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The Development of a Laminated Copolyester Electric Guitar

Addison S. Karnes
East Tennessee State University

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The Development of a Laminated Copolyester Electric Guitar

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In partial fulfillment
of the requirements for the degree
Master of Science in Technology, concentration in Engineering Technology

by
Addison Scott Karnes
December 2014

William K. Hemphill, Chair
D. Dean Isham
Andrew J. Czuchry, Ph.D.

Keywords: Copolyester, electric guitar, lamination, waterjet, sustain

ABSTRACT

The Development of a Laminated Copolyester Electric Guitar

by

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This thesis is an investigation of the fabrication and assembly methodologies employed in the development of a proof-of-principle prototype electric guitar composed of laminated copolyester. The objective of the project was to develop the processes and procedures to create an optimized physical and visual bond between layers to minimize vibratory dissipation, thus maximizing sustain. A high speed CNC router, abrasive waterjet, laser engraver-cutter, as well as various manual fabrication and assembly methods were investigated in the construction of the guitar prototypes. The lamination processes explored include low-temperature, heat-assisted pressure bonding, solvent and chemical welding, and contact adhesives. The project concluded with the completion of a working guitar comprised of a laminated copolyester body and a traditional bolt-on wooden neck.

ACKNOWLEDGEMENTS

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- Mr. Dean Isham and Dr. Andrew Czuchry, my thesis readers, who were a tremendous help throughout this project.
- Dr. Bill Heise, Innovation Manager of Eastman's Innovation Lab, who donated the copolyester to ETSU
- Mr. Daniel O'Brien, ETSU's Director of Environmental Health & Safety, who provided me with lab space and materials for my experiments
- Mr. Brian G. Evanshen, ETSU's Environmental Health Sciences Lab Research Specialist, who provided me with my lab safety training and equipment.

I would also like to especially thank Mr. William Hemphill, my thesis chair and advisor, without whom, I would not have been able to complete this project. He went above and beyond the scope of a typical thesis chair, devoting more time and energy into helping me develop this thesis than I could have ever imagined.

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CHAPTER 1

INTRODUCTION

A Copolyester Guitar

The concept of a copolyester guitar was originally conceived in the Spring of 2012 during a meeting at Eastman Chemical Company. The purpose of this meeting was to discuss the possible applications of Eastman's specialty plastic, copolyester. Eastman offered to donate copolyester sheets to the Machine Tool Fabrication Lab at East Tennessee State University in exchange for an electric guitar constructed from their material.

Mr. William (Bill) Hemphill, Associate Professor of Engineering Technology at ETSU and coordinator of the guitar building project, was informed of their offer, and a cooperative relationship between ETSU and Eastman was established. Soon thereafter, Eastman provided several sheets of copolyester for experimental research. Mr. Hemphill created a proof-of-principle "space frame" guitar (see Figure 1) created from ¼" thick copolyester using ETSU's OMAX waterjet. Upon receiving the prototype, Dr. William Heise of Eastman's Innovation Lab provided additional copolyester to ETSU for further research.

Figure 1. First Proof-of-Principle "Space Frame" Copolyester Guitar

This proof-of-principle prototype demonstrated that the engineering geometry required for the construction of an electric guitar body could be generated in a sheet of copolyester using an abrasive waterjet. Typically electric guitar bodies are CNC machined from solid slabs of laminated wood known as guitar blanks. This project, however, documents the processes and procedures performed in order to build an electric guitar body from sheets of copolyester. This required the copolyester sheets to be machined as individual layers and laminated together.

Solid body and semihollow body electric guitar blanks typically range from 1.625" to 1.750" in thickness planed down from 8/4 stock (i.e. 2" rough cut). Wooden guitar blanks are typically laminated longitudinally (i.e. along the long or string axis) and clamped transversely (see Figure 2). The center is one solid piece directly connecting the neck to the bridge in order to best transmit vibration.

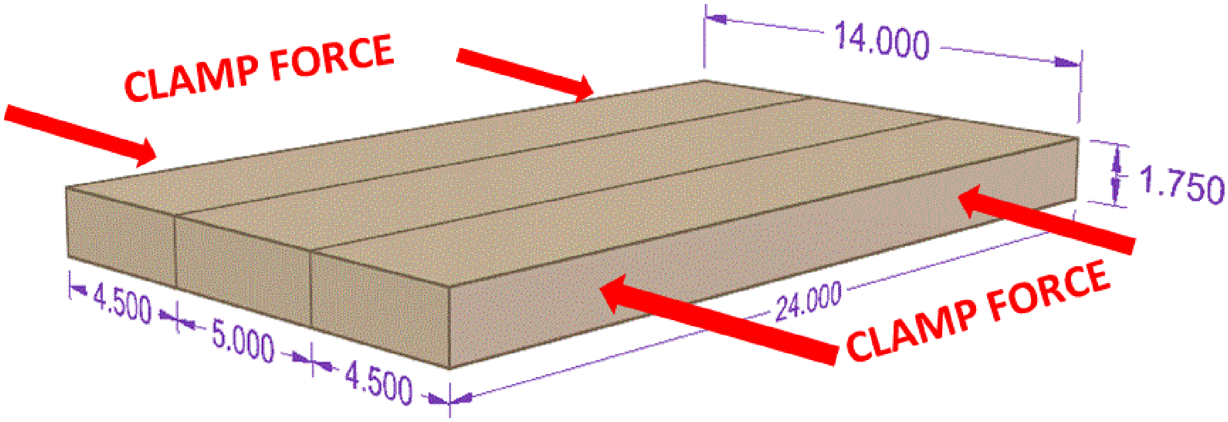


Figure 2. Longitudinal Lamination of Wooden Guitar Blank

Some solid body and semihollow electric guitars use highly figured, high cost "caps" of figured wood (e.g. book-matched maple) produced in a two-part hybrid process: (1) create longitudinal laminations (standard solid body electric guitar blank); (2) secure cap piece(s) to top of laminated blank using vertical clamping veneer press (See Figure 3).

The top cap is for aesthetic purposes only. The vibrations are transmitted through the lower 1.500" core.

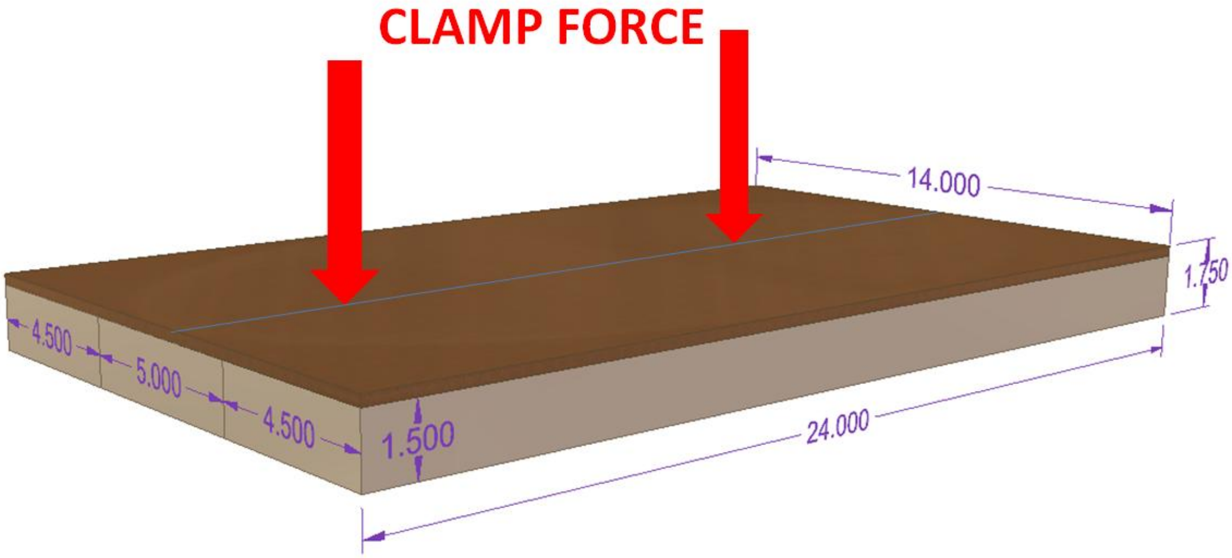


Figure 3. Vertical Clamping Veneer Press of Capped Wooden Guitar Blank

Copolyester is commercially available only in sheets of specific thicknesses: 0.060 (nominally 1/16"), 2mm (nominally 5/64"), 3 mm (nominally 1/8"), 4mm (nominally 5/32"), 6mm (nominally 1/4"), and 9.5mm (nominally 3/8"). In preparation of the blank, the lamination of copolyester sheets would be more along the lines of preparing multiple "caps." There is no central homogenous "core," so the vibration pathway is more diffuse.

Production Phases

The following production phases are required to create the necessary components of a laminated polymer guitar body and assemble a playable guitar:

- Conceptual design using AutoCAD 2D, Rhinoceros 3D, and Solid Edge
- Layers cut on OMAX 5555 JetMachining Center
- Layers laminated on alignment tooling using Loctite® spray adhesive
- Reference hole spotting on AXYZ 4010 high speed CNC router
- Body finishing with drill press, belt sander, and blowtorch
- Faceplate and cavity cover cut using Universal Laser Systems laser cutter-engraver
- Hardware and electronics installation
- Neck fabrication and assembly
- Final assembly of neck and body

CHAPTER 2

LITERATURE REVIEW

Anatomy of a Solid Body Electric Guitar

Figure 4 (below) depicts 15 of the principal features of solid body electric guitar.

Figure 4. Anatomy of a Solid Body Electric Guitar

Body - The primary part of the guitar to which the bridge and neck are attached. It houses the pickups and electrical components.

Bridge - Attached to the body, it anchors or turns the strings and transmits string vibrations through the guitar body. The type of bridge used in this development effort is a nontremolo, string-through design wherein the strings are held in place on the back side. This bridge has individual saddles for each string that can be adjusted to set the string height and length for intonation.

Fretboard - Often called the fingerboard, it is the surface on which the strings are pressed when playing a note.

Fret Dots - Reference indicators of fret position on the fretboard.

Frets -Pressed into the fretboard, these metal wires serve as tension points when the strings are pressed against the fretboard.

Headstock -The flat end of the neck where the tuners are mounted for tensioning the strings.

Neck - Attached to the body, the neck supports the fretboard and provides the playing surface.

Nut - Located at the end of the fretboard 25.5" inches away from the bridge , the nut cradles the tensioned strings.

