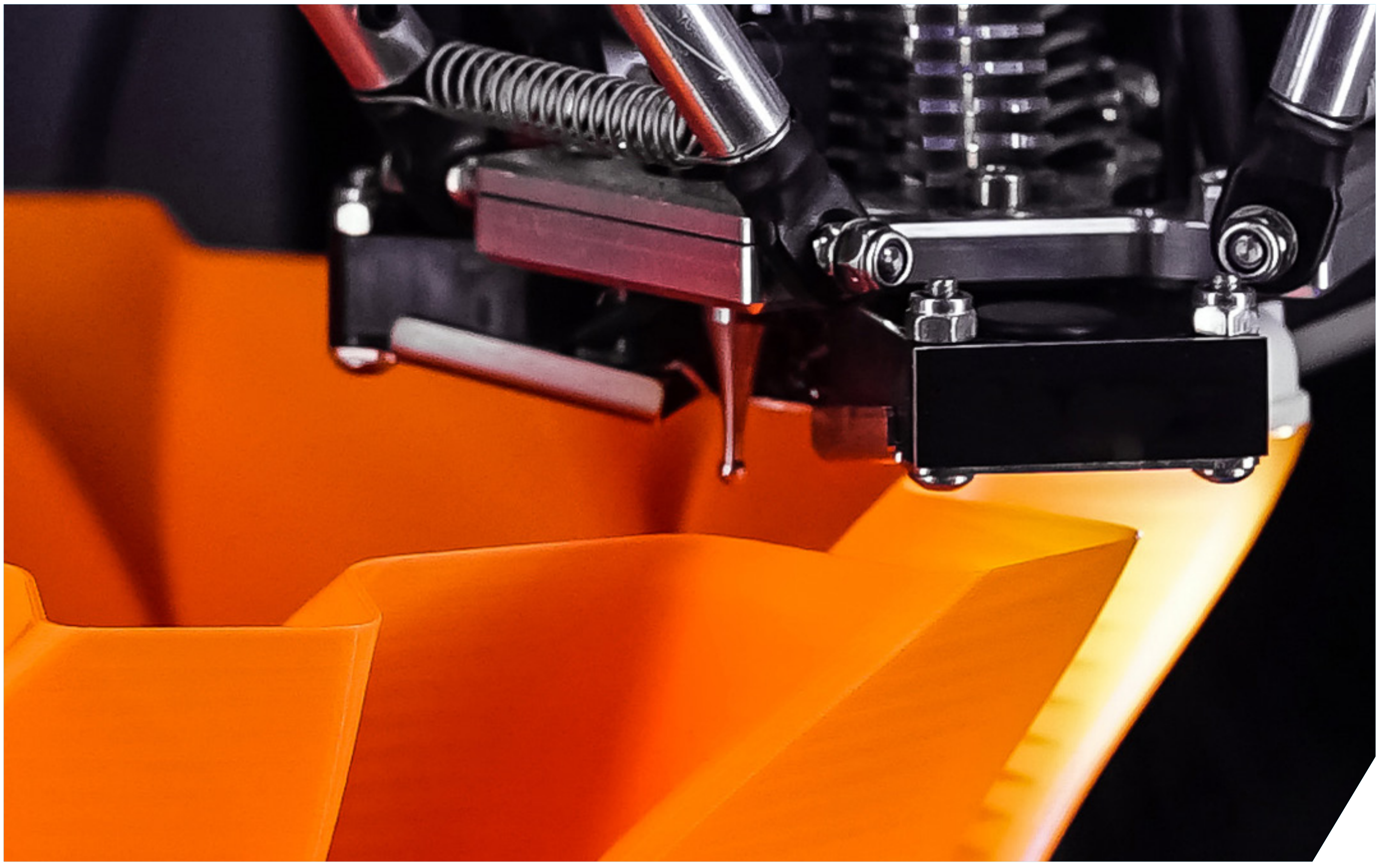

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RECYCLING MATERIALS AND MORE

STUDIES INTO ADDITIVE MANUFACTURING FOR IN-SPACE MANUFACTURING

Three-dimensional (3D) printing or additive manufacturing (AM) using thermoplastic materials has had a profound impact on the engineering field. The ability to use AM for one-off special parts or as a tool for conceptualizing complex details has been applied successfully in various applications. AM using plastics has been applied in areas ranging from rapid prototyping of complex parts to brain surgeons employing models of patient brains to visualize the surgery procedures in advance. However, the use of plastics in additive manufacturing is coupled with an increased public awareness on the need for recycling technologies that will limit the amount of waste going to the landfills.

