Layer Alignment and Lamination for the Fully Dense Freeform Fabrication (FDFF) Process

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REVIEWED, August 17 2011

Abstract

Fully Dense Freeform Fabrication uses an adaptive layering method for predefined sheets and uses slices cut by a water cutter or laser cutter machine for manufacturing functional parts through smart layer alignment, adjustable compression system, and compatible bonding materials. Under pressure and heat, layers are attached and form a 3D prototype. This paper presents an automated alignment mechanism and compression bonding method that is functional for a variety of complex parts. The alignment system makes a nest setting by using five linear actuators and the compression system is using an array of uneven pins that are locked by sliding surfaces.

Keywords: Fully Dense Freeform Fabrication, FDFF, Layer Alignment, Layer Bonding

Introduction

Stacking up layers to build a 3D geometry has been practiced at least since the 18th century, using wax layers for topography and photo sculpture (Abd Elghany, 2009). In recent years, different researchers have reported the idea of building metallic prototypes from metal sheets or foil slices. The first research in the area of layer-by-layer or laminated tooling fabrication was reported by Nakagawa and Kunieda (1984). Their work focused on manufacturing blanking dies for sheet metal components. Vouzelaud et al. (1992) reported that

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tools were made by horizontally stacking layers of sheet steel and then joining them. In order to clamp the sheet metal slices together more easily, particularly for cavities, Glozer and Bervick (1992) as well as Walczyk and Hardt (1996) concentrated on stacking the sheets vertically. To investigate robust methods of joining metal sheets for the manufacture of tools, Bryden et al. (2001) described the Lastform project, a three-year EPSRC (IMI) program, in which industry partners and three universities tested different suitable adhesive and braze joining methods under several process conditions. Following the Lastform project, a group of researchers (Gibbons et al., 2003) and industry partners conducted comprehensive research on the laminate manufacturing of die-cast tooling. In their project, suitable material for die-casting industry was carefully selected. The analysis of cutting condition, thermal fatigue, heat treatment of bonded laminate structure, the selection of perfect joining material bearable at extreme high temperature, the optimal way of cutting direction, the design of suitable cooling channels and finally finishing of the prototype by CNC machine followed. Other researchers have proposed the application of the CNC material removal processes in building functional prototypes (Frank, Wysk, & Joshi, 2004; Schmitz, Davies, Dutterer, & Ziegert, 2001).

In more recent research, Himmer et al. (2003) adopted a multiple laser process for cutting the sheets, joining them using laser welding and finally CNC machining for improvement of surface quality in a fully automated manner. To prototype injection moulds for plastic parts, Mognol et al. (2006) proposed hybrid rapid tooling (i.e. high speed machining, electro discharging machining and direct metal laser sintering) for the purpose of achieving the manufacture of each component of the mould and greater reaction to diverse group of products. Additional research in rapid tooling presented by Perchtl et al. (2005) addressed the potential challenge of the low self stiffness of metallic foil which is used in the manufacture of moulds for gravity casting, die casting or injection molding. To solve this problem, he developed a two sub-process technique. In the first sub process, each layer is stacked and positioned accurately over the previous slice by laser beam spot welding. To enhance the mechanical properties of the part, a second sub-process followed, involving diffusion welding in a furnace with inert gas or vacuum. Ultrasonic bonding of thin foils has also been introduced to rapid prototyping of sophisticated layered parts by which the selected patterns of the new thin foil slice is ultrasonically welded to the previous laid layers (Devine, 1984; Gao & Doumanidis, 2002; Kirzanowski, 1989).

This paper proposes a layer aligning and a multi layer bonding approach for the fully dense freeform fabrication (FDFF) that can accurately align and position layers together in a short period and then bond them together under pressure and heat. The rest of this paper is structured as follows. The FDFF process is described and the FDFF application of metallic parts is demonstrated in section 2. The potential error accumulation for the layered model is shown in section 3. The proposed layer alignment mechanism and compression bonding method are then presented in section 4 and 5, respectively. To ensure the quality of the fabricated parts, mechanical tests are developed and conducted in Section 6, and the functional parts are illustrated in Section 7. Section 8 offers conclusions and suggestions for future research directions.