Output Jack - Typically 1/4" in diameter, the output jack transmits the electrical signal from the guitar to the amplifier via a 1/4" signal cable.

Pickguard - An optional plate covering the surface of the guitar protecting it from pick scratches. In some solid body designs the electrical components are mounted onto the pickguard.

Pickups - Inductive electromagnetic coils that produce an electrical signal when the strings vibrate across the pole magnets. The weak signal produced by the guitar is amplified externally. Single coil pickups consist of either North or South pole magnets. Humbucking pickups consist of two single coil pickups with opposing magnetic pole orientation wired in series.

3-way Pickup Selector - Switches the output signal between the neck, bridge, or both pickups.

Volume Control - A potentiometer and external knob that regulates the output signal voltage. Typical humbucker guitars use 500 kΩ audio or logarithmic resistance taper.

Tone Control - Coupled with a capacitor, this potentiometer and knob allow the guitarist to control the shape of the signal waveform creating differences in sound by adjusting the high or low pass filter. Typical humbucker equipped solid body electric guitars use a 0.022µF or 0.047µF capacitor with 500 kΩ audio taper pots.

Tuners - Mechanical tensioners mounted into the neck's headstock used to adjust the frequency of string vibrations.

Guitar Engineering

String Length

One primary consideration when constructing a stringed instrument is string length. On solid body electric guitars, as long as the proper string length is matched to the fret spacing, everything else is negotiable. String length is measured as the distance between the nut and the bridge saddle. For the High E string a standard string length of 25.5" will produce a fundamental frequency of 330 Hz and a first harmonic of 660 Hz. That means that the 12th fret (50% of the string length) will produce a frequency exactly twice that of the open string if its distance is exactly half the distance between the nut and bridge saddle (see Table 1).

Table 1.

String Properties for Standard Electric Guitar Tuning

String	6	5	4	3	2	1	String Length (From Bridge Saddle)
Note	Low E	A	D	G	B	High E	
Fund. Frequency (Hz)	82	110	147	196	247	330	25.5"
First Harmonic (Hz)	164	220	294	392	494	660	12.75"
Second Harmonic (Hz)	246	330	441	588	741	990	8.5"

In a process known as intonation the bridge saddle can be adjusted forward or backwards to fine tune the relative position of the 12th fret. During the process of intonation the bridge saddles are adjusted individually for each string to ensure that the 12th fret generates a frequency exactly twice that of the open string for each string to accommodate the strings of different diameters and construction. The second harmonic of the High E string would be 990 Hz or three times the fundamental frequency. However, the second harmonic can only be fretted on a 24-fret (or greater) guitar neck. On a 21-fret neck, the second harmonic can be only measured as an undertone when playing the fundamental frequency or first harmonic or played as a "harmonic" by touching and removing a finger to the string at the virtual location of the 24th fret.

Sustain

Sustain refers to the duration of time for which a string vibrates before its amplitude drops below the threshold of hearing. There are many factors affecting the sustain of an electric guitar such as body material, body design (solid, hollow, etc), body shape, neck material, fretboard material, nut material, string placement (through body or surface-mounted), string gauge, string spacing, electronics, and so on. It is generally accepted that the body material, neck material, fretboard material, and quality of any body-neck joint will all have a significant effect on the sustain of the guitar.

When a guitar string is plucked, the magnitude of the vibration quickly swells to a peak in approximately 0.5 seconds then exponentially decays, or attenuates, over a period of time (see Figure 3). The duration for which this frequency remains audible is known as sustain.

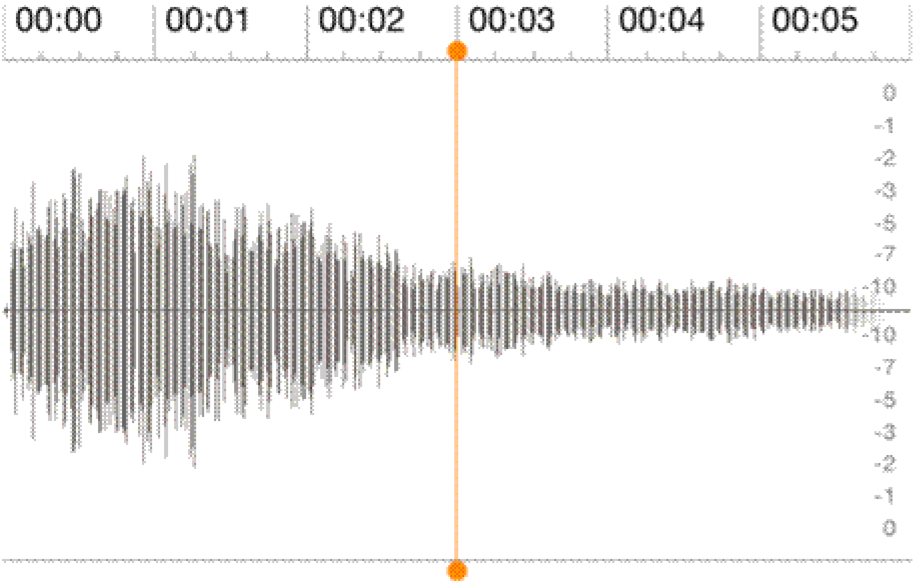


Figure 5. Sample Vibration Over Time

The key to maximizing the mechanical sustain of an electric guitar is ensuring the structural stiffness between the bridge and the nut. This is accomplished through the tight joining of the neck to the body (i.e. the more rigid the joint, the greater the vibratory transmission). Some solid body electric guitars feature bolt-on necks (Fender), and others feature glued mortise-and-tenon neck joints (Gibson). The greatest sustain, however, is produced by through-neck body construction. In a through-neck guitar, the neck and central body are machined from a single slab of wood. There are no vibratory transmission losses across the neck joint because there is no joint at all.

Electronics

One standard electronics package used in solid body electric guitars consists of two humbucking pickups, one 500kΩ audio taper volume potentiometer, one 500kΩ audio taper tone potentiometer with a 0.047µF or 0.022µF capacitor, a three-way pickup selector switch, and a ¼” output jack. The configuration shown in Figure 6 allows the humbuckers to be selected individually or together. Note that the configuration used in this guitar differs slightly from the schematic below. Humbucking pickups provide the added benefit of signal interference cancellation. Wired in series, the two pairs of oppositely oriented magnets cancel or “buck” any electromagnetic hum induced by stray radio frequency interference, thus creating a cleaner output signal. The passive resistor-capacitor (RC) circuit serves as a low-high pass filter. The RC circuit varies the resultant frequency profile between bass-pass (warm sound) and high-pass (bright sound).

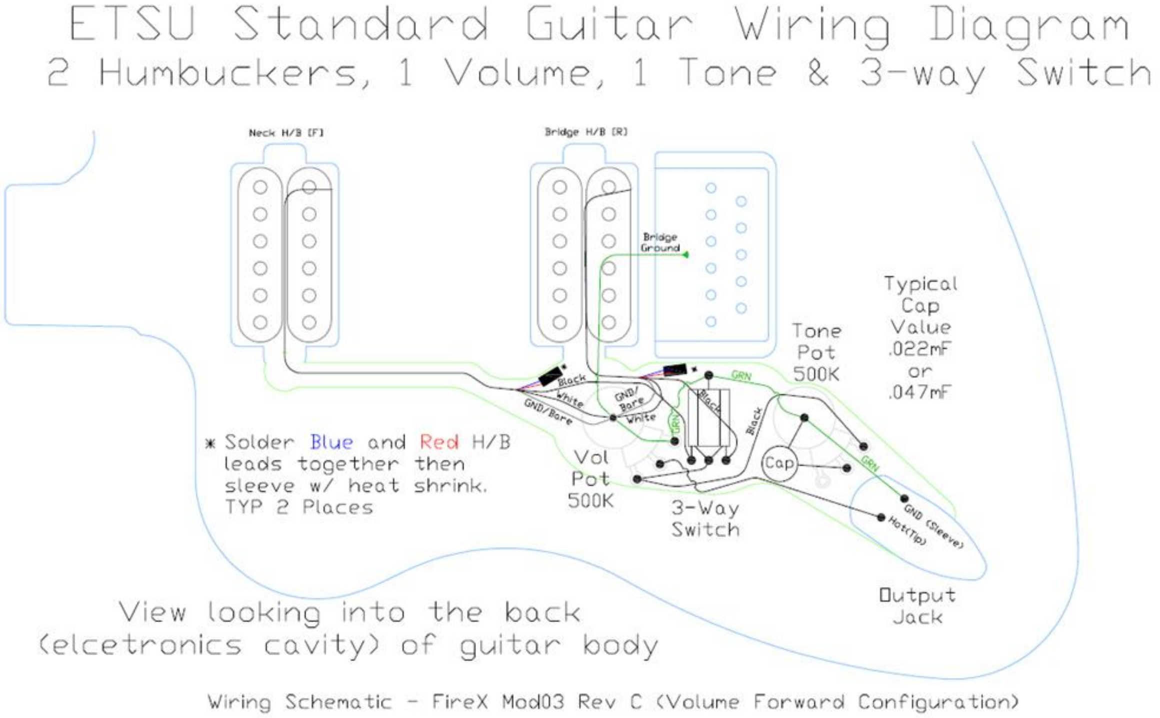


Figure 6. Example Partial Guitar Wiring Schematic

Fabrication Resources

AXYZ CNC Router

The AXYZ Automation Inc Series 4010 (see Figure 7) is a high speed gantry-style CNC table router. It features a five 5 by 10 foot processing envelope. Its normal operating spindle speed is nominally 18,000 RPM. It is primarily used for machining wood, plastic, and foam. The rotating bits used in CNC routing may develop high side and vertical loads, thus requiring work-pieces to be secured to the table.

Figure 7. AXYZ 4010 CNC Router

For repetitive processing operations (i.e. routing wooden bodies and necks), dedicated tooling is often developed for secure and accurate work-holding. Using special tooling installed as shown in Figure 8, the AXYZ CNC router is used to fabricate both bodies and necks from laminated or solid wooden blanks.

