Solid Freeform Fabrication 2025: Proceedings of the 36th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Development of a Novel ShL AM Process for Deployable and Metamaterial Devices

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Abstract

Sheet lamination (ShL) has found little commercial use as an Additive Manufacturing (AM) process for making 3D parts, but it may have unique potential for fabricating origami-inspired and deployable devices. While such devices have promising applications in packaged goods, robotics, and metamaterials, producing them at commercial scales remains challenging. An automated manufacturing method could help origami-inspired devices overcome the barrier-to-entry for many industries. To address this, we present a ShL-based method for manufacturing multi-material deployable mechanisms and metamaterials. The process integrates single-layer laser cutting, adhesive deposition, and stacking into one continuous, automated workflow on a modified CNC router. A demonstration part, a Kresling pattern, validates the feasibility of this approach, showing that complex foldable geometries can be fabricated with automated precision. By establishing ShL as a viable route for scalable, low-cost production, this work lowers barriers to industrial adoption and opens new opportunities for functional deployable systems across multiple fields.

Introduction

The ancient art of origami (paper folding) and related processes such as kirigami (folding and cutting) have inspired the engineering of many [1] novel, reconfigurable mechanisms, including soft robotic grippers [2], large, deployable solar arrays [3], and a metamaterial with reconfigurable shape, volume, stiffness [4] and acoustic wave guide behavior [5]. Metamaterials, in general, are a promising field for their potential to create entirely new behaviors in a variety of fields. Metamaterials use controlled structure, or geometry, to achieve unique behavior, such as tailored stiffness, rigidity, and compressibility, allowing combinations of effective material properties that do not naturally exist [6]. When the 3D geometry can be reconfigured in operation, this adds functionality and, when paired with the concepts of origami and metamaterials, provides a promising opportunity for valuable, new multifunctional products. However, origami-inspired designs and metamaterials have primarily been limited to low-volume applications, such as specialty products, aerospace, or research [1]. This is due to the difficult and time-intensive nature of precisely manufacturing and assembling them. For origami-inspired devices or metamaterials to have impact beyond laboratories and bespoke applications, precise, scalable manufacturing methods are needed.

The manufacture and assembly of origami-inspired mechanisms is challenging for many reasons. For one, engineered origami often requires multi-material assemblies composed of many individual components, including the rigid panels and surrogate folds(hinges), to achieve the desired stiff, rigid behavior (in panels) and motion (experienced by folds). The number of individual components and separate process steps increases as multi-functional components are added, like integrated electronics. In addition, many origami patterns are tessellated patterns which create large, over constrained mechanisms. Over constrained mechanisms are more sensitive to tolerance issues, making precise manufacturing and assembly important. All of this leads to assembly steps that can be time- and labor-intensive, driving up costs. Design for AM can reduce assembly steps by producing more pieces monolithically (as a single part), such as by use of multiplanar configurations described in [7]. However, research into these production methods and related design tools is currently lacking [1]. Li and Daqaq [8] suggested that origami and kirigami fabrication are one of the main areas for further research in the field and emphasize that methods should "combine automation, repeatability, and low cost". Such a process should also easily handle simultaneous multi-material manufacture with materials of vastly different properties. To reduce the time and cost of making origami-inspired mechanisms, an automated process is needed that can manufacture and precisely locate many, often small, multi-material pieces.

A process that can meet these needs is Sheet lamination (ShL) Additive Manufacturing process (AM). In ShL AM sheets of material are cut and bonded together to form a 3D object. As summarized by Gibson et al. [9], various cutting and bonding methods have been used on various materials, including metal, paper, polymer, and ceramics. The order of these cutting and bonding steps also varies. Form-then-bond processes involve first cutting the objects and then adhering and placing them. Bond-then-form reverses this by first bonding and placing the sheet and then cutting away excess. Form-then-bond requires additional features for precise alignment [9], whereas alignment of objects in bond-then-form is dependent only on the relative alignment of the toolhead and stack and not each individual piece. This makes bond-then-form a better candidate for origami-inspired, mass-manufacture. ShL has seen some recent commercial success. The company Impossible Objects has used ShL to produce 3D printed objects at 15x the speed of other AM processes [10]. Similarly, Fabrisonic used an ultrasonic variant of ShL to successfully make multi-material parts from dissimilar metals and high-strength ceramics [11]. In addition to the demonstrated high-throughput and multi-material capabilities, ShL can also easily leverage origami's inherently sheet-based design. This preserves material, negating one of bond-then-form ShL's primary drawbacks: excess waste material. For all these reasons, the ShL process is well-suited to meet the needs of origami-inspired engineering.

