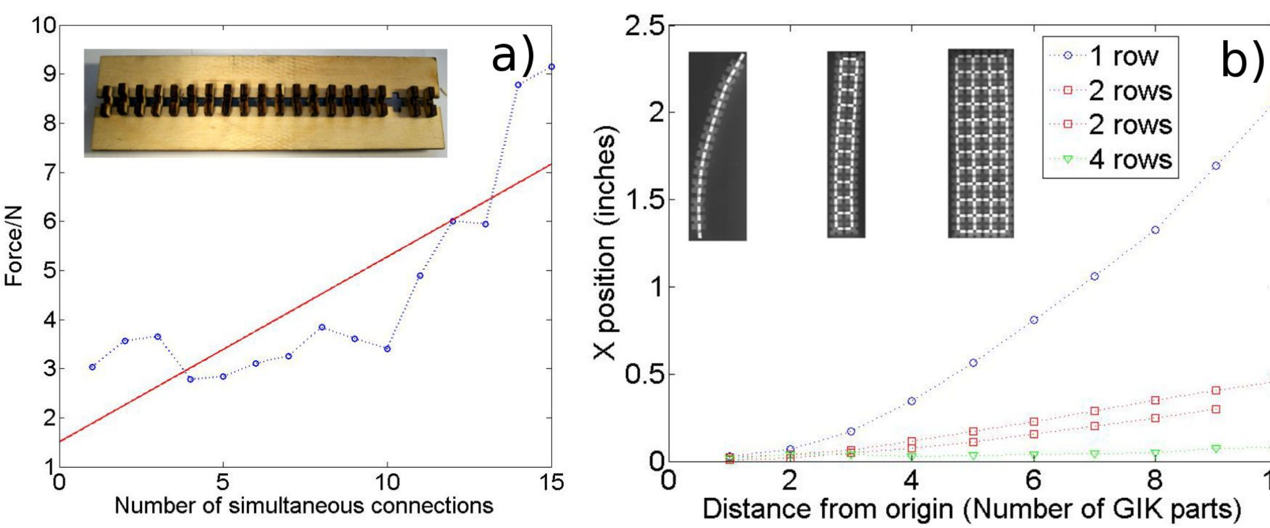

Figure 4

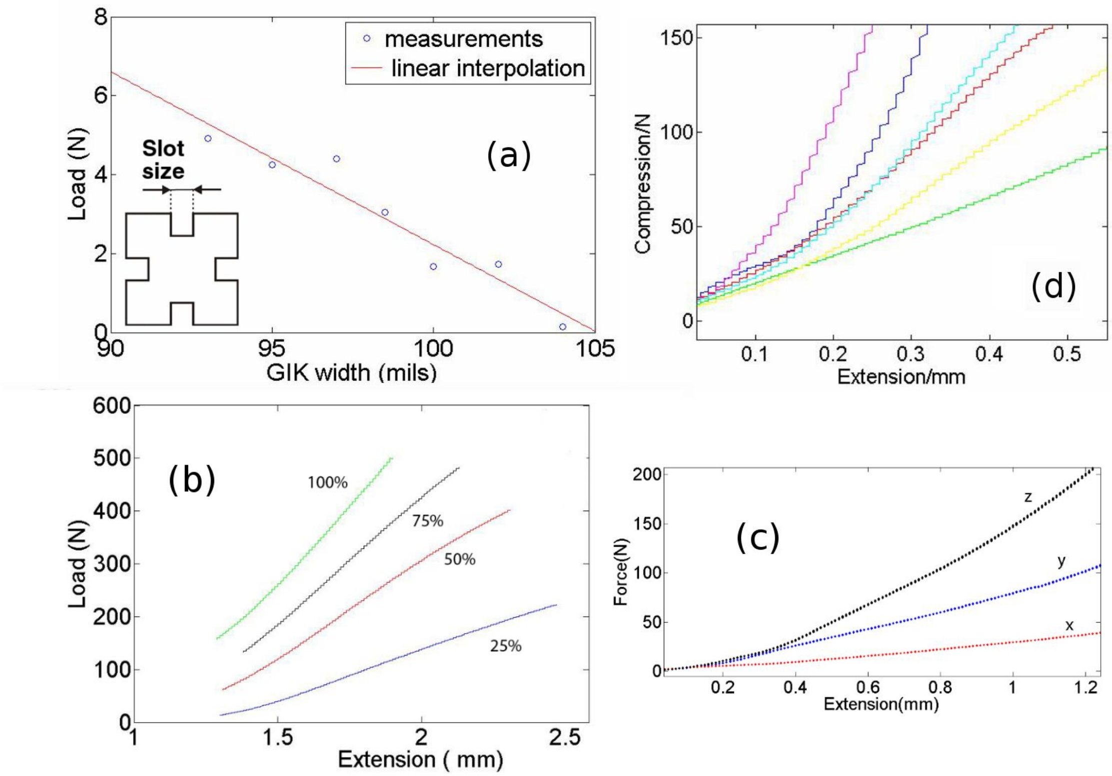

Figure 5

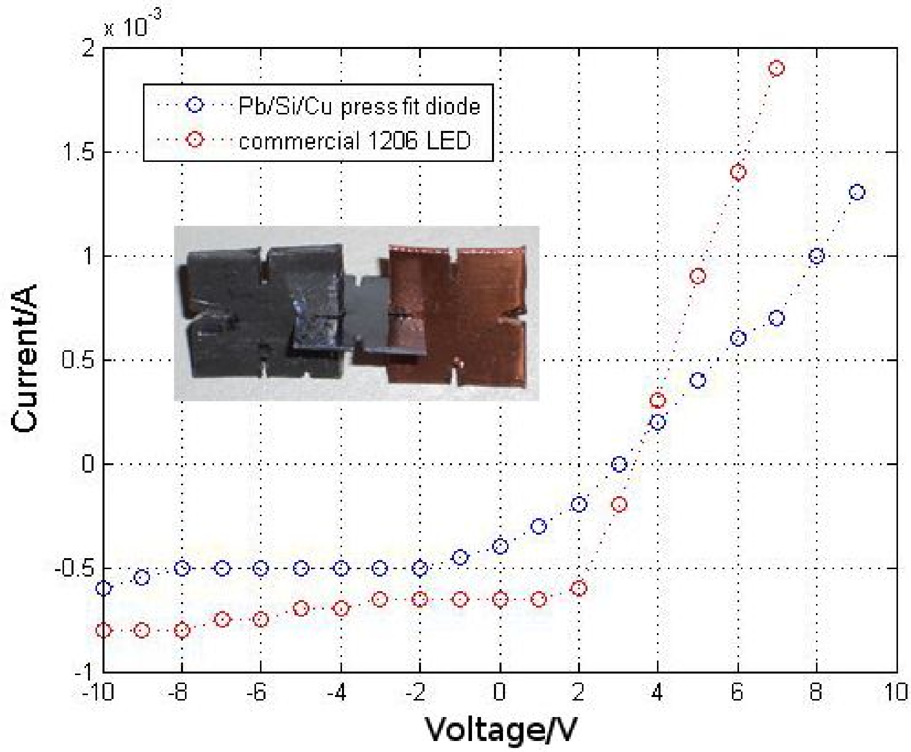

Figure 6