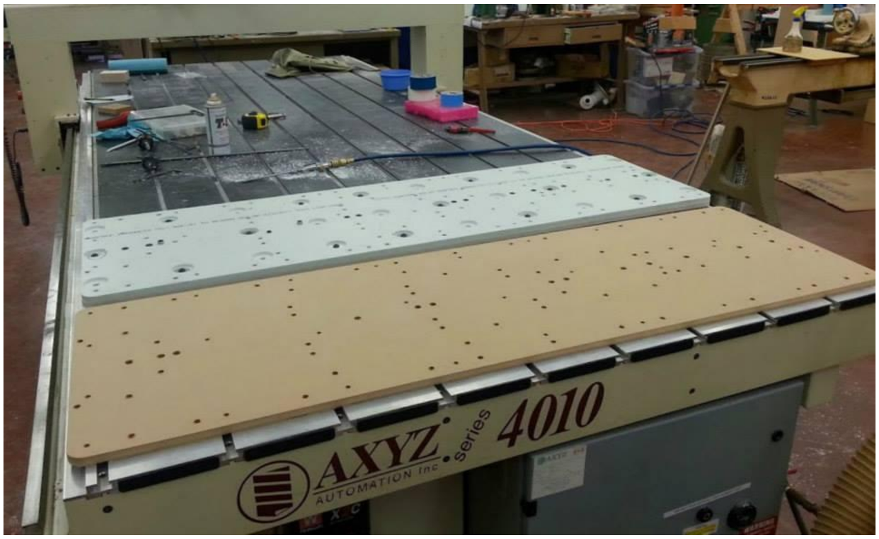


Figure 8. AXYZ 4010 CNC Router and Guitar and Neck Tooling

In an earlier configuration of body blank mounting tooling (as shown in Figure 9), guitar bodies were routed out of blanks mounted on the body tooling. Note in Figure 9 the 3/8" diameter centerline alignment pins at the far left and right of the photo.

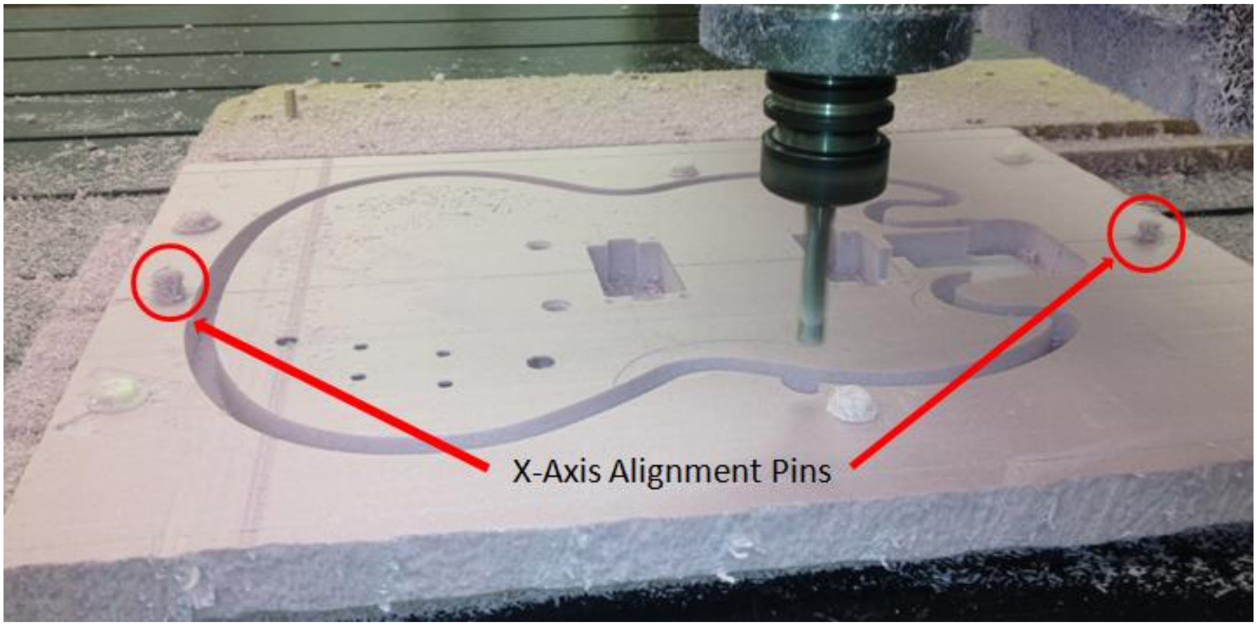


Figure 9. Routing of Prototype Guitar Body Using AXYZ CNC Router

Universal Laser Systems Laser Cutter/Engraver

The Universal Laser Systems ILS 12.75 Platform Series laser cutter/engraver (see Figure 10) features a 48” x 24” work area with a maximum part size of 52.5” x 30” x 12”. It is equipped with a 75 Watt Class IV CO2 laser with a cutting tolerance of +/- .001”. A major benefit of laser cutting is that it is a zero-force process requiring no hold-down tooling.

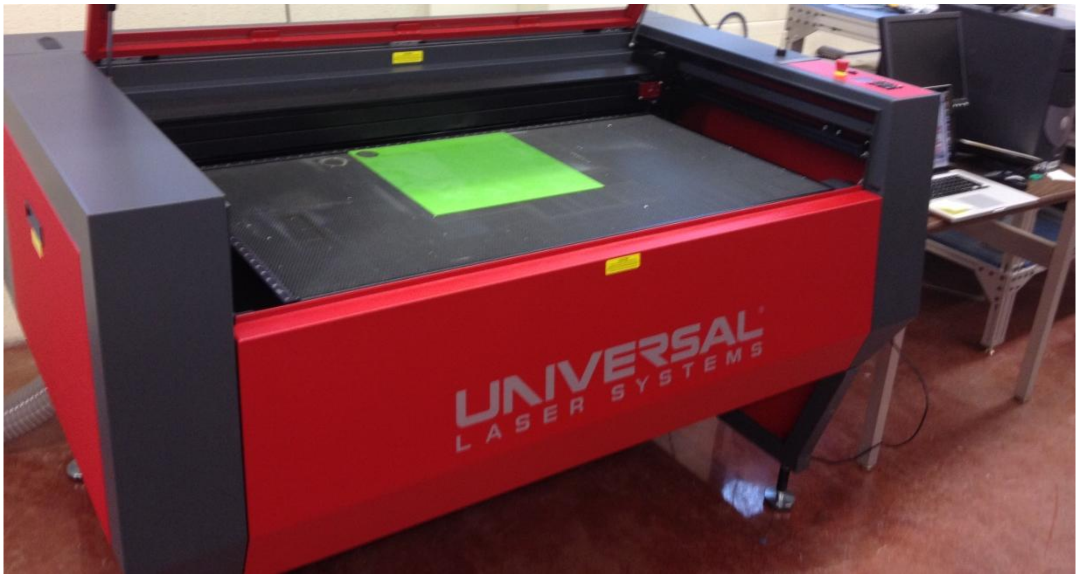


Figure 10. Universal Laser Systems Laser Cutter-Engraver

It may be noted that most commercial pickguards are made from PVC. The laser cutting of PVC-based materials is strongly discouraged, as one of the by-products of the high temperature decomposition of PVC is the highly corrosive and poisonous chlorine gas. The entry for PVC in the Universal Laser Systems Materials Library reads "WARNING - PVC is not compatible with laser processing" (Universal Laser Systems, 2014).

This is not a problem with copolyester (see Figure 11). According to *Eastman Spectar™ Copolyester 14471 Fabricating and Forming Sheet*, any laser cutter that may be used for acrylic may also be used to cut copolyester. A fume extraction system is still recommended for the removal of the by-products of copolyester processing (Eastman Chemical Company, 2011a).

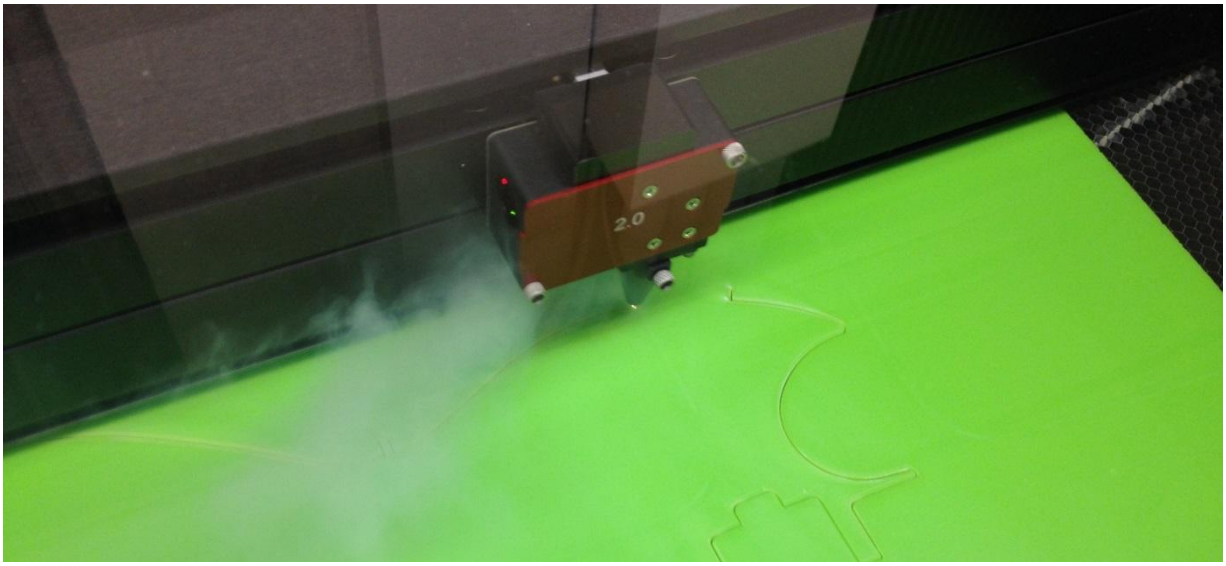


Figure 11. ILS 12.75 Cutting 3mm Copolyester

OMAX 5555 Abrasive Waterjet

The OMAX 5555 JetMachining® Center (see Figure 12) is an abrasive waterjet that uses a combination of vary high pressure water (20k to 60k psi) and garnet abrasive to cut through almost any flat material. The OMAX website states that its machines can machine metal, composites, stone, plastic, foam, wood, and ceramics. OMAX specifically states that it can through 4” titanium plate. The 5555 series has a table size of 6’ 8” x 5’ 5” with a nominal 48" x 48" work envelope. The exit diameter of the standard nozzle is 0.0125"; its cutting tolerance is +/-0.003” (OMAX Corporation, 2014a).