A few researchers have developed origami-inspired prototypes using a manual or semi-automated bond-then-form ShL process. The reconfigurable metamaterial by Overvelde et al. [4] was made by layering plastic and double-sided tape with digitally defined laser-cutting steps of selective depth. However, this method limits adhesive selection to tape sheets and requires significant post-process assembly of the individual laminated parts. This unnecessarily limits the design space. Stevens et al. [12] similarly used manual sheet placement and selective depth laser cutting, however layers were bonded manually using a stencil to mask a deposited spray-adhesive. Stevens et al. successfully created a multi-layer origami-inspired compliant louvre. This louvre would reduce the weight and cost of satellites if produced at-scale. However, the stencil-based bonding method used led to significant increases in manufacturing time and process variability. A ShL machine with both automated cutting and automated bonding would be the next step towards fully automated ShL of origami-inspired reconfigurable mechanisms.

This work presents and describes an automated ShL system using a combination of laser cutter, adhesive dispensing system, and CNC router for motion. This system was specifically designed to manufacture complex, multi-material, origami-inspired mechanisms in a way that allows rapid iteration and modification of designs. Before prototypes can be manufactured, the system must be tested for accuracy and suitable operating parameters. This work describes methods of testing the accuracy of selective laser cutting and adhesive deposition, as well as results. After parameter selection, a demonstration part was produced: a multilayer Kresling pattern design was adapted to this process, manufactured entirely on the ShL system, and then deployed into a 3D shape. The Kresling demo shows the suitability of this process for origami-inspired metamaterials. In the future, other designs could be easily prototyped and developed on this system, as it greatly reduces the manual, tedious assembly and manufacturing steps of current manufacturing methods. Even compared to previous work using ShL-based methods, this system adds an automated, selective bonding step to increase material and geometry design freedom. Overall, this work seeks to increase the adoption of origami-inspired metamaterials and deployables through the introduction of an automated, digitally-defined, ShL manufacturing process.

Methods

Description of system

The integrated laser cutting and bonding ShL machines needed for origami-inspired applications are not commercially available, so a custom one must be made. This ShL system consists of four main features: the commercial, off-the-shelf (COTS) CNC motion system (STEPCRAFT M.1000 CNC System, Stepcraft Inc., Torrington, CT, US), COTS laser cutter for automated cutting (PLH3D XT-50, Opt Lasers, PIaseczno, Poland), the automated adhesive deposition system (customized from several COTS systems), and a custom-built laser safety enclosure. The system itself is depicted in Figure 1, while the enclosure and safety features are depicted in Figure 2.

The system has an overall, modified build volume of 1005×565×270 mm^3 (L×W×H). The CNC motion can achieve speeds of 5100 mm/min in X and Y and 3000 mm/min in Z with a repeatability of ± 0.025 mm [13]. The diode laser operates at a wavelength of 445 ±10 nm and an optical power of 6 watts, with the ability to cut various woods, plastics, and textiles [14].

The adhesive deposition system is controlled through two inputs: the manually set pressure applied to the pneumatic dispenser and a digital pneumatical controller operating a pinch tube valve. A pneumatic dispenser (Pneumatic MK Dispenser TS408MY-8, medmix Switzerland AG, Switzerland) continuously pushes the adhesive or two-part epoxy into a mixing nozzle, and then into the pinch tube. A pinch tube is a commercial product that is pinched shut via spring. It can be quickly opened by an applied pressure pushing against that spring. The pinch tube is operated by a pinch tube valve (Fisnar 710PT-U Pinch Tube Valve, Fisnar, Germantown, WI, US) which is controlled by on/off commands sent from the computer program to a digital pneumatic controller (Metcal DX-250 Digital Dispenser, Metcal).