Advances in AM for space exploration has also been a subject of growing interest as ideas and concepts of long-range space missions evolve. In partnership with the National Space Grant Foundation and NASA, students from the University of Wisconsin-Milwaukee participated in the 2014-15 X-Hab Academic Innovation Challenge. This program is a university-level challenge designed to engage and retain students in science, technology, engineering, and math and simultaneously engage students in pressing research and design topics of interest to the space exploration community.

NASA has recognized the need for new AM technologies not only for environmental sustainability but also for recycling capabilities for replacement parts on long-range spacecraft missions. NASA has embarked on an ambitious program to integrate additive manufacturing techniques and to develop processes for the microgravity environment. The most recent example of this program is the successful launch and deployment of the first 3D printer on the International Space Station. In this one-year effort, students were required to meet a series of milestones to design, manufacture, and test their ideas in close cooperation with members of the NASA Exploration Augmentation Module (EAM) concept team. The X-Hab approach provides a unique method by placing the student teams on the NASA mission-critical path for the technologies considered. The participants in this project were tasked with thinking of new solutions using AM that would simultaneously be recyclable with minimal loss in mechanical properties but also have the capacity for high mechanical properties. The challenge outlined broad criteria for the requirements, including the cradle-to-cradle approach without pre-conceived judgment on the results.

Previous research has shown that the mechanical properties of 3D printed parts depend not just on the type of filament material used, but also on the various build parameters associated with AM. Various process parameters have been found to influence the mechanical properties of AM parts; these include raster orientation, air gap, bead width, color, and model temperature. However, there has been a limited understanding of the process development necessary for recycling 3D printed parts from the procedure from breaking up the component to creating the filament and finally to printing with a recycled filament. Working in interdisciplinary teams, the participant teams investigated the use of recycled materials, characterization, testing, modeling, and tool development. The underlying philosophy adopted in these papers is the ability to use a strut-and-tie approach that integrates reusable carbon-fiber tension ties for tension zones. All materials are designed so they can be recycled or reused. The tools developed show that it is possible to employ thermoplastic polymer materials fabricated using AM together with reusable and flexible high-performance carbon-fiber-based composite ties. The AM printed part is completely recyclable, whereas the carbon-fiber composite ties are repurposed into new structural configurations without loss in properties.

The results of this project encompass a series of interconnected studies exploring the issues surrounding 3D printing in a space environment.

Extrusion and 3D Printing of Recycled ABS Filament for Use in FDM – Lessons Learned

The main component of this study is exploration of the ability to recycle previously 3D printed acrylonitrile butadiene styrene (ABS) parts, as well as to study the effects of the recycling process on the mechanical properties of the material. A number of challenges were encountered which may impact the ability to implement a 3D printing environment utilizing 100% recycled feedstock. Consistency of the filament extrusion process, possible sensitivity of fillers used in the ABS to the recycling process, and the critical nature of the 3D printer's hot end design were all determined to be factors important to the ability to reliably recycle 3D printed ABS objects. The issues encountered were addressed and a successful printing environment established, though room for improvement exists.

During the course of the attempts to establish a consistent and reliable environment for 3D printing of 100% recycled ABS, a number of issues were encountered and addressed. First, the diametral consistency of the filament produced during re-extrusion of previously printed ABS needed to be addressed in the absence of any readily available means to automatically regulate it. This was done by judicious selection of extruder nozzle diameter, as well as adjustment of extrusion temperature and filament drop height. Contamination of the filament became an issue when severe clogging of the 3D printer was encountered. A number of attempts were made to address this, and a partial improvement was seen when hot end cooling was improved. The final success came after the discovery of particulate matter in the filament and the subsequent expansion of the 3D printer nozzle diameter to a size significantly greater than the largest contaminant particle. Though the use of a larger nozzle diameter means a reduction in the ability to print finely detailed parts, it is still small enough for the purpose of printing various hand tools and relatively large structural parts. The expansion of the extruder nozzle was found to reduce the operating pressure inside the 3D printer's hot end and contributes to the reliability of the final parts.

Despite the success in 3D printing of the recycled ABS feedstock, further research would be beneficial. The use of a feedback controlled filament winding mechanism would improve the diametral consistency of the recycled feedstock. Definite identification of the exact cause of clogging in the 3D printer would lead to the ability to print more detailed parts. The first step in such a study could be performed rather simply, by attempting to recycle ABS with no colorant in it. Further spectroscopic analyses could also be performed, in the event that clogging still occurred and a process-based cause was indicated.