Figure 12. OMAX 5555 JetMachining® Center

Unlike the CNC router, depending on the thickness and type of material, the OMAX is considered "low force" machining, wherein little to no side load is generated. Workpieces are typically clamped in place to keep them from shifting and do not require specially developed tooling. The OMAX's Tilt-A-Jet Cutting Head (shown in Figure 13) imparts side loads in thick materials; water turbulence due to entrained air bubbling back up underneath the workpiece may dislodge unsecured lightweight materials.

Figure 13. OMAX Tilt-A-Jet Cutting Head

Copolyester

Copolyester, or more formally known as Polyethylene Terepthalate Glycol-Modified (PETG), is a thermoplastic polymer known for its incredible toughness, chemical resistance, and fabrication versatility. The primary source of information regarding copolyester came directly from the Eastman Literature Center, an online repository of product information (available URL: http://www.eastman.com/Brands/Pages/Brands.aspx). The specific types of copolyester used in these experiments are branded under the names Spectar® and Tritan®.

Spectar® Properties

According to the *Spectar® 14471* Product Data Sheet,

> [Spectar® brand copolyester] is easy to fabricate, allowing greater design freedom. It can be laser cut, routed, welded, drilled, die-punched, bent hot or cold, or joined by screws, rivets, or bolts. It can also be cut on conventional table, band, or radial-arm saws with blades commonly used for plastic. *Spectar* copolyester can be vacuum-formed at lower temperatures than other plastics without predrying the sheet. *Eastman Spectar* copolyester can be finished easily. Its edges can be polished by using commercial edge-finishing equipment, sanding, solvents, flame-polishing or buffing. It forms clear, strong bonds with commercially available solvents (Eastman Chemical Company, 2008).

Copolyester Bonding

According to the Eastman's *Ask the Spectar Team*,

> There are many different ways to bond Eastman Spectar® copolyester depending on the needs of the application. Solvent bonding is generally preferred when the components to be joined are made from Spectar sheet. However, adhesives, mechanical fasteners, or

> plastic welding may be needed when joining dissimilar materials or when considerations such as part size, bond flexibility, or bond appearance prevail (Eastman Chemical Company, 2013a).

Eastman Tritan™ Copolyester Medical Secondary Operations Guide advises that Tritan can be bonded via chemical, thermal, or mechanical means. The chemical methods include solvent bonding, adhesive bonding, UV curable adhesive, and cyanoacrylate adhesive. The thermal methods include ultrasonic welding, heat and ultrasonic staking, spin welding, vibration welding, RF sealing, heated bar and impulse sealing, laser welding, and hot-plate welding. Mechanically, Tritan can be joined using screws, threaded inserts, and snap fit methods (Eastman Chemical Company, 2011b).

CHAPTER 3

METHOD OF RESEARCH

Lamination Experimentation

Limitations

Of the various bonding methodologies recommended by Eastman, three types of bonding experiments were performed over the course of the investigation: low-temperature, heat-assisted pressure bonding; solvent and chemical welding; and contact adhesives. These methods were selected for experimentation due to the numerous limitations imposed upon this project. The key factors limiting this investigation include funding, equipment, and environment.

Due to financial restraints imposed by the University, funding for this project from student fees became unavailable after mid- January 2014. Therefore, many research expenditures (other than the costs of copolyester materials and guitar hardware and electronics) had to be paid out-of-pocket. The objective of the effort became focused on finding ways to effectively and efficiently bond copolyester using affordable and commercial products available from local vendors (e.g. local hardware and auto supply stores).

Many of the bonding methods suggested by the manufacturer require the use of specialized equipment that is unavailable at ETSU. Also, the size of the copolyester sheets and the required overall thickness posed its own problems to the project. Eastman's in-house capability was limited to bonding 12" x 12" sheets; laminating 24" x 16" sheets was, therefore, out of the question.

The feasibility of the experiments was heavily constrained by the environment in which they were performed. Creating a contamination-free environment is nearly impossible amidst the dust and debris of East Tennessee State University's first floor laboratory spaces (specifically the

Machine Tool Fabrication Lab and adjoining spaces). In addition, the use of volatile hydrocarbons was deemed only appropriate under a laboratory ventilation hood or outdoors. The latter proved impossible due to persistent cold weather conditions.

Lamination

In the context of these experiments, *lamination* refers to the bonding processes and procedures through which individual sheets of copolyester are permanently joined to form a single sheet. The objective of these experiments was to determine the most effective method of affordable lamination resulting in an optimized physical and visual bond between layers to minimize vibratory dissipation, thus maximizing sustain.

The sustain of a guitar refers to the length of time a string will audibly vibrate after being plucked. There are several factors that affect sustain including material, solidity, string placement, etc. Any attenuation of vibratory energy, or dampening, reduces the sustain of the guitar. Ideally, a copolyester guitar body with maximum sustain would be injection molded. The desired deliverable of the development effort was to create a playable, proof-of-principle solid body electric guitar from laminated sheets of copolyester material. Because of the constraint of not incorporating a solid bridge-to-neck core, sustain may be compromised. Therefore, maximizing the bond strength between layers is important. The types of lamination explored in this project include thermal bonding, solvent bonding, and adhesive bonding.

When considering the possible methods of bonding copolyester sheets, the primary source of information was the online Eastman Literature Center. There is, however, no precedent for bonding sheets measuring 24" x 16" in area. Therefore, additional research needed to be conducted in order to determine the best copolyester bonding method achievable using available resources and products.

Experimentation

Low-Temperature, Heat-Assisted Pressure Bonding

An available Technal Model 550 Dry Mounting Press (see Figure 14) was considered as a potential bonding method. The low temperature press was originally designed for mounting photographs to a support backing using a variety of adhesives that are heat activated. The heat plate (22.5" x 18.5") is attached to a clamping hinge that applies pressure to the work pieces when it is closed. The temperature of the heat plate can be adjusted via a potentiometer across the power supply input. The operating temperature of the press ranges from 180°F to 325°F. According to the Eastman Product Data Sheet Eastman Tritan™ Copolyester WX500, copolyester has a softening temperature of 214°F and a melting point of 455°F (Eastman Chemical Company, 2014).

Figure 14. Technal Model 550 Dry Mounting Press

The first test consisted of a pair of 4" x 4" nominal ¼” (6mm) thick clear squares of copolyester. The squares were pressed together for 30 minutes with the heat plate set to 250°F. Upon opening the press, it was observed that the copolyester squares had indeed fused together. Unfortunately, they had also fused to the surface of the heat plate (as shown in Figure 15). They could only be removed once the heat plate had returned to room temperature.

Figure 15. Test Squares Fused to Heat Plate (30 Minutes at 250°F)

After the test squares were chiseled off of the heat plate, it was observed that they had been severely deformed by the heat and pressure (as shown in Figure 16). It was determined that the next test would be conducted at a lower temperature setting.

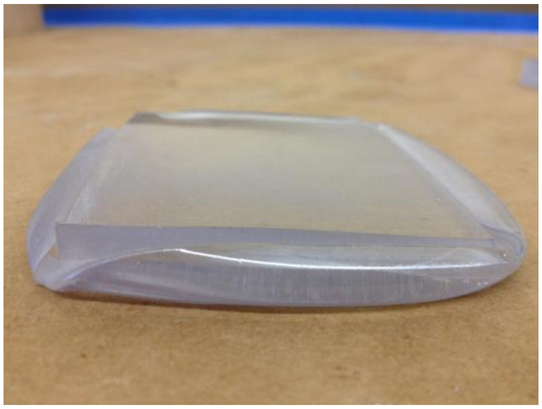


Figure 16. Deformation of Test Squares (30 Minutes at 250°F)

A second experiment was conducted using another pair of 4" x 4" nominal 1/4" (6mm) thick clear copolyester squares. The test squares were pressed together for 30 minutes with the heat plate set to 180°F. When the test squares were removed, it was observed that they had fused together with only mild bond occlusions due to air pockets (as shown in Figure 17).

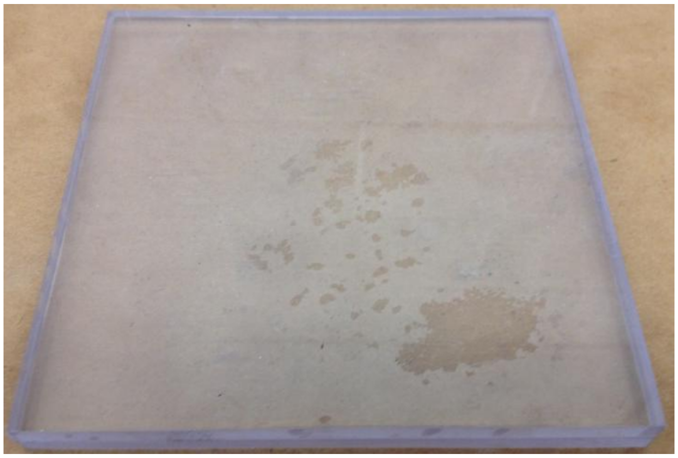


Figure 17. Resulting Air Pockets (30 Minutes at 180°F)

Regardless of the bond appearance, the Technal Model 550 Dry Mounting Press was unsuitable for bonding as it was originally designed. It was observed that the edges of the test squares were thinner on one side (as shown in Figure 18). This was due to the angular force applied by the hinged design of the heat press. The heat press was subsequently disassembled to use only the heat plate.

Figure 18. Deformation Due to Angular Compression of Technal Model 550 Dry Mount Press

A third experiment was performed on a pair of 16" x 12" (nom. 1/8" thick) sheets of clear copolyester. Using a set of four clamps with 3/4" heat resistant MDF shims, the heat plate was clamped at each corner to in order to apply vertical compressive force to the test sheets as shown in Figure 19. Again, the experiment was conducted for 30 minutes at 180°F.

Figure 19. Clamps Applying Vertical Compressive Force to 16” x 12” Test Specimens

Upon removal of the test sheets, a cloudy bond was observed exhibiting large, visually unappealing air pockets trapped throughout (as shown in Figure 20). Regardless of the bond appearance, the heat press was not large enough to bond the 24" x 16" copolyester sheets necessary for fabricating a laminated guitar body. Therefore, the Technal Model 550 Dry Mounting Press was deemed unsuitable for the lamination process.

Figure 20. Resulting Air Pockets in the 16” x 12” Test Specimens (30 Minutes at 180°F)

Solvent and Chemical Bonding

As purely heat and pressure forms of lamination were not yielding the desired bonding quality, chemical bonding methods were explored. According to *Eastman Tritan™ Copolyester Medical Secondary Operations Guide,*

> "Solvent bonding utilizes the solubility of the mating plastic surfaces to accomplish a bond. The solvent softens the materials, allowing the surfaces to fuse as the solvent evaporates out of the joint" (Eastman Chemical Company 2011b).