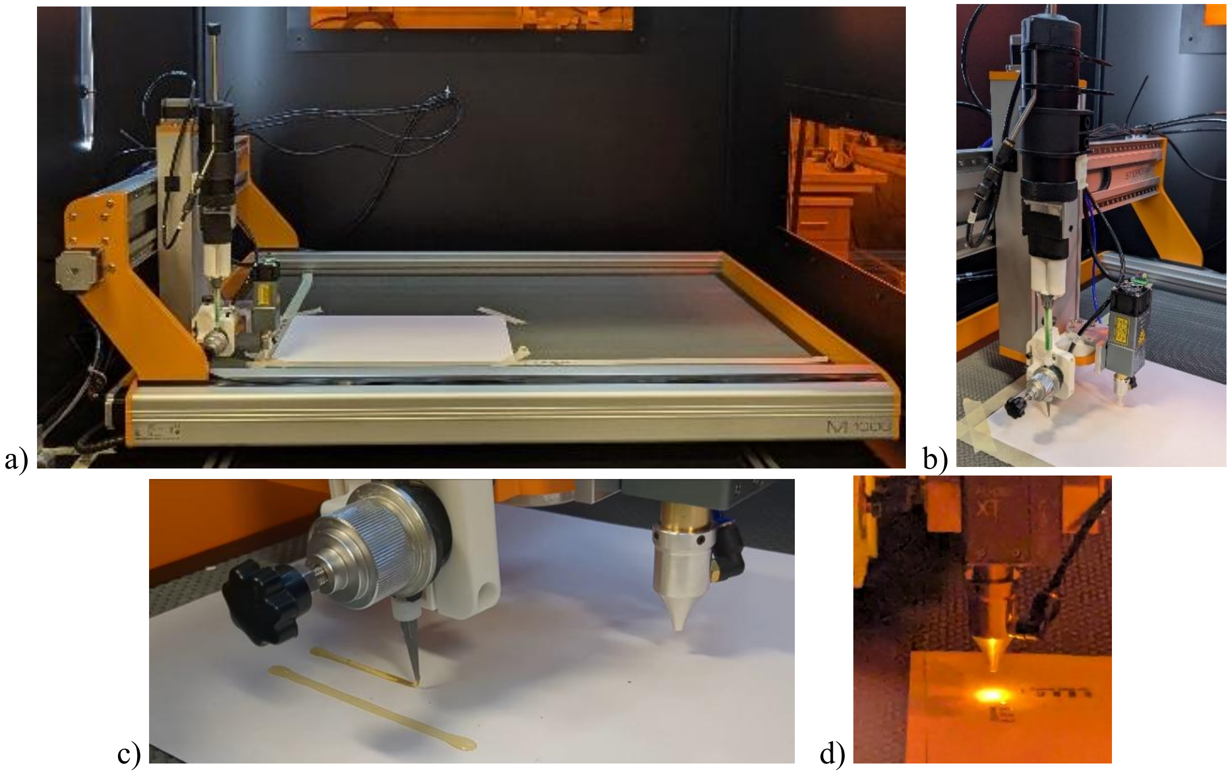


Figure 1: Overview of key system features: a) COTS CNC motion system, with adhesive and laser cutting systems attached, b) close view of attached adhesive and cutting systems, c) adhesive dispensing system in-action while laser is off, d) laser cutting system in-action while adhesive system is off, viewed from outside the system enclosure.

Safe use of the designed system, which included a class IV laser, required several safety measures to ensure any laser light was absorbed before reaching human eyes. This included a light-tight enclosure with all main surfaces coated in black anodized aluminum to minimize reflectivity. This also included laser-safe windows (OD 5+, Acrylic Laser Safety Window, Laser Safety Industries MN, US) to monitor printing progress and watch for any other dangers, like fires. Safety interlocks were hard-wired to disarm (and turn off) the laser when the door is opened. To further prevent unintended use, a COTS laser control panel (PLH3D-CNC Adapter PRO, Opt Lasers, PIaseczno, Poland) was used, requiring a manual key and button input before the laser can be armed. Whenever the laser is armed, safety warning lights turn on to warn others in the room. E-stops are placed on both sides of the enclosure, which turn off the laser, adhesive dispensing, and CNC motion. To remove any fumes, an air vent is placed at the top of the enclosure. This also helps seal the enclosure by providing negative pressure.