Fundamentals of the FDFF Process

FDFF is a freeform fabrication process based on thin line cutting processes (e.g., abrasive waterjet cutting or laser cutting), variable thickness layering, slicing in different orientations, and bulk layer attachment. The combination of these capabilities enables the production of good quality complex parts from practically any material, including metals, plastic, wood, wax, ceramic, and even glass, at a very fast pace. Using this method, a CAD model is sliced into computer layers; the material sheet is then cut from the computer layers. After adding the bonding materials between layers, the layers are aligned into a workholding system. Using pressure and/or heat, layers are attached to form a 3D prototype from a fully dense material (see Figure 1). The following paragraphs describe the subsystems of this process.

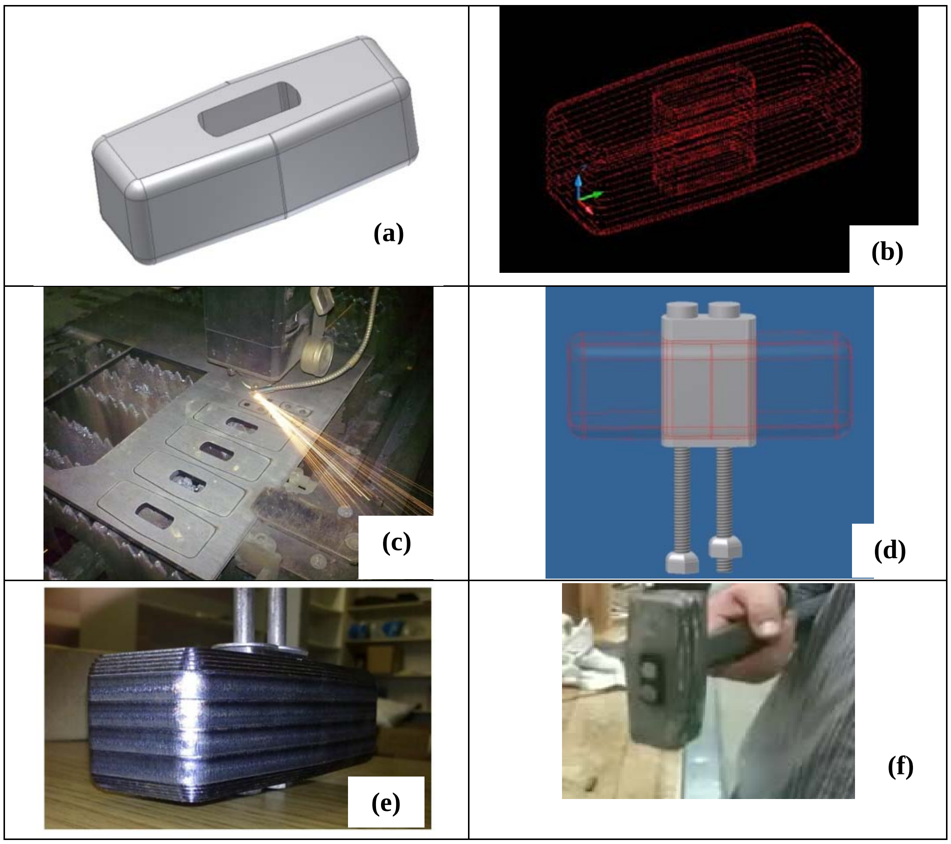

Figure 1. General steps for the fully dense freeform fabrication (FDFF) method for a demolition hammer head: 3D solid modeling (a), adaptive slicing (b), abrasive waterjet cutting or laser cutting (c), alignment tooling design (d), bonding layers (e), and final product test (f).