Mechanical Properties of 3D-Printed Recycled ABS Materials for FDM Applications

The need for 3D printed recycled parts is vital to the deep space exploration missions NASA hopes to achieve. The need to understand the effect of recycling on the mechanical properties of 3D printed materials is critical to the feasibility of this technology. The science of recycling plastics is not entirely understood. There are a multitude of variables to take into account such of particle size after grinding, melt temperature, humidity during extrusion, and possible inclusion of impurities along with potentially unknown variables that may be over looked. On top of this, several more variables must be contained in the process of 3D printing the new rounds of material. Although there are several routes that can be taken to help make 3D printing in space a reality, getting to understand what controls the consistency of recycling will undoubtedly be at the top of the list. This fundamental understanding of the basic principles will help to drive future research in developing a material that can maintain its properties through multiple rounds of recycling.

This study focuses on the impact that recycling has on 3D printed tools and components on the mechanical properties. It also emphasizes the need to develop a process that has tight controls over all the print and recycling parameters. Material coupons were 3D printed and were put through five rounds of recycling. Each round of recycling was subjected to a tensile test and examined via SEM analysis. The study found that as the material is recycled, there is a noticeable decrease in strength and a more brittle fracture is observed. However, print processing parameters may be critical in influencing the microstructure of the printed parts. Future studies could be as simple and singling out one of the many processing variables and test how the mechanical properties changes and affect the final product.

Effects of Orientation Angle on the Mechanical Properties of FDM Parts

The need for 3D printed recycled parts is vital to the deep space exploration missions NASA hopes to achieve. The need for understanding the effect that various print angles have on the mechanical properties is important to maximize strength while minimizing the material needed. This study focuses on testing the mechanical properties of different print patterns of ABS polymer materials. Material coupons were printed in two separate print patterns, rectilinear and hexagonal, and at angles of 30°, 45°, 60°, 90°, and 180°. Each coupon type was subjected to tensile, compressive, three-point bend and dynamic mechanical analysis.

Tests run to date have been on two different print patterns with increasing print angles. A maximum UTS value of 13.9 MPa (2.02 ksi) was found in the Honeycomb-60° sample, while a maximum UCS of 25 MPa (4.22 ksi) was achieved in the Honeycomb 60° sample. The maximum flexure strength of 41.1 (5.96 ksi) was achieved with the Honeycomb 180°. In tension, compression and flexure, Young's Modulus did not have visual trend in both print patterns with an increase in print angle from 30° to 180°. Analysis of the data showed that the honeycomb pattern was preferred in most cases.

The study found that as the print angle increases from 30° to 180° the variance of the tensile strength increases. In addition the tensile strength increases with increasing print angle whereas different trends were found for compressive strength.

Finite Element Modeling of 3D Printed Materials Using Unit Cell Methods

Mechanical properties of 3D printed material can be modulated by using unit cell method. In this research, a finite element process has been proposed to extract mechanical properties of the 3D-printed structure. The process uses a sub-modeling technique considering unit cells as material properties representatives. The premier tensile and compressive mechanical properties have been obtained by applying appropriate boundary conditions on unit cells. Honeycomb and rectangular architecture of constructed unit cells based on actual printed coupons have been modeled. Unit cell models have the advantage of parametric sizing enabling designer to explore the effect of the cell shape on mechanical properties. The extracted unit cell (UC) properties have been used as the material properties of the coupon level. The verified FE technique has been used to show the effect of cellular structure sizing on 3D printer part.

The study in honeycomb pattern found that as the print angle increases from 0° to 30° the variance of the stiffness decreases. There is a raise in stiffness where the angle increases from 30° to 60°. This trend occurs for the rectangular pattern where the changing behavior angle is 45°. The effects of varying cell wall thickness and leg length have been obtained from parametric sensitivity analysis.

By increasing the thickness and decreasing the leg length, the infill pattern increases. As a result, the stiffness tends to reach solid stiffness properties. The effect of the skin has been determined showing about a 20 percent increase in the unit cell stiffness.

Design of a Carbon-Fiber Reinforced Fused Deposition Modeling Modular Wrench Tool

During extended missions in space, development of methods of extraterrestrial manufacturing are important to give astronauts the ability to create parts and tools on demand. This design study is part of a series for development and application of a carbon-fiber fused deposition modeling Spacecraft Structural Fabrication System (SSFS) for the X-Hab 2014-15 Academic Innovation Challenge. The research focus is on additive manufacturing techniques, composite carbon fiber reinforcement, experimental testing and finite element simulation. Advantages of the SSFS are an increase in manufacturing capability, reduction of the amount of material needed for basic tools in space, and recyclability of part materials. This study specifically focused on design and production of modular tool assemblies, presenting new ways to optimize a proposed modular tool in terms of strength, reliability, weight and print time.