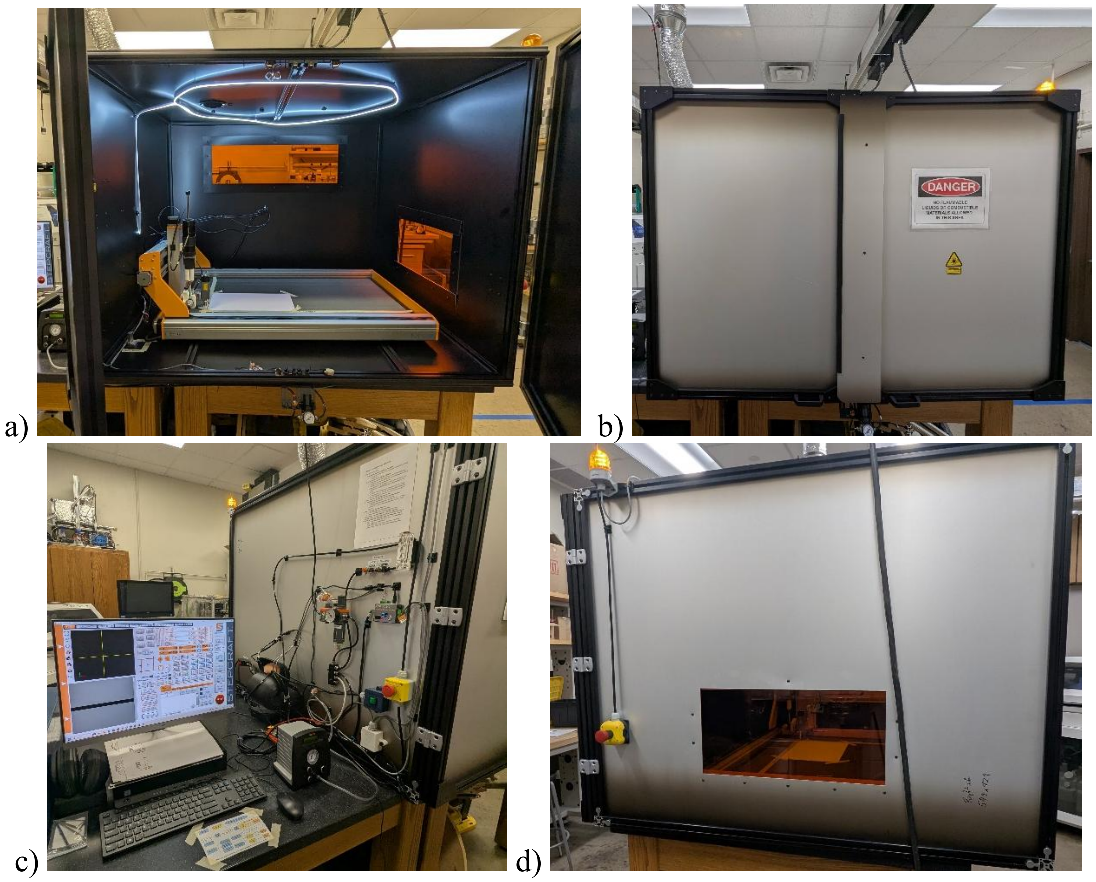


Figure 2: View of system safety features and controls: a) front of light-tight enclosure with doors open, b) front of light-tight enclosure with doors closed, c) left side view of enclosure, including controls d) right side view of enclosure, including window, e-stop, and safety warning light

Manufacturing process and materials

In this process, g-code is generated using Lightburn software from digitally defined, 2D CAD patterns for cutting and adhesive deposition. Z-position changes for the height of new layers and custom g-code insertions are added to the g-code using a custom Python script. This G-code is then sent to the COTS control software, a Stepcraft-specific version of UCCNC. The user first places down the first layer of material, then the machine is allowed to proceed. It first repositions the Z-axis to focus the layer to the top of this new layer height, then it cuts this top layer according to the provided 2D CAD pattern. When completed, the laser proceeds to apply adhesive to the layer according to the corresponding 2D CAD pattern. The machine then waits for the user to apply the next layer before repeating the process as programmed. A diagram of this process is shown in Figure 6.

Although this process may be compatible with a wide range of materials, materials used in this demonstration include paper of varying sizes (Springhill Vellum Bristol Cover, Sylvamo Corporation, Memphis, TN, USA), and cardboard (4 mm thickness, single wall, B Flute corrugated sheet of cardboard, sources vary). A single adhesive was tested and used for manufacture (PlasticBonder Tan, J-B Weld, Sulphur Springs, TX, US). This high-viscosity adhesive was chosen because much lower viscosities led to leakage from the adhesive dispensing system.

Laser performance quantification methods

For ShL processes, it is necessary to successfully cut the top layer in a stack without damaging any preceding layer. To do this, proper laser parameters must be determined for each new machine and material. Like the work by Stevens et al. [12], two layers of material were stacked, and then varying laser parameters were used to attempt to cut the top layer. The performance was classified into three categories:

- Single-layer, or selective cutting –top layer cut completely with minimal damage to lower layer
- Multi-layer, or over cutting – top and lower layer are cut completely or the top layer is cut completely and the bottom layer is significantly damaged
- Other – all other cases are undesirable parameter combinations

The power, travel speed, and passes were varied in several test grids (using the Material Test generated by Lightburn software). Power was varied by incrementing the laser's duty cycle as an equal percent of the maximum . Air assist was used while laser cutting at a value of 5 - 10 PSI, as recommended by the manufacturer [14].

Adhesive deposition quantification methods

To measure the volumetric flow rate, first the mass flow rate was measured by weighing the amount of adhesive deposited over a ten-second interval. The adhesive was purged before measuring to ensure it was unaffected by any potential time delays related to long periods between depositing, if present. The mass flow rate was converted to volumetric flow rate using the density listed by the manufacturer. A baseline linear travel speed for the adhesive was calculated by dividing the volumetric flow rate by the cross-sectional area of the nozzle, although other travel speeds also performed well.

Discussion and Results

Several tests were performed to quantify the performance of the laser-cutting and adhesive deposition system. Although these parameters may not be cross-transferable to other machines, they provide an example of the capabilities of this ShL system. These parameters were also used for manufacturing the demonstration part. Similar ShL systems can follow this method to obtain their own values for use in their system. Additionally, the fundamental process steps are listed and compared by the amount of automation in current and previous (as described by Stevens et al. [12]) process methods. Finally, a Kresling pattern demonstration part is shown.

Laser cutting and adhesive deposition performance

Selective-depth laser cutting performance tests were performed for a stack of two paper sheets (Figure 3) and a stack of one cardboard and one paper sheet (Figure 4). The results are shown in each respective figure. The range of acceptable single-layer-depth cutting parameters was relatively narrow, compared to the total range of parameters.