The Error Accumulation and Workholding Requirement

The tooling necessary for the construction of a FDFF part must satisfy two requirements. First, the tooling must be able to maintain alignment of the slices relative to each other. Second, the tooling must maintain pressure on the part in order to get a proper bond. Unlike the 3D parts in the space that have six degrees of freedom and 12 movements (moving along and rotating around X, Y, Z axes and their opposite directions), for the stacked slices six movements including movement along X+/- and Y+/- and rotation around Z+/- need to be limited. Similar to the concept of 3-2-1 rule (Nee, Dufraine, Evans, & Hill, 2010), to limit these movements at least four locating points for each layer are needed. These locating points need to touch the part, limit one of the X+/- or Y+/- movements, and be perpendicular and as far as possible from adjacent ones (Figure 2).

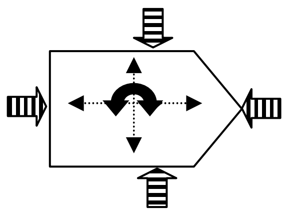

Figure 2. Six movements and four locating points (hatched arrows).

Accuracy of the final part depends on the geometrical accuracy (related to abrasive waterjet cuter) and the dislocation (deviation from position and orientation) of the actual layer compared to the CAD model of each layer. Figure 3 illustrates the error of the positioning of the layer. The surface that is formed between the boundary of the actual layer and CAD model is the error for the layer.

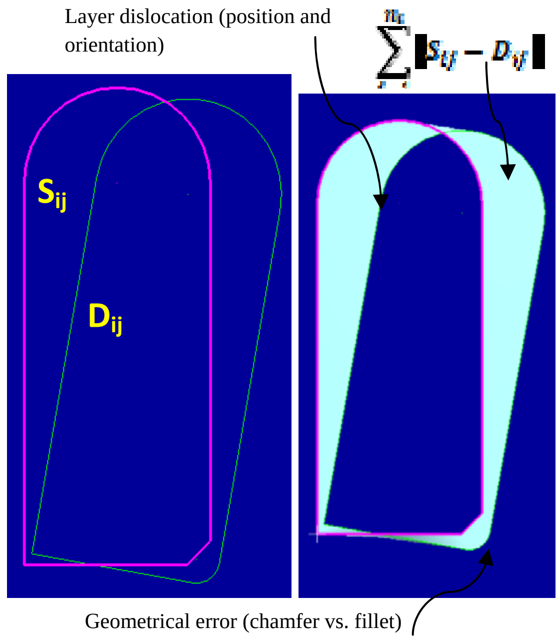

Figure 3. Error calculation for layer k with dislocation and geometrical error.

The optimum point will be minimization of the following equation:

$$\sum_{i=1}^{m} \sum_{j=1}^{n_i} |S_{ij} - D_{ij}| \qquad \text{Equation (1)}$$

Where:
m: Number of layers
n_i: Number of features in layer *i*
S_{ij}= Actual position of feature *j* layer *i*
D_{ij}= CAD model position of feature *j* layer *i*

Layer Alignment Mechanism

The design was broken up into subsystems. The first major subsystem would be a work table that could be raised and lowered, forming a stable, but traveling platform for the work piece to rest on. The second was an x and y positioning system that could reach any point above the work table and on its perimeter from two screw-driven actuators powered by stepper motors. The third was a means of temporarily holding pieces together after they had been placed so they could be safely transferred to the heating and clamping process. This was determined to be best supplied by a low-temperature solder or an adhesive for non-ferrous parts.

The alignment mechanism uses a list of variables corresponding to the extreme points of the outline of each layer generated in the FDFF adaptive slicing software. A system of linear actuators move pins horizontally to each of the points, providing a stencil for the location of the layer to be placed. The sliced layer and bonding material is then placed into the four-point stencil. Another actuator lowers the work table to proceed to the next layer, and the process is repeated.