Three different common solvents were tested to determine their suitability for bonding copolyester sheet: acetone, methyl ethyl ketone, and methylene chloride.

Acetone. The first solvent bonding experiment was conducted using acetone purchased from a home improvement/hardware store. The chemical was applied to one surface of a 6" x 6" square of copolyester using a foam brush. A second square of coployester was then placed on top and the two were pressed together under a stack of aluminum blocks with a combined weight of approximately 20 lbs. After allowing 24 hours to cure, it was observed that extreme hazing and solvent induced crystallization had occurred (see Figure 21).

Figure 21. Example of Hazing and Crystallization with Acetone

In addition to the poor visual bond, acetone resulted in a poor physical bond. A drop test was performed from approximately four feet; the two sheets separated completely. Upon further investigation, it was discovered that the material had become brittle and exhibited stress fracturing when minimal flexural force was applied (as shown in Figure 22).

Figure 22. Example of Stress Fracturing Induced by Application of Acetone

Upon consulting the Eastman Literature Center documentation, it was discovered that acetone is not a suitable solvent for bonding copolyester. Therefore, the use of acetone was abandoned in search of a recommended solvent. *Eastman SPECTAR™ 14471 Copolyester Fabrication and Forming Sheet* recommends the use of the solvents methyl ethyl ketone (MEK) or methylene chloride. "MEK, a fast-acting solvent, gives quicker setup with more likelihood of freeze-off (setting up before the joint is filled). Methylene chloride, on the other hand, is a slower solvent and offers more work time with less potential for freeze-off" (Eastman Chemical Company, 2011a).

Methyl Ethyl Ketone. The second set of solvent bonding experiments were conducted using the powerful thinning agent butanone more commonly known as methyl ethyl ketone or MEK. The use of MEK required a battery of additional safety precautions. The Material Safety

Data Sheet (MSDS) provided by Science Lab.com identifies MEK as a skin irritant and permeator as well as a lung irritant (Science Lab.com 2005).

Therefore, it was deemed necessary to wear chemical resistant gloves and an approved respirator. Throughout the course of these experiments, Nitrile gloves and a Gerson® Organic Vapor/P95 respirator were worn (as shown in Figure 23).

Figure 23. Gerson® Organic Vapor/P95 Respirator

Special consideration was given to the proper fitment and usage of the respirator. When working with hazardous organic solvents such as MEK, this is arguably the most important article of personal protective equipment (PPE). The inhalation of volatile hydrocarbons can cause severe lung irritation and central nervous system damage.

Several methods of application were attempted throughout the course of the MEK experimentation: pouring, spraying, rolling, and brushing.

The first bonding experiment consisted of pouring MEK directly from the can onto a 12" x 12" square piece of copolyester. A second identical piece of copolyester was placed on top of the first along with several aluminum blocks (approximate combined weight of 20 lbs) for compressive force. The weights were removed after 24 hours, revealing large areas of encapsulated MEK trapped between the mated surfaces (as shown in Figure 24).

Figure 24. Example of MEK Laking

The entrapment of liquid solvent, commonly called “laking,’ occurs when excessive solvent is applied. When bonding two pieces with large surface areas, the solvent will evaporate more quickly around the edges of the joint. The edges will fuse together trapping "lakes" of liquid solvent between the two sheets of copolyester. This is a particular problem with MEK because of its short setup time. The short setup time does not allow any repositioning once the mating surfaces meet. Solvent welding of copolyester with MEK therefore requires precise layer alignment before bonding as well as a “center out” method of force application.

MEK is also notorious for undesired solvent attack resulting from overspill (as shown in Figure 25). When too much of the solvent is applied and squeezes out and around the edges of the sheets, it attacks external surfaces. This can distort the geometry of the layers being laminated, and it also increases the respiratory hazard resulting from the evaporation of the excess MEK.

Figure 25. Undesired Solvent Attack

The extreme volatility of MEK requires the use of active ventilation in an isolated environment. After initial experiments on small specimens proved to be hazardous to others working in the machine tool lab, all subsequent experiments were performed in a shipping and receiving space closed off from the lab and the loading doors completely open. A large fan was positioned behind experiment and the loading doors to exhaust the fumes from the building.

A PETE (MEK resistant) spray bottle was used to test the feasibility of MEK spray-on application on two sets of 10" x 14" nominal 1/4" (6mm) copolyester sheets. Unfortunately, the nozzle of the spray bottle was made of a plastic that was not resistant to MEK. The nozzle began to degrade with each use, so only two trials were attempted. The first trial resulted in a weak, hazy bond due to premature solvent setup as shown in Figure 26 (Left). On the second attempt, the MEK had dissolved the nozzle in such a way that it spewed, not sprayed, diagonally. This resulted in a weak bond essentially consisting of a field of solvent spot welds as shown in Figure 26 (Right).

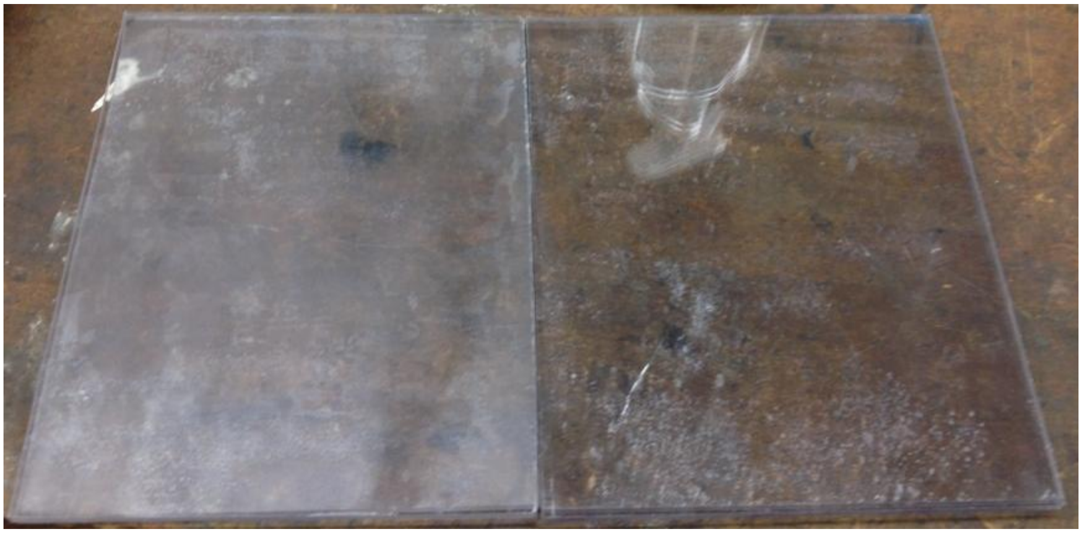


Figure 26. MEK Spray Application Tests Results

Another experiment was conducted using a foam roller brush to apply MEK to a set of 8" x 10" nominal 1/4" (6mm) copolyester sheets. The foam roller was dissolved by the MEK as it was applied causing contamination which resulted in weak, hazy bond (as shown in Figure 27). The foam roller was clearly an unsuitable application method.

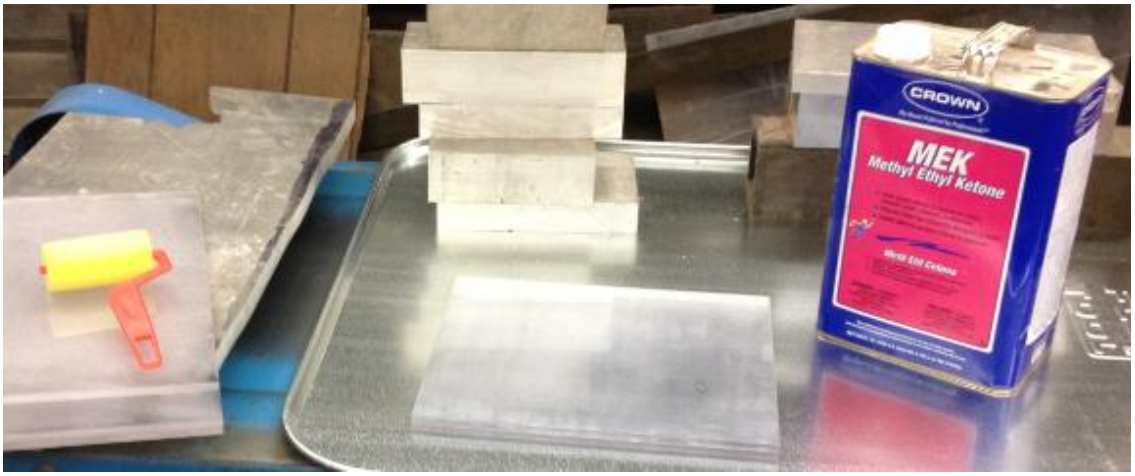


Figure 27. Foam Roller Brush Experiment

The most successful MEK experiment resulted from the use of an inexpensive commercially available sponge brush used to apply latex or oil based paints. Although the MEK did degrade the sponge over time, it did prove useful it its ability to store a small volume of MEK. The sponge would only release the MEK when it was brushed across the surface of the copolyester. A pair of 6" x 6" nominal 1/4" (6mm) squares of copolyester sheet was wiped with the MEK-soaked sponge brush. Before the two squares were mated together, the excess MEK was allowed approximately 5 seconds to evaporate. The affected surfaces were then quickly and precisely mated. At this point, a nominal 20 pound stack of aluminum blocks was placed on top of the squares in order to squeeze out the excess MEK and air gaps.

This process resulted in strong bond with minimal solvent laking. A frosted appearance (shown in the upper left-hand corner of Figure 28) - the result of a piece of paper that adhered to the bottom of the sample during the test. It was determined to be a surface defect rather than a bond occlusion. Because some degree of laking appeared to be unavoidable when bonding surfaces greater than 36 in² with MEK, far less than the required 384 in² for a guitar body blank, additional tests were conducted with methylene chloride.