The solution to this problem, through the use of additive manufacturing, was to completely redesign a baseline wrench. Traditional wrenches have separate head pieces or are separate tools all together; these were seen as a waste of space and weight onboard the spacecraft. Combining all these tools into one versatile tool would be favorable for weight and space reduction, and an overall decrease in spending. Two fundamental designs were developed, simulated, and tested, each with their own unique benefits and application. The two tool concepts were proposed specifically for modularity and optimization of the strength to weight ratio of tools using the FDM process and CFRP reinforcements. The two modular designs were a peg-type for bolt size versatility and reach – and Matryoshka nested insert-type wrench tool for maximum torque. Each tool was experimentally tested and analyzed using computational finite element analysis to improve on the design.

The results show that a matryoshka-type nesting design tool achieves maximum strength with a slot insert deign for reach and versatility. The Matroyshka tool exceeded the goal of 3 in-lb capabilities by over 1200% reaching a maximum load capacity of 220 in-lb. This tool was then chosen for optimization for reduction of weight while maintaining the 3 in-lb capacity. The optimized design for the Matryoshka tool saw a 73.9% reduction in volume. This improvement means less material needed to print the part and, hopefully in turn, a reduction in print time. Simulation results proved that by adding CFRP strips to the optimized Matryoshka design, it is possible to achieve reductions in stress intensity and displacement of 778% and 190%, respectively. However, the optimized design ultimately became more complicated to print with the hollow cavity, thus extending print time; see Table 3. In conclusion, creating modular tools would save materials and reduce power consumption adding a cradle-to-cradle technique for manufacturing onboard the International Space Station or for long range missions.

Results are a promising improvement from an existing baseline tool strength of a 3 in-lb rating of the first 3D printed tool in space to nearly 9 ft-lbs in the proposed design. This research shows how it is possible to help reduce the cost in the amount of materials needed to fabricate high-performance and optimized tools. However, optimization may come at a cost of print time, power usage, or post processing for the addition of reinforcement materials. A simple model is a quick and resource effective way to produce a reliable tool. Yet, further exploration of optimization and reinforcement can be beneficial for the overall cradle-to-cradle philosophy.

Carbon Fiber Reinforced 3D Printed Ratchet: Feasibility and Application in Deep Space Missions

A ratchet is a very useful tool in applications on Earth as well as in deep space missions. Being able to create a device like this on demand via a 3D printing process is especially important because of its wide range of practical uses. The ability to 3D print parts in space provides great flexibility for astronauts. It eliminates the need for an inventory of parts that occupy valuable storage space.

An original provided ratchet was designed to withstand a torque of 3 inch-pounds (in-lb) or 0.339 Newton-meters (N-m), but in reality many applications require more than this amount. This original ratchet was designed by Made in Space Inc. and introduced as the first tool 3D-printed on the International Space Station while in space. This project team presents a method of reinforcing the ratchet device with particular use of carbon fiber-reinforced plastics/polymers (CFRPs).

The tool was redesigned in order to incorporate reinforcement by means of CFRP strips for increased strength and stiffness to widen the flexibility of the tool in a space environment. Implementation of carbon fiber strips in the reinforcement of tools for deep space missions reduces the amount of time and material needed for printing parts. Developing a standard for length and width of the carbon fiber strips to be used helps limit the amount of stock material needed, however a supply of virgin material strips is still needed.

Additional improvements to the existing device were reducing the amount of material needed to print it, reducing the time required to print, increasing its strength-to-weight ratio, and improving its recyclability and sustainability. The ability to use carbon fiber in its recycled state allows for a reduced amount of stock material. Due to the savings in stock material used in the modified ratchet, a significant weight reduction of 54.4% was also achieved. In addition to the weight reduction that was observed, the build time for the modified ratchet was improved by 56.25%, which reduced the power consumption by 24%. The use of CFRPs in the ratchet handle with reduced infill density increases the maximum load that the handle can withstand. These improvements enable the tool a greater range of flexibility for the user and reduce overall costs in tool production for use in deep space missions.

As the ability for ratchets to induce higher torques increases, the use of CFRPs becomes more significant. Considerations moving forward in the design of a 3D printed ratchet for sustainable deep space missions would be to design the ratchet to function both clockwise and counterclockwise, and to incorporate a removable pawl. Failure occurs when the pawl becomes deformed after extended use and replacement would allow for higher torque values while only needing to print small replacement parts.