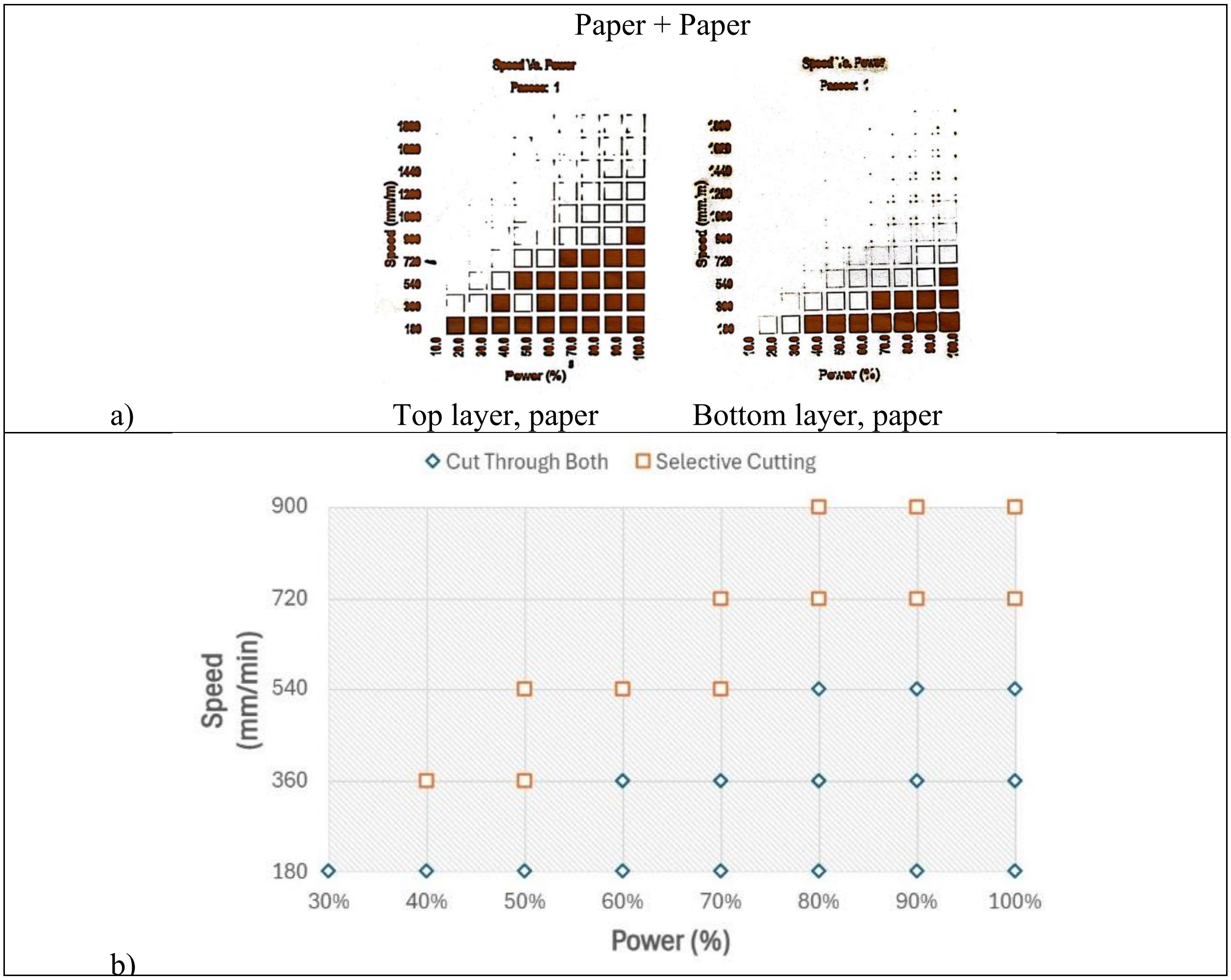
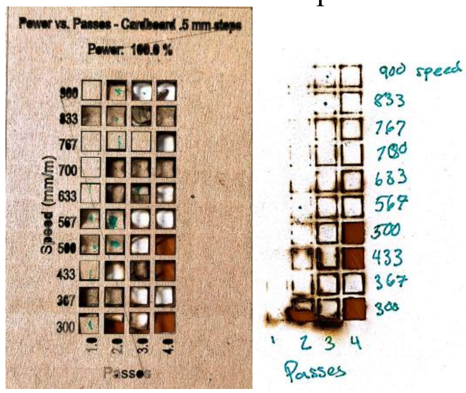


Figure 3: Cutting depth performance against relevant laser cutting parameters for two stacked sheets of paper. a) Experimental. b) Graphed. Power is on the X-axis, varied in 10% increments from 10 to 100%. Speed is on the Y-axis, varied from 180 to 1800 mm/min in 180 mm/min increments.