Figure 28. MEK-Saoked Sponge Brush Experiment 6" x 6" Nom. 1/4" (6mm) Specimen

Methylene Chloride. Methylene chloride was by far the most dangerous chemical tested during this project. The first bonding experiment with diluted methylene chloride employed the use of an aerosol-based commercial paint stripper called Klean Strip®. The foam spray was applied evenly to one 12" x 10" sheet of 6mm copolyester and mated to another identical sheet. A large aluminum plate was placed on top of the copolyester, and approximately 100 pounds of bricks, aluminum blocks, and steel stock were stacked for compressive force (as shown in Figure 29).

Figure 29. Pressed Bonding with Klean Strip®

Upon removal of the weights, it was observed that the foam spray had produced a cloudy white bond between layers (see Figure 30). The test piece survived a four-foot drop test cracking slightly, but the bond remained intact. Although mechanically sound, the bond was aesthetically unappealing. As a foam solution, the encapsulation of air bubbles would be unavoidable.

Figure 30. Entrapped Air Bubbles Resulting from Aerosol Application of Klean Strip®

Pure liquid methylene chloride was the next bonding method tested. Obtaining this substance proved to be a significant challenge in itself. Furthermore, the use of pure methylene chloride is strictly confined to chemistry laboratory settings inside a specialized fume extraction hood. The maximum exposure limit for methylene chloride is four times lower than that of MEK, meaning that pure methylene chloride is considered to be four times as hazardous.

East Tennessee State University's Director of Environmental Health & Safety, Mr. Daniel O'Brien, arranged for this experiment to be performed inside of a fume hood in the Environmental Health Sciences Lab (see Figure 31). The pure methylene chloride, as well as all of the required safety training, was provided by the resident Research Specialist Mr. Brian G. Evanshen.

Figure 31. Environmental Health Sciences Lab Fume Extraction Hood

Extreme precautions are necessary when working with methylene chloride. All of the experimentation was required to take place inside the small enclosed compartment shown in Figure 31. The sash (sliding window) could not be raised while methylene chloride was in use, which severely restricted mobility. Upon measuring the length of the workspace, it was discovered that both halves of the guitar tooling alignment fixture would not fit in the hood. In addition, simply maneuvering multiple sheets of 24" x 16" copolyester, aligning them, and laminating them together inside the small ventilation compartment would be very difficult.

As depicted in Figure 32, a single experiment was performed using 4" x 4" nominal 1/4" (6mm) squares of copolyester. A disposable sponge brush was used to apply methylene chloride to one of the copolyester pieces. The second piece was placed atop the first, and an aluminum block weighing approximately five pounds was stacked on top of the copolyester for compressive force. Additional force was supplied manually for approximately 60 seconds.

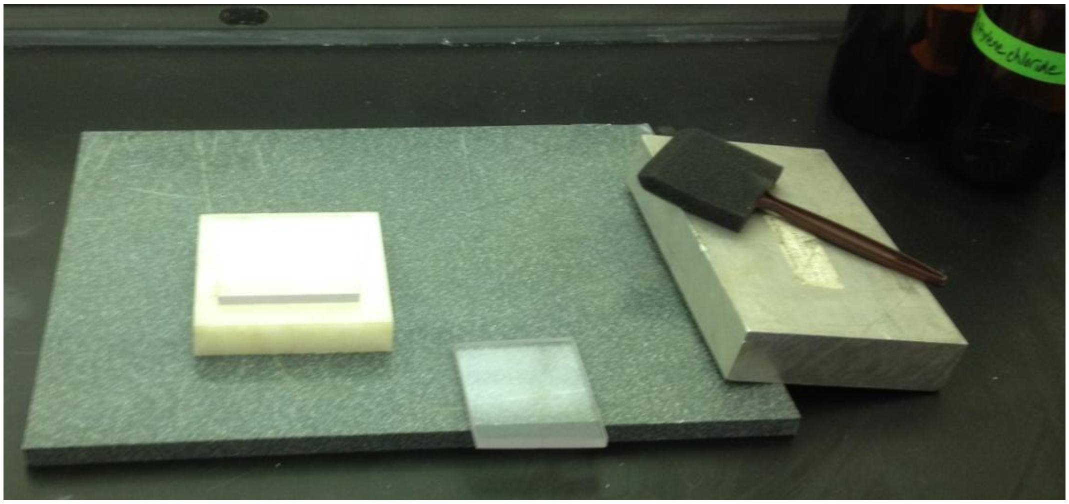


Figure 32. Methylene Chloride Solvent Bonding Test Setup in Fume Hood

The resulting bond exhibited heavy laking but remained perfectly clear (as shown in Figure 33). Additional experimentation may have been warranted to improve these methods; however, the challenges to performing full-scale laminations inside the available chemical hood as well as the potential health hazards of applying methylene chloride to large surfaces precluded any further investigation. The safety precautions required in order to conduct an experiment at full scale was beyond the scope of this project.

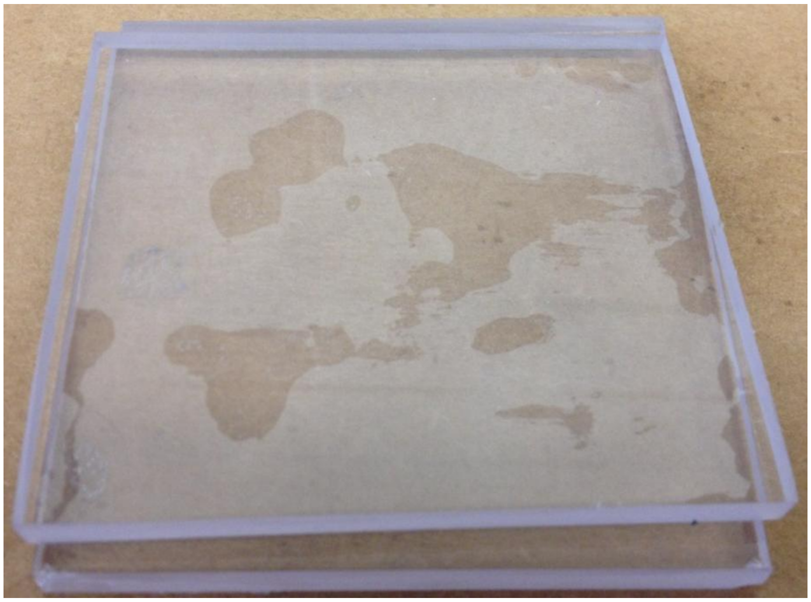


Figure 33. Liquid Methylene Chloride Test Specimen Exhibiting Laking

Adhesive Bonding

Permatex® 118 DA All Purpose Spray Adhesive. Permatex® spray adhesive, another aerosol-based adhesive sold in auto supply stores for securing headliners and carpet, was tested on a pair of 12" x 9" nominal 1/4" (6mm) copolyester sheets. This pressure-sensitive adhesive is either temporary or permanent depending on whether it is applied to one or both of the mating surfaces. To ensure a permanent bond, both sheets were sprayed with a thick, even coating and allowed to dry for 1 minute before they were mated and pressed together for a period of 24 hours. The same compressive bonding method as the Klean Strip® experiment was implemented. This resulted in a strong bond with a uniformly frosted, semitransparent appearance (as shown in Figure 34). The test piece survived the four-foot drop test. In addition, the test piece survived being cut on the table saw, belt sanded, and flame polished with a hand-held torch fueled with UN 1060 stabilized methylacetylene-propadiene (MAPP) gas. The Permatex® 118 DA All Purpose Spray Adhesive produced the best results of all experiments thus far.

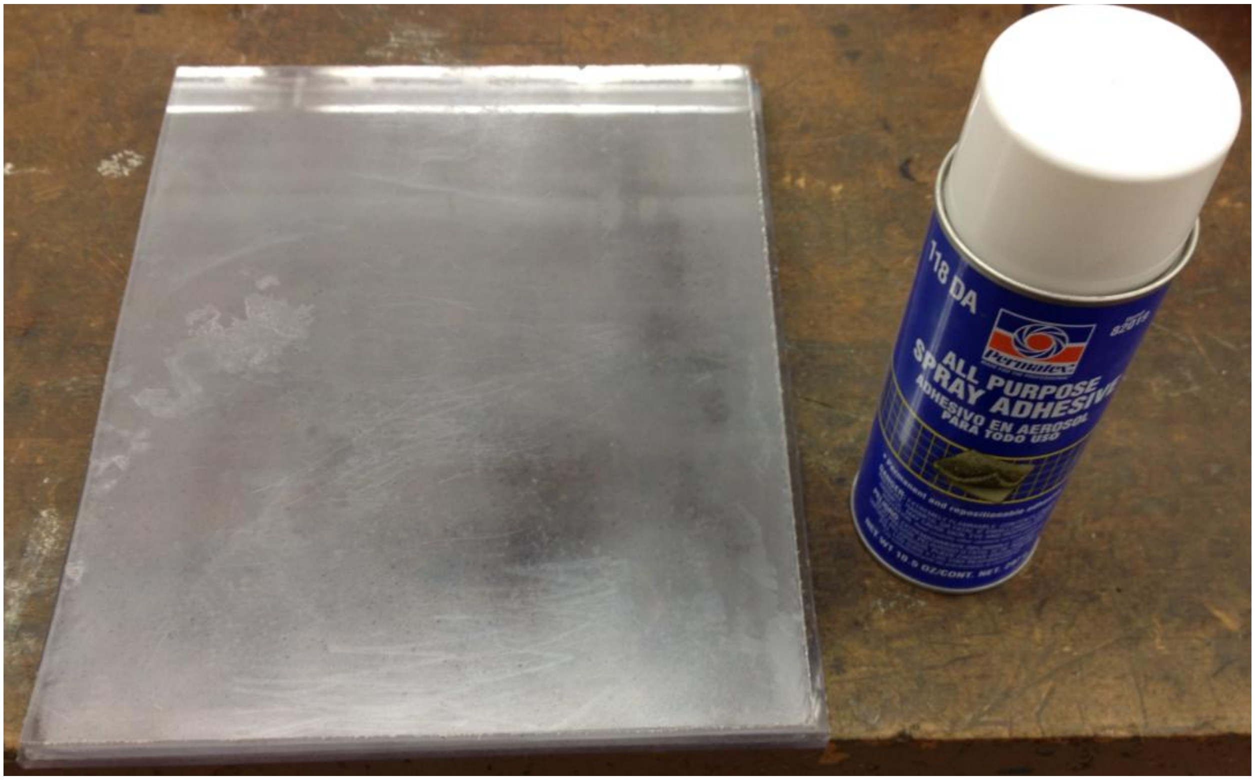


Figure 34. Results of the Permatex® 118 DA All Purpose Spray Adhesive Test

Loctite® Spray Adhesive. A can of Loctite® Spray Adhesive High Performance Middleweight Bonding 200 was purchased for comparison with the Permatex® 118 DA All Purpose Spray Adhesive. The experiment was identical to the Permatex® 118 DA All Purpose Spray Adhesive test performed with the Loctite® product. The two surfaces were sprayed individually, allowed 1 minute to dry, then compression bonded using bricks, aluminum blocks, and steel stock. The resulting bond produced by Loctite® exhibited most of the same characteristics as the Permatex®. The only difference between the two spray adhesive products was the sparkling effect in the frosted appearance of the bond created by Loctite® (as shown in Figure 35).