High Performance 3D-Printed Carbon-Fiber Reinforced Crowfoot Adaptive Tool

One of the most important matters in today's industry is the ability to recycle and reuse materials. As the National Aeronautics and Space Administration (NASA) is beginning to create tools using a 3D printer in the International Space Station (ISS), the demand for stronger and recyclable tools has increased.

The focus of this study is on the development and design of a crowfoot attachment for a recyclable ratchet. The focus is to optimize the crowfoot's strength, reliability, and recyclability by using carbon-fiber/ epoxy reinforcement strips. The overall objective is to increase the strength of the crowfoot tool, while maintaining a cradle-to-cradle design. The proposed carbon fiberreinforced polymer (CFRP) design used increased the strength of the tool by 63%.

Experimental results show a significant improvement in the strength of the CFRP aided design over the unreinforced design. The final design utilized a channel printed within the crowfoot which was fitted with CFRP and secured with fasteners. The final design improved the torque over the unreinforced design by 63%. This significant improvement is strong evidence for the viability of using carbon fiber to reinforce tools and other objects manufactured with an FDM process.

The problem of stiffness was evident during testing. Slippage due to deflection of the jaws is an obstacle that must be overcome for creation of a fully successful crowfoot to be useful in a working environment. Without proper stiffness the crowfoot is unable to benefit fully from the added strength afforded to it from the use of CFRP.

Further research into strengthening the current design would begin with methods to stiffen the crowfoot jaws. Possible methods might include using a denser infill pattern in critical areas, or using a jaw design that fully surrounds the nut.

A Recyclable ABS/Carbon-Fiber Reinforced Locking Pliers Tool Using Fused Deposition Modeling 3D Printing Technique

The National Aeronautics Space Administration (NASA) has expressed the need to be able to 3D print strong, reliable, recyclable tools via fused deposition modeling (FDM). In this study, the design of a novel 3D printed locking pliers tool is presented. Although the International Space Station (ISS) toolbox has different variations of metal pliers on the space station, a locking plier tool and other clamp mechanisms would be of great help when the user in space needs to free up their hands.

The locking pliers would need to be adjustable and also have replaceable pieces to account for wear and damage to the acrylonitrile butadiene styrene (ABS) material. The locking pliers tool was designed based off of an industrial designed metal material that is superior in part properties to the ABS printed material used on the space station. The screw located in the average locking pliers tool was removed in favor of a more robust adjustable pin and clip design which would resist wear much better than a threaded ABS design. By reducing the ABS material used in the locking pliers design, the print cost and print time can be reduced. Carbon fiber reinforced polymer (CFRP) strips can then be added as anchors in high tension areas to strengthen and reduce the weight of the part. The printing time required for the pliers sub models is also effectively decreased with less ABS material used.

Through finite element analysis (FEA) and mechanical testing, the part was analyzed for weak points in the design geometry and strength was improved in each stage of the design process. Through mechanical testing, it was found that the weak part of the pliers design was in the jaw area. This jaw weakness was lessened with changes to the part radiuses, the addition of ABS material, and the placement of CFRP strips in high tensile regions. Once the jaw strength was increased to withstand a reasonable applied torque (~11 ft-lbs), FEA was performed on the phase 2 design using ANSYS Workbench (ANSYS Ver. 14.5, ANSYS Inc., Canonsburg, PA) software. This FEA accentuated the areas where the pliers could be optimized for the final design. The final design resulted in a 2.3% reduction in weight and a 50% increase in torque. Print time was also decreased for the final design. The ABS tool design would greatly benefit the space station crew by freeing up the users hands when clamping forces are desired.

The locking pliers product of the tool group offers a strong design that can be recycled after repeated use and part fracture or when significant wear occurs. The carbon fiber strips are designed to be removed when the ABS material is recycled and can be then reused on a reprinted pliers tool or another tool group's tool if needed. This process yields a fully recyclable tool on the space station, which its benefits are realized as tool demand changes.

The original ABS part was strengthened in high stress areas to overcome failure found through FEA and mechanical testing. The FEA and mechanical testing were used in order to optimize the tool design in terms of strength and weight. The design weaknesses found during testing were addressed and the tool design was reinforced to avoid part failure. After the part was optimized in ABS, the handle of the pliers was then reinforced using carbon fiber strips in order to decrease the amount of ABS material used, and also to increase the strength of the handle to allow the pliers to experience larger forces acting on it when turning an object in the jaws. The result of the project is a high strength to weight tool that can be entirely recycled as needed and reprinted if necessary by removing the carbon fiber strips and recycling the ABS material.

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