Two types of actuator were designed. The actuators that controlled motion of a rod into and out of the 8 x 8-inch worktable area would be mounted onto the traveling part of the second type of actuator that moved along the perimeter of the worktable. They would be controlled by an Arduino micro-controller board with 54 outputs and an array of H bridges. The controller board is given input via an Arduino developed command language that works in a Java virtual machine environment.

The lower actuators would be mounted on a wooden table with an eight-inch square hole in the center parallel to the sides of that hole. The hole would surround an 8 x 8 inch work table that travels up and down due to a 12-volt, 10-ampere, motorized carjack powered by a power supply from a personal computer.

Extreme x and y coordinates are obtained from computer-assisted design files for each metal slice and are used to provide coordinates for the stepper motors to move at a fixed speed. The stepper motors move so that the end effectors of the rod extending from the top actuators are located on the entered coordinates. The effectors restrain the placement of the metal slice in relation to a reference point on the work table. They form a reconfigurable tooling fixture for each slice. After being cut, and removed from the source plate or sheet, if necessary, each slice is sandblasted or otherwise cleaned of corrosion, oils, or other debris. The slice is gently coated with slurry composed of tin, bismuth, and flux. The slice, once prepped and placed, is lowered manually on the worktable, using the control switch for the carjack, until the top is flush with the edge of the hole in the outer table. Accuracy and precision are more important in the x and y directions that the z direction, so height of the table does not need to be exact.

A set of new coordinates are entered. The end effectors of the top actuators are moved to the extreme coordinate boundaries of the new slice, which is placed on top of the previous slice, guided by the effectors. Next the slice is soldered or glued to the previous slice. The prototype is then removed from the work table and clamped and heated until it is fused into the finished prototype. Eight 1.8-degree, NEMA 17-size stepper motors running at 12 V and .91 A are controlled by eight SN75441 dual H-bridge drivers, which are controlled by an ATMega2560 running Arduino firmware. The SN75441 chips are capable of outputting 1 A of current and have thermal protection built in. Nonetheless, the chips have heat sinks attached because they operate very close to their maximum current rating. The linear actuators use lead screws with 20 threads per inch. Coupled with the 200 step per revolution stepper motors, this gives the actuators a theoretical accuracy of 1/4000 of an inch. Both momentary switches in the project use a basic pull up configuration (Figure 4).

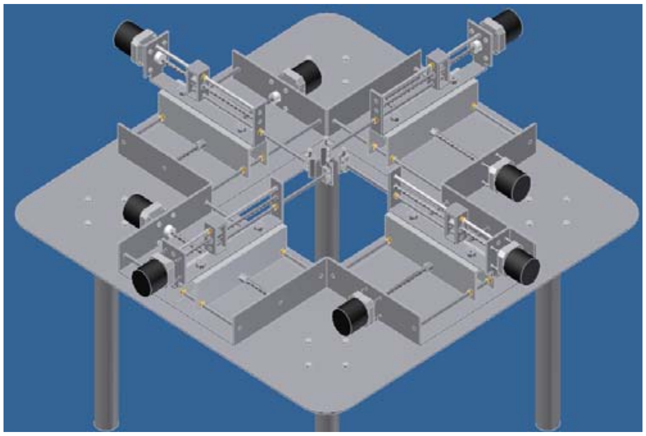


Figure 4. Layer alignment system design and implementation

Compression mechanism. After all layers are aligned and temporarily bonded, they are placed in the laminating mechanism consists of the compression and heat components. The main requirement for this mechanism is to provide secure clamping on oddly shaped surface, provide sufficient clamping force, provide constant force while heat is applied, and allow for even and thorough application of heat.

In the laminating system, a series of pins are used to touch the surface of the part and then be secured to prevent movement. Pins in uneven heights allow uniform pressure to the part top and bottom. The number of pins is the user's choice. More pins give more flexibility on shapes while fewer pins are easier to lock. To create the required locking friction for the pins, three plates with concentric hole patterns are used for multiple pin placements. Clamps are then placed on the edge of the three plates to secure the pins by means of misalignment. Threaded pins are then used to increase the friction between the plates and the pins. After locking pins, a lifting mechanism lifts the bottom part and provides the required bonding force. In addition, a heat source is used to melt the bonding materials and join the layers (Figure 5).