Based upon the results of various solvent-based and spray adhesive-based bonding tests, the Loctite® Spray Adhesive High Performance Middleweight Bonding 200 was determined to be the most effective method of laminating copolyester sheets resulting in an optimized physical and visual bond that can be achieved using affordable, safe, and commercially-available products and resources to an end user.

Figure 35. Uniform Frosted Bond Appearance of Loctite® Spray Adhesive Test

Design and Fabrication

Prototype #1 Design

The objective of this investigation was to answer the question: “Can a playable electric guitar body be fabricated solely of laminated sheets of copolyester?” It was postulated that copolyester sheets could be machined as individual “slices” of two-dimensional geometry and laminated together in order to create the three-dimensional geometry of an electric guitar body (as shown in Figure 36).

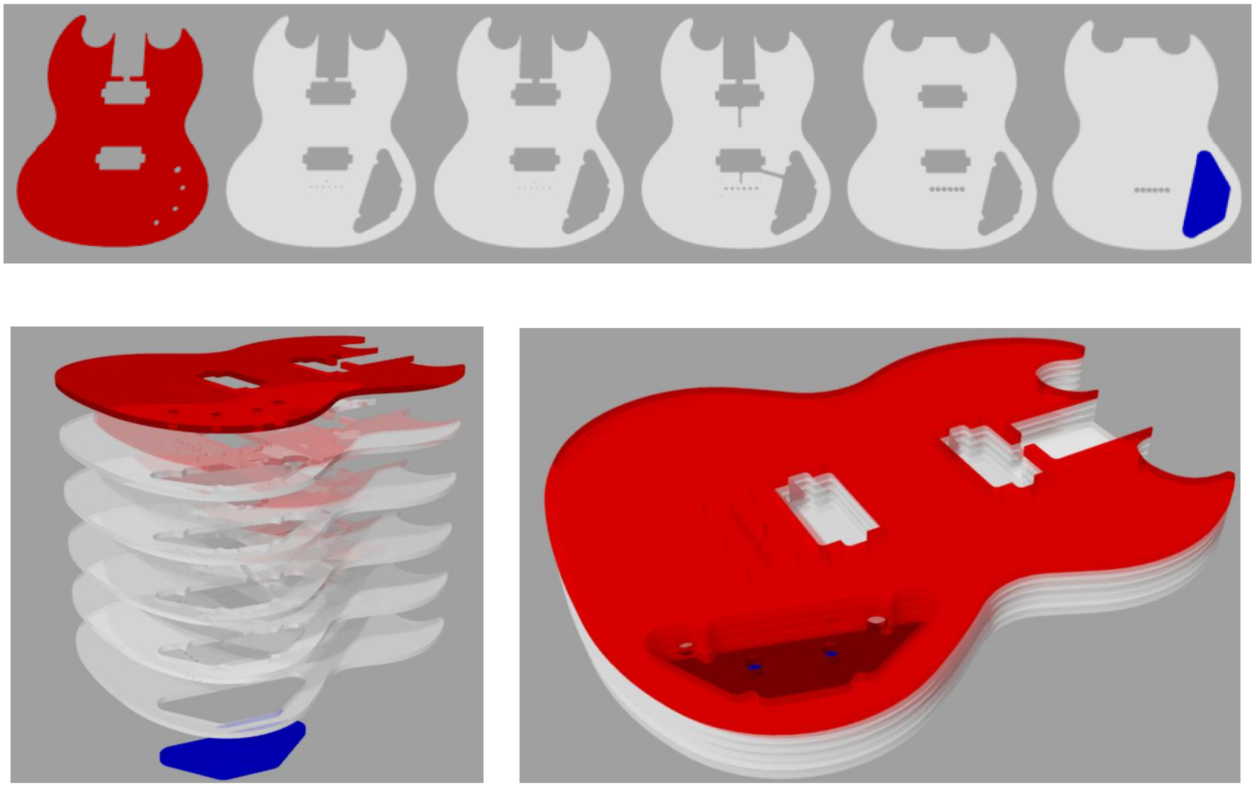


Figure 36. First Prototype Design of Laminated Copolyester Solid Body Electric Guitar

A Gibson SG variant body style was chosen for the prototype guitar because of its easily recognizable, classic shape, and compact design. The Gibson SG is one of the thinnest of all production solid body electric guitars ranging from 1 5/16 to 1 3/8". Because the coployester sheets provided by Eastman are available in a maximum standard thickness of nominally ¼” (6mm), the total number of layers required to achieve the target overall thickness of the laminated guitar body is determined by the combined thicknesses of the individual copolyester sheets. Therefore, a thinner guitar body would require fewer laminated layers.

A thinner body profile was also desirable when considering the total weight of the laminated copolyester layers. A standard Gibson SG is made of solid mahogany, which has an average density of approximately 40 lbs/ft^3. Copolyester has a density of approximately 80 lbs/ft^3. By comparison, a copolyester guitar body would weigh twice as much as its mahogany counterpart.

The first prototype design proposed that a nominal 1.5" (36mm) thick guitar body could be constructed by stacking six individually cut layers of nominal 1/4" (6mm) copolyester. By featuring the edges of the neck pocket on only the first four layers of geometry, the resulting three-dimensional neck pocket would have a depth of 0.945" (24mm). If the first five layers featured the edges of the humbucker pockets, their three-dimensional depth would be 1.181" (30mm) and so on.

Theoretically, as shown in Table 2, the six layers of nominal 1/4" (6mm) copolyester could be cut out individually, aligned, and laminated together in the correct order to form a solid body electric guitar. Because the copolyester sheet provided by Eastman is available in nominal metric thicknesses, all layer calculations feature metric units.

Table 2.

Layer-Feature Specs for Laminated Copolyester Electric Guitar Prototype #1

Laminated Copolyester Electric Guitar Prototype #1					
Layer	**Thickness**	**Features**	**Feature**	**Abbreviation**	**Depth**
1	6mm	E, N, H, B, S	Electronics Holes	E	6mm
2	6mm	N, H, B, S, C	Bridge Screw Holes	B	24mm
3	6mm	N, H, B, S, C	Neck Pocket	N	24mm
4	6mm	N, H, B, C, T, W	Humbucker Pockets	H	30mm
5	6mm	H, C, F	Electronics Cavity	C	30mm
6	6mm	L, F	Wire Channels	W	6mm
			String Holes	S	18mm
			Ferrule Taper Holes	T	6mm
			Ferrule Lips	F	12mm

The tooling used for fabricating electric guitar bodies on ETSU's AXYZ high speed CNC router features two bushings for 3/8" alignment pins and six threaded inserts for mounting bolts. A conventional wooden guitar blank is match drilled using a template to accommodate these tooling holes. The locations of the two exactly-sized alignment holes and the six oversized mounting holes were incorporated into the design of each layer of the copolyester guitar in order to provide alignment references during the lamination process. In addition to the alignment aspect, the tooling holes also allowed the laminated layers to be mounted on the AXYZ guitar tooling, as shown in Figure 37, in order to machine any features that cannot otherwise be generated using the abrasive waterjet and/or the laser engraver-cutter system.

Figure 37. Copolyester Body Blank Mounted on AXYZ Guitar Tooling

The body of the guitar needs to be secured to the alignment and mounting blank . Small tabs are commonly used in waterjet and other CNC designs to prevent the part from falling out or rotating during fabrication. These tabs can be strategically located to support the piece then be removed by drilling and cutting and sanding flush. As shown in Figure 38, seven nominal 1/4" tabs were used for this design. The important mounting geometry for the neck, forward humbucker pocket, truss rod cavity, and stylistic cutouts were created in one long, uninterrupted path early in the process of creating the body geometry.

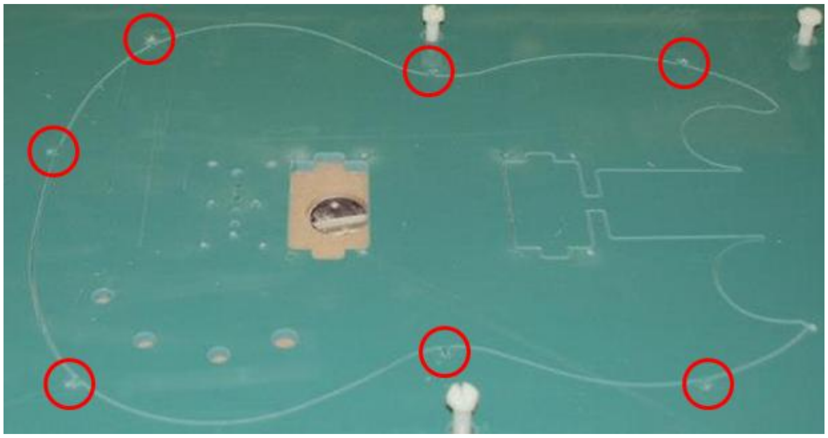
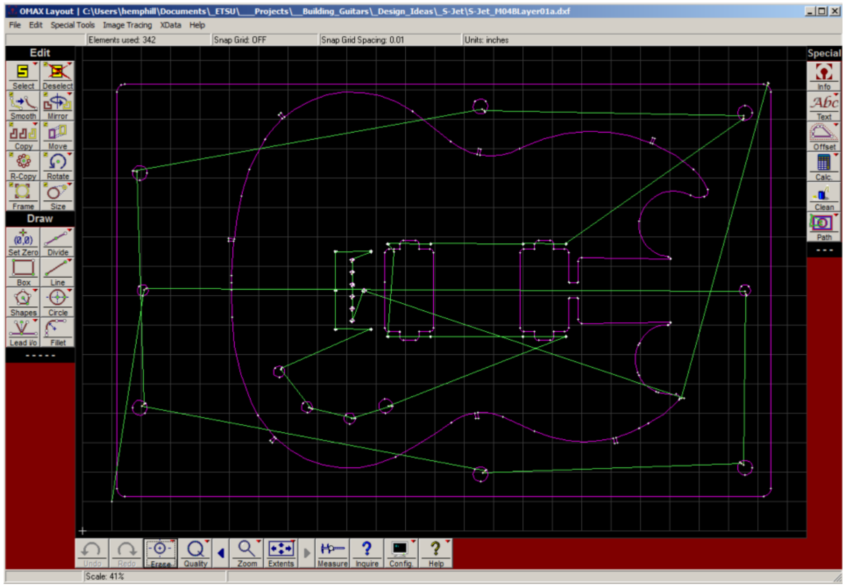


Figure 38. Seven Nominal 1/4" Support Tabs Used in Prototype #1

Prototype #1 Fabrication

The six individual layers of the first prototype laminated copolyester solid body electric guitar were cut out using the OMAX 5555 JetMachining® Center. Using a combination of abrasive and water set on low pressure mode (20k psi) or brittle, polymer material cutting, the nozzle's cutting stream was directed along the 2D paths generated using the OMAX CAM software (as shown in Figure 39).