The adhesive performance was also evaluated. As shown in Figure 5b, the adhesive followed the intended deposition path, allowing for freedom of movement between components on adjacent layers. However, the thickness of the adhesive deposition varied noticeably over the duration of a deposition layer. This points to time-delay or shear-thinning behavior in the adhesive, which would need to be accounted for or selected against for more precise deposition. Additionally, the start and stop behavior of the lines and the cornering behavior were not as precise as is possible, as shown in Figure 5a and b. This is another opportunity for further optimization. However, the adhesive behavior was satisfactory enough for the demonstration.

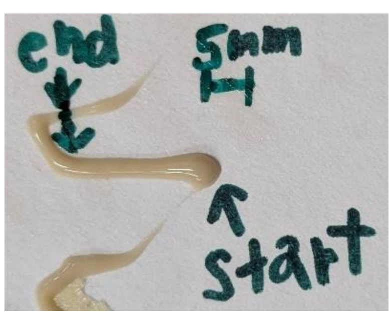
Cardboard + Paper



a) Top layer, cardboard Bottom layer, paper

b)

Figure 4: Cutting depth performance against relevant laser cutting parameters for one sheet of carboard stacked on one sheet of paper. a) Experimental. b) Graphed. For the carboard and paper the X-axis is the number of passes from 1-4 at 100% power and with 0.5 mm steps down into the cardboard per pass, while the Y-axis is also speed but varied from 300 to 900 mm/min in 67 mm/min increments.

a) 

b) 

Figure 5: Selective adhesive performance. a) Imprecise start and stop behavior in adhesive deposition leads to a build up at the start and a tail at the end. b) Defects in the triangular deposition patterns are observed where adhesive thickness varies across the deposition, as well as imprecise start and start behavior.

Comparison of manual and automated methods

In the previously used process, only the cutting step was automated, which occurred on a COTS laser-cutting machine. This machine allows for the automation of the Z-axis repositioning, cutting, and bonding steps. The difference in automation levels is shown in Figure 6. Automation of these steps, back-to-back, on the same machine increases repeatability, reduces manufacturing time, and eliminates the chance of alignment errors when moving between working areas (for bonding). Increasing repeatability and reducing operator and alignment errors improves the quality of manufacturing. For multi-component, multi-layer, complex systems, having consistently high quality of manufacture across all components and layers is necessary to achieve function. Additionally, increasing complexity tends to increase manufacturing time on its own. Decreasing manufacturing time through other means counteracts this increase. Thus, these improvements altogether pave the way for constructing complex, multi-layer metamaterials.

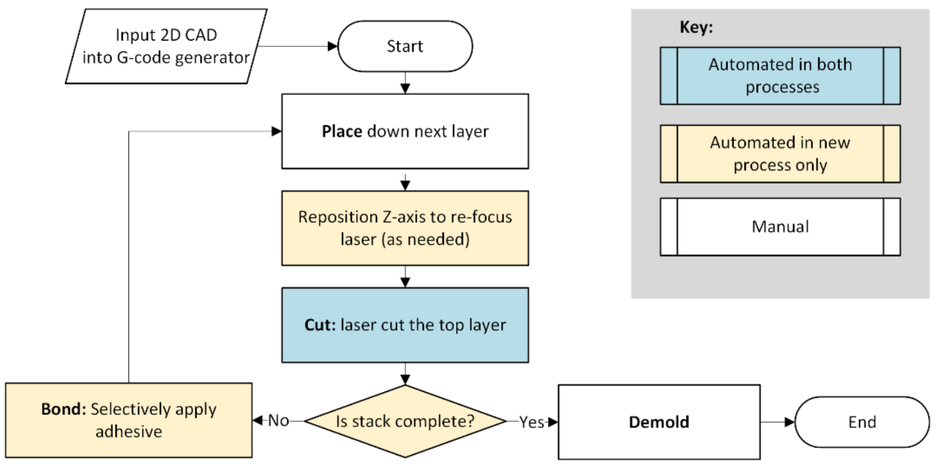


Figure 6: Comparison of automation level in manual vs automated processes

Demonstration part

A demonstration part was chosen to highlight the improvements made by this new process- specifically selective and automated adhesive deposition, selective depth laser cutting, multilayer alignment consistency, metamaterial capability, and fundamental needs for automated methods. For this reason, a multiplanar Kresling pattern was chosen.

The Kresling origami pattern exhibits interesting metamaterial properties. It consists of a tessellation of triangles that, when folded into a cylinder, exhibit a collapsing, buckling behavior when axially twisted. Masana et al. [15] collected a review of the current research into the Kresling pattern's abilities and applications. By either twisting or compressing, it can switch between two stable states. According to Masana et al., promising applications for the Kresling pattern include primarily soft robotics, as well as vibration isolators, shock absorbers, hopping robots, and metamaterials. Repeatable, automated mass-manufacturing methods are currently a bottleneck for Kresling-based products.