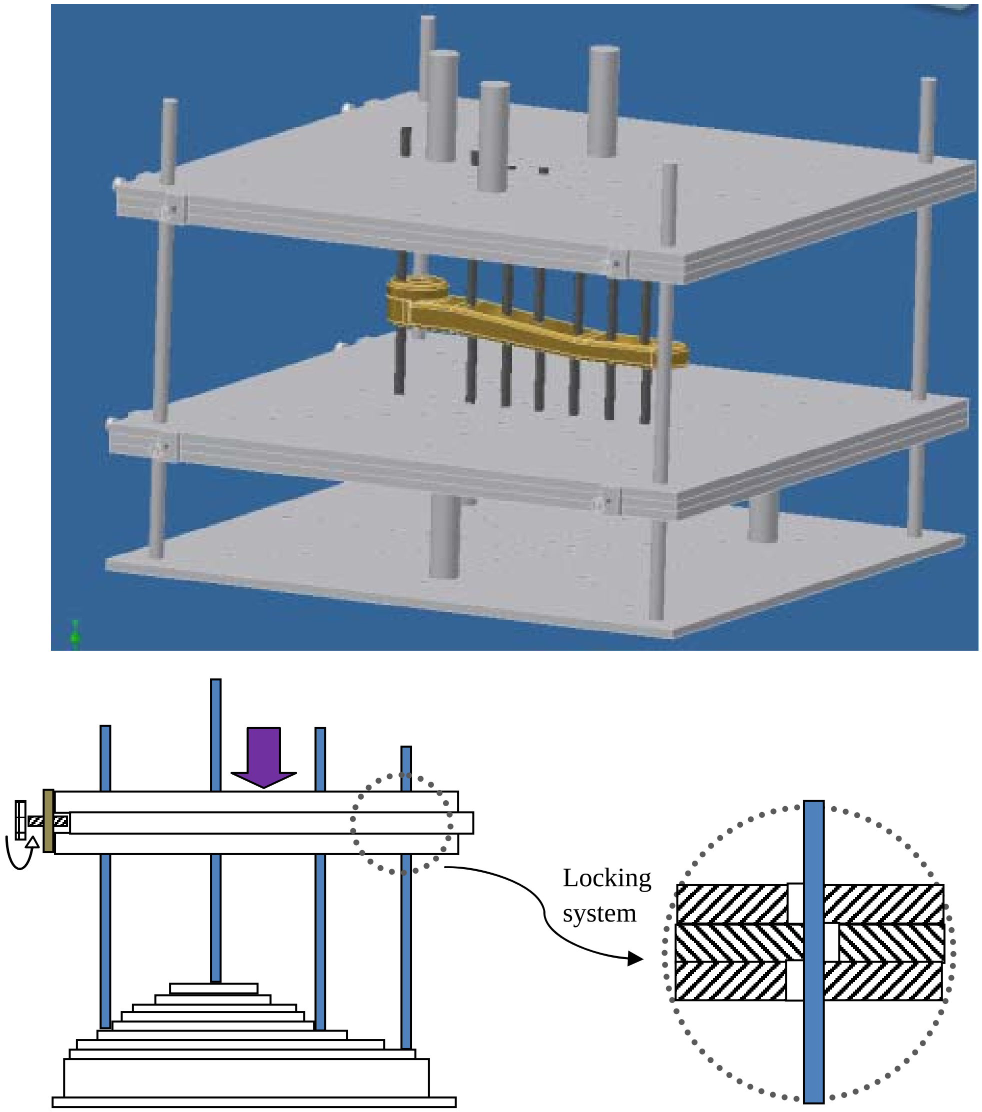

Figure 5. Uniform force distribution to the layers by adjustable pins

Mechanical Tests: Bonding (Tensile) Test

ASTM Standard D 2294-96 is the standard testing method for creep properties of adhesives in shear by tension loading for metal-to-metal contact. In this test, maximum tension that leads to the bond fracture is a good criterion for evaluating the bonding strength (Figure 6).