OMAX Layout | C:\Users\hemphill\Documents_ETSU___Projects__Building_Guitars_Design_Ideas_S-Jet\S-Jet_M04BLayer01a.dxf

Elements used: 342
Snap Grid: OFF
Snap Grid Spacing: 0.01
Units: inches
Scale: 41%

Figure 39. OMAX Layout Preview of Cutting Paths

As shown in Figure 40, Layer 1 of the first prototype was cut using the abrasive waterjet on April 3, 2013. The purpose of this experiment was to determine the extent of the engineering geometry that could be generated in a 6mm sheet of copolyester. It should be noted that this particular test was conducted using a sheet of copolyester that was nominally 15 years old. Therefore, it was unclear which defects were due to the age of the material.

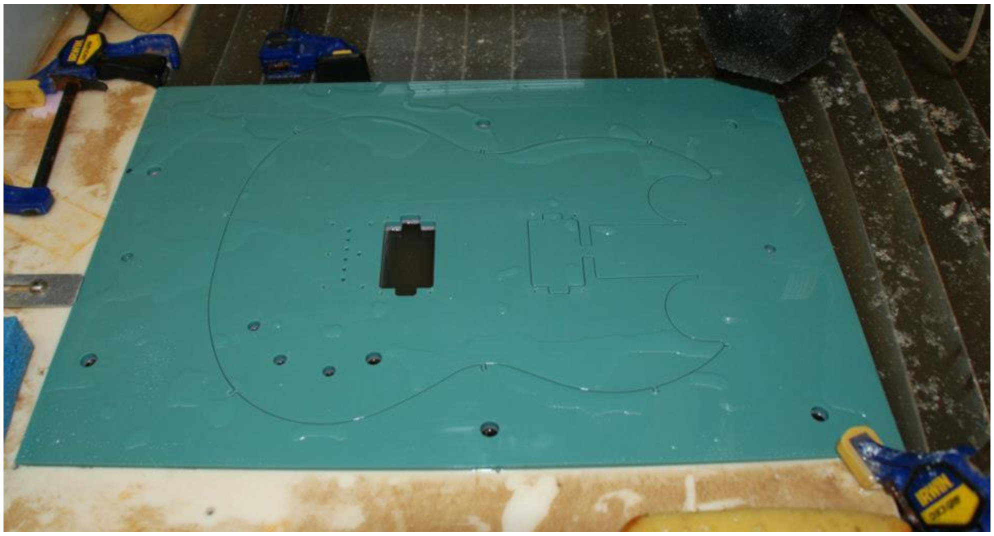


Figure 40. Waterjet Machining Layer 1 of Prototype #1

After the first layer was cut, it was placed on the AXYZ guitar tooling to confirm the proper location of the alignment and mounting holes. As shown in Figure 41**,** the experiment successfully demonstrated that the design data were correct and that existing tooling could be used when aligning sheets during the lamination process.

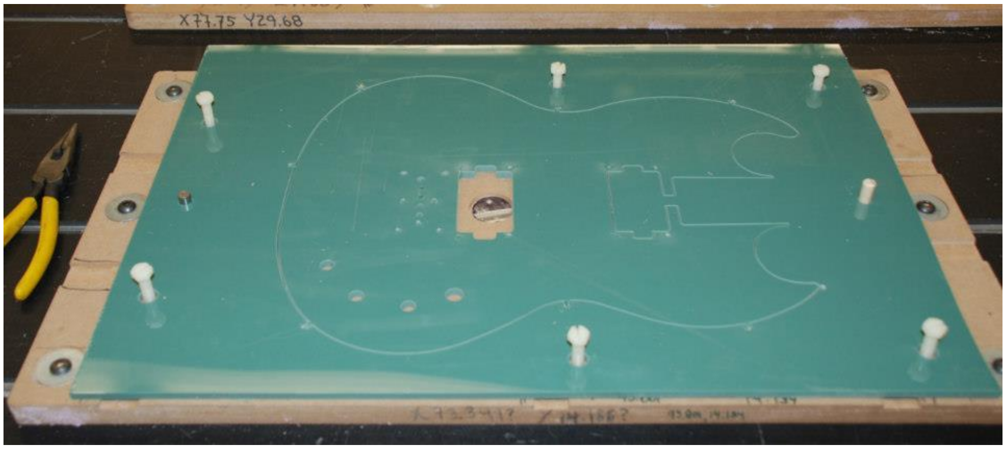


Figure 41. Tooling Hole Position Test

As shown in Figure 42, the electronics were then test fit to ensure that the electronics holes were the correct size. Although the holes were the correct diameter, it was discovered that the shafts of the potentiometers, switch, and input jack were not long enough to be correctly mounted through a nominal 1/4" (6mm) thick copolyester sheet.

Figure 42. Test Fitting the Electronics

Upon closer inspection of the test specimen, it was also discovered that several instances of bottom-side blowout had occurred during the waterjet machining process as shown in Figure 43. *Blowout* refers to the undesired removal of chunks of material (typically from the bottom surface) during initial penetration by the water and abrasive stream.

Figure 43. Example of Waterjet-Induced Blowout on Bottom Surface

In order to solve the electronics fitment issue, the same geometry was generated in a sheet of 4mm copolyester. The second experiment was also performed in order to investigate the waterjet cutting characteristics of thinner copolyester sheet. In Figure 44, note the use of a nominal 1/4" thick piece of pink foam underlayment between the copolyester sheet and the support slats of the waterjet tank. The foam prevents damage due to high pressure "blowback" by the stream reflecting off of the support slats onto the copolyester sheet bottom.

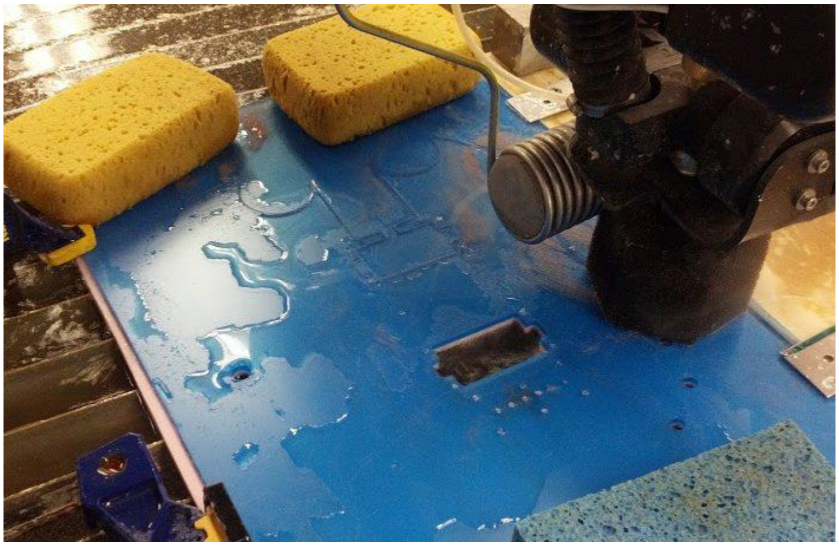


Figure 44. 4mm Copolyester Waterjet Test

As expected, the electronics fit perfectly using a 4mm sheet. However, it was observed that the 4mm sheet also exhibited the same instances of bottom-side blowout when pierced by the water/abrasive stream (as shown in Figure 45). Therefore, it was concluded that the waterjet was unsuitable for generating spot holes for hardware mounting screws as well as the string holes.

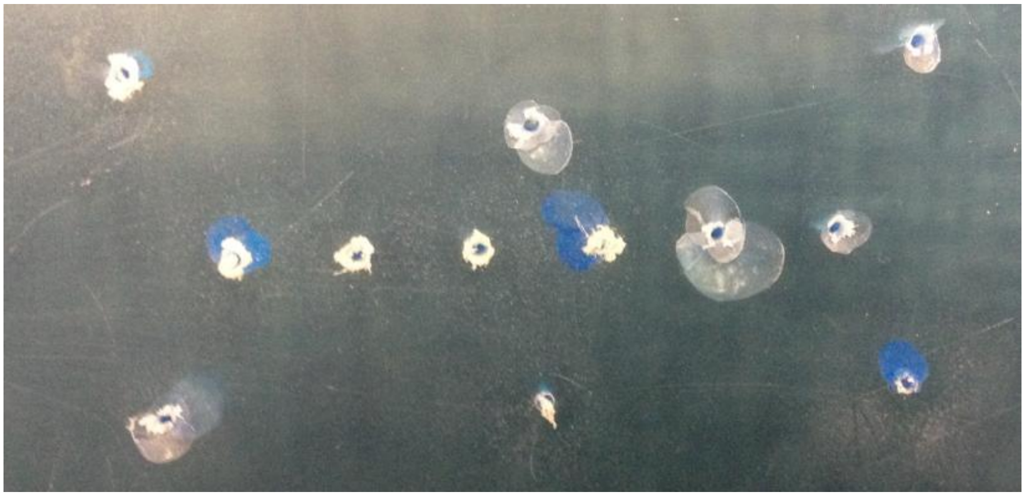


Figure 45. Example of Blowout in 4mm Copolyester

In addition to the occurrence of blowout when attempting to generate spot holes, the spacing of the standard 1/4" support tabs proved to be problematic when piercing the copolyester by the waterjet stream (as shown in Figure 46). The tabs would require redesigning in order to prevent this type of defect from defeating the purpose of the tabs.