The design used here is based on a multiplanar manufacturing layout by Stevens and Crane [7] modified for ShL processes. The multiplanar layout requires a layer in which bonding occurs only on the outer edges, meaning selective bonding. It also involves the consistent alignment of many individual parts. A copy of the intended design, as manufactured by the previous, semi-automated method is depicted in Figure 7.

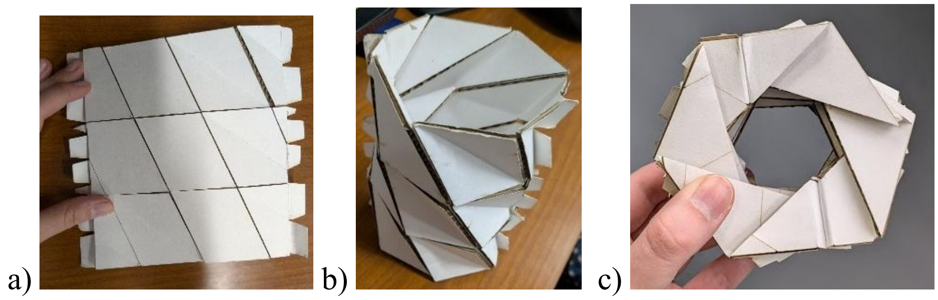


Figure 7: Demonstration of Kresling pattern made using previous, semi-automated process after a) demolding, b) deploying, and c) compressing

To manufacture the part on the current, automated process, the same general steps were followed. As this part requires six different layers, seven cutting operations, and four adhesive deposition operations, the time savings and reliability improvements from automating many of these steps (as shown in Figure 6) compound significantly. The manufacturing process steps are detailed below, in numbered order and with corresponding images for notable steps, as shown in Figure 8. The only manual steps were imprecisely placing down each layer, double checking the performance and adjusting the adhesive as needed, and pressing start on the next sequence.

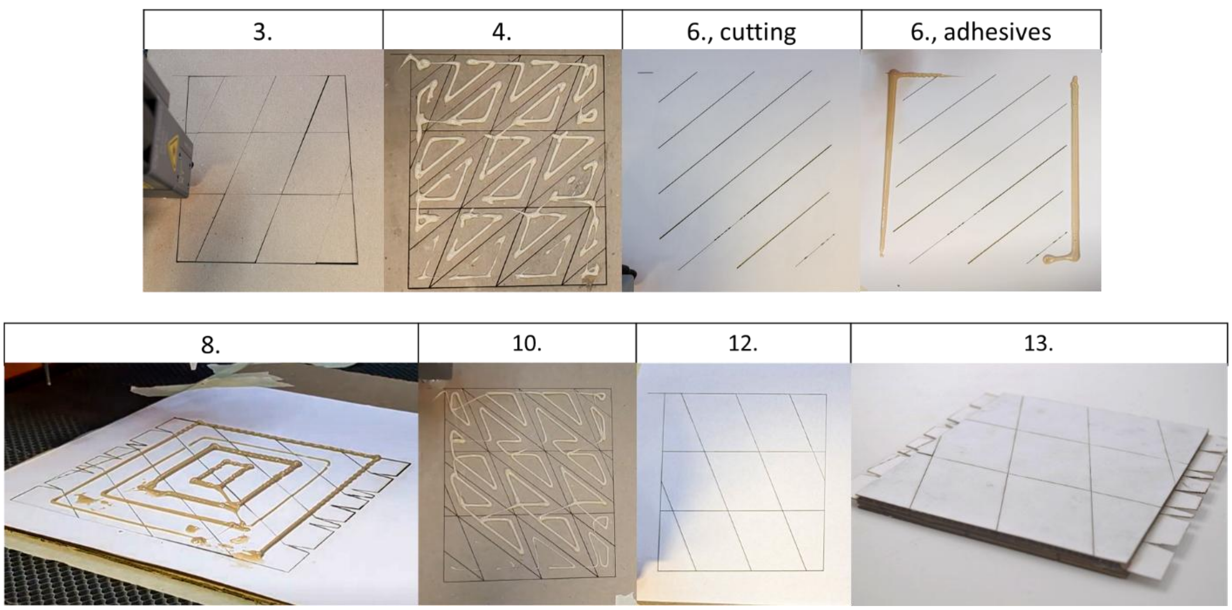


Figure 8: Images of selected steps from the Kresling demo's manufacturing process, with numbers corresponding to the listed step

Manufacturing process:

1. Pre-bond the first paper (P1) and cardboard (C1) layers together
2. Manually place pre-bonded P1 and C1 layer into the machine, with P1 on bottom
3. Automatic cutting, first through both layers (P1 and C1), and then only through C1
4. Automatic adhesive deposition across C1

5. Manually place P2 on top of the previous layers (stack)
6. Automatic cutting and then adhesive deposition (only in tab areas) for P2
7. Manually place P3
8. Automatic cutting and then adhesive deposition (everywhere except the tabs) for P3
9. Manually place C2 onto stack
10. Automatic cutting and then adhesive deposition for C2
11. Manually place P4 onto stack
12. Automatic cutting for P4
13. Demold and deploy final part