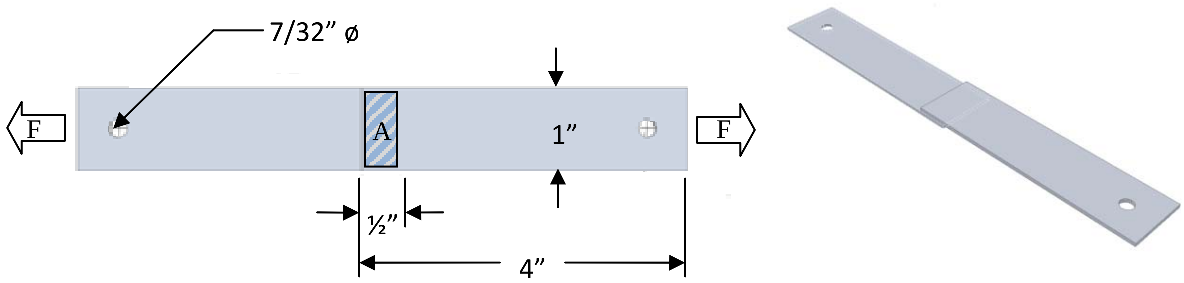

Figure 6. ASTM standard 2294-96 configuration.

Two samples for each of three bonding materials of 0.1, 0.24, and 0.5 grams for Tin-Bismuth mixtures of 50%, 60%, 70%, 80%, 90%, and 100% Tin percentages (total 36 sample) were pulled apart using a Tinius Olsen Electro Mechanical Tester, 600kN capacity. The software determined the pull rate and measured the ultimate psi required to pull the joints apart. Two similar experiments using stainless steel and galvanized sheet metals were conducted.

After comparing the results from similar tests for two different materials for the sampling sheets (Galvanized and Stainless steel), it is obvious that weight and Tin-Bismuth have minimal effect on the bonding and tensile strength compared to the base material that is used for the sheet. As shown in Figures 7 and 8, galvanized sheet metal has considerably higher tensile strength than stainless steel sheet metal.

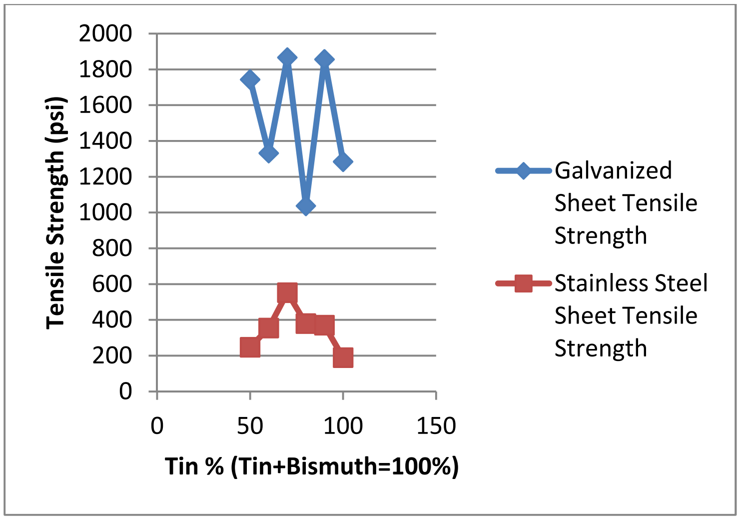

Figure 7. Galvanized and stainless steel sheet tensile strength comparison based on the tin-bismuth percentage

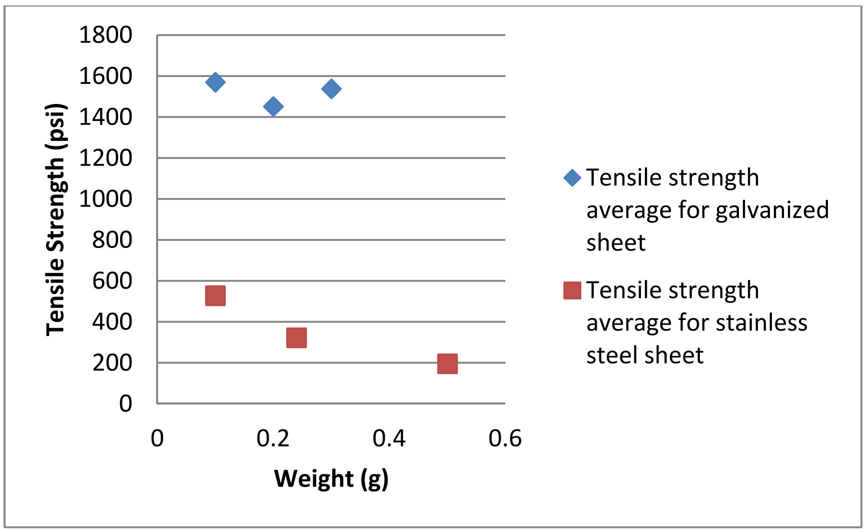

Figure 8. Galvanized and Stainless steel sheet tensile strength comparison based on the bonding mix weight

Functionality test for metallic parts. To illustrate the flexibility of the FDFF process in producing a variety of functional parts, this section presents and tests several functioning parts, including a demolition hammer head and bike crank.

Prototype 1: Demolition hammer head. The main expected mechanical property for a hammer is its high impact strength. For this hammer, a 0.25-inch stainless steel and a 0.03-inch stainless steel sheet were inserted as the available sheets into the FDFF software. As expected, the adaptive layer assigned a thicker sheet for the areas with a uniform cross-section and a thinner one for the curved area. The FDFF software output is compatible with both abrasive waterjet and laser cutter machines. In this example, both thick and thin hammer head layers were cut using the laser cutter. To attach the layers, a 60%–40% tin-bismuth powder mix wetted by J.W. Harris Stay-Clean® paste flux was used. After alignment, the layers were clamped and the part was heated in an oven at 550^{o} F. Figure 9 illustrates the hammer head prototyping and test. More videos illustrating the hammer head functionality tests are posted in the following links: http://www.youtube.com/watch?v=aF1o1L3TYvU and http://www.youtube.com/watch?v=GerJOYjc57M.