The final part, as manufactured, after demolding, and after deploying, are all shown in Figure 9. The cut pieces of the final part were very consistently aligned between layers. The piece demolded successfully with minor effort. Although the current process provided alignment and manual manufacturing time improvements, this demonstration part also had some flaws. Due to the imprecision of the adhesive deposition and the high stiffness of the adhesive after curing, some pieces required manual post-processing to separate or bend them. Some smaller regions had insufficient adhesive deposition, leading to paper-cardboard delamination, as shown in Figure 9e. Additional tuning of the adhesive deposition and exploration of other adhesives could improve the process. Additionally, although the selective-depth laser cutting parameters were tuned to minimize damage to underlying layers, damage still occurred in some regions. Figure 9d shows how overcutting during step 10 caused one side of the tabs connecting the two halves to become weak and shear during deployment. The difference between calibrated and actual cutting performance in these areas may have been due to warping in the stock material or how the cardboard flutes and their orientation affect the cutting parameters. Despite these issues, this demonstration part successfully demonstrated the core goals of the machine and its capabilities for improved performance.

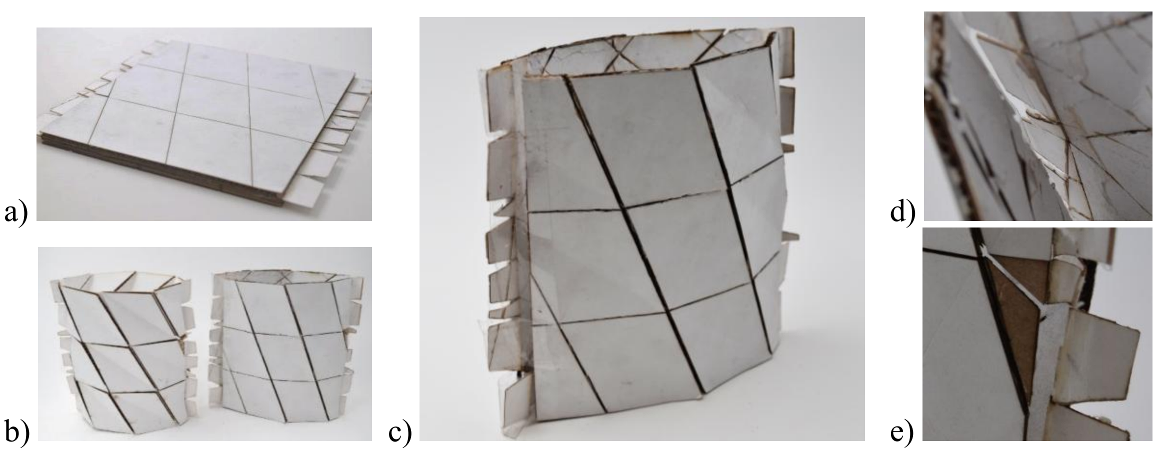


Figure 9: Kresling final part, manufactured using current, automated process. a) isometric view of the as-manufactured (undeployed) state, b) comparison between demos made by the previous, semi-automated manufacturing method (left) vs the automated manufacturing method (right), c) side view of deployed state, d) close view of left, internal edge of the deployed demo, showing sheared edge, e) close view of front right of deployed demo, showing where the paper and cardboard delaminated during deployment

Conclusion

Both prototyping and commercial production of origami-inspired engineering are currently limited by the lack of repeatable, automated mass-manufacturing methods. To address this need, this work describes an implementation of sheet lamination processes that incorporates CNC motion, laser cutting, and adhesive dispensing into an automated workflow. This approach can reduce inter-operator error, increase repeatability, and decrease manufacturing time. Additionally, faster manufacturing of complex designs enables the fabrication of assemblies in a pre-assembled state, eliminating tedious manual assembly. The benefits of automation are especially evident in intricate, multilayer parts, such as the Kresling pattern demonstrated here. Manufacturing a pre-assembled Kresling pattern required precision in both cutting and adhesive deposition. Satisfactory precision was demonstrated through single-layer depth cutting tests, adhesive start-and-stop tests, and the successful fabrication of the digitally-defined demo itself. The Kresling demo was produced with minimal human input and deployed into a 3D shape despite additional calibration needs. Importantly, the Kresling pattern is not the only design with potential for broad, real-world impact if manufactured at scale. As this simple, low-cost manufacturing system matures and scales, it could advance origami-inspired mechanisms and metamaterials from prototypes into transformative commercial technologies.

Acknowledgments

Thank you to Kyle Thatcher, Jackson Hancey, Kelvin Wang, and Terri Bateman for their contributions to development of this project.

This research is based on work that received funding from the U.S. National Science Foundation (NSF Grant No. CMMI-2349124; Funder ID: 10.13039/501100008982).

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