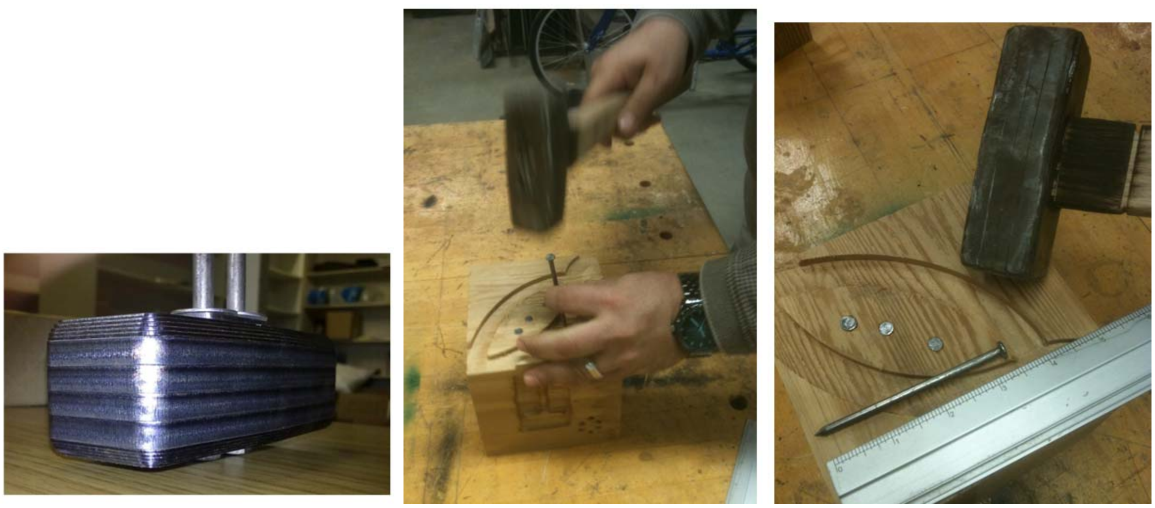

Figure 9. Demolition hammer assembly and test

Prototype 2: Bike crank. The second prototype is a bike crank. This sample is made of 0.25 in. and .025 in. stainless steel sheets and bonded with .003 in tin foil. The internal feature tooling method was used to align the layers. A propane torch was used to heat the crank for three minutes. The functionality of the sample was tested on a real world condition experiment (Figure 10). This part later was tapped and installed on a bike and used as a functional part. A video illustrating the bike crank functionality test is posted on YouTube in the following link: (http://www.youtube.com/watch?v=Jjn9fCpwpvA)

Figure 10. Fully dense bike crank manufactured by the FDFF process and functional test

Conclusion

Fully Dense Freeform Fabrication (FDFF) process utilizes an adaptive layering method for predefined sheets and uses slices cut by a water cutter or laser cutter machine for manufacturing functional parts through smart layer alignment, adjustable compression system, and compatible bonding materials. Under pressure and heat, layers are attached and form a 3D prototype from a fully dense material.

This paper presents an integrated alignment and compression method that is functional for variety of complex parts. The alignment mechanism uses a list of variables corresponding to the extreme points of the outline of each layer generated in the FDFF adaptive slicing software. In the layer bonding system, a series of pins are used to touch the surface of the part and then secured to prevent movement. Pins of uneven heights allow uniform pressure to the top and bottom parts.

The advantages of the FDFF system over other processes are its fast cutting processes, capability of generating slices of variable thicknesses from a predefined standard sheet, and ability to produce parts from any material; an abrasive waterjet cutter can cut any solid material up to 8 inches thick. The latest generation of abrasive waterjet cutters is capable of micro machining. Therefore, this process can be used for fully dense micro scale components.

Future research directions of the FDFF process should focus on materials and processes to improve bonding properties between layers as well as extensive stress and flexure tests following ASTM standards. As shown in the results section for bending and tensile tests, there may be a tradeoff among the desired mechanical properties for different thicknesses and bonding materials. Research should also explore the generation of adaptive paths with variable cutting angles for the five-axis abrasive waterjet cutter machine to cut with both positive and negative angles. Such additions will significantly improve the dimensional accuracy and the surface quality of the parts.

Another area of research is the elimination of the layer attachment stage. A robotic arm addition to the layer-cutting stage will enable the process to position the new layer to the predefined position accurately, eliminating the need for a layer alignment step.

With the use of five axis abrasive waterjet cutter machines that are capable of making angular cuts to each layer, the staircase effect of the parts can be significantly reduced, producing more accurate parts (Figure 11).

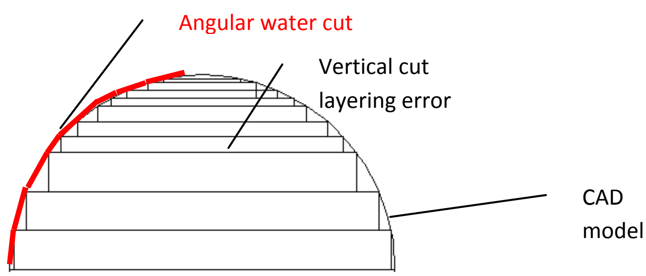

Figure 11. CAD model, layered part, layering error, and near perfect angular abrasive waterjet cutter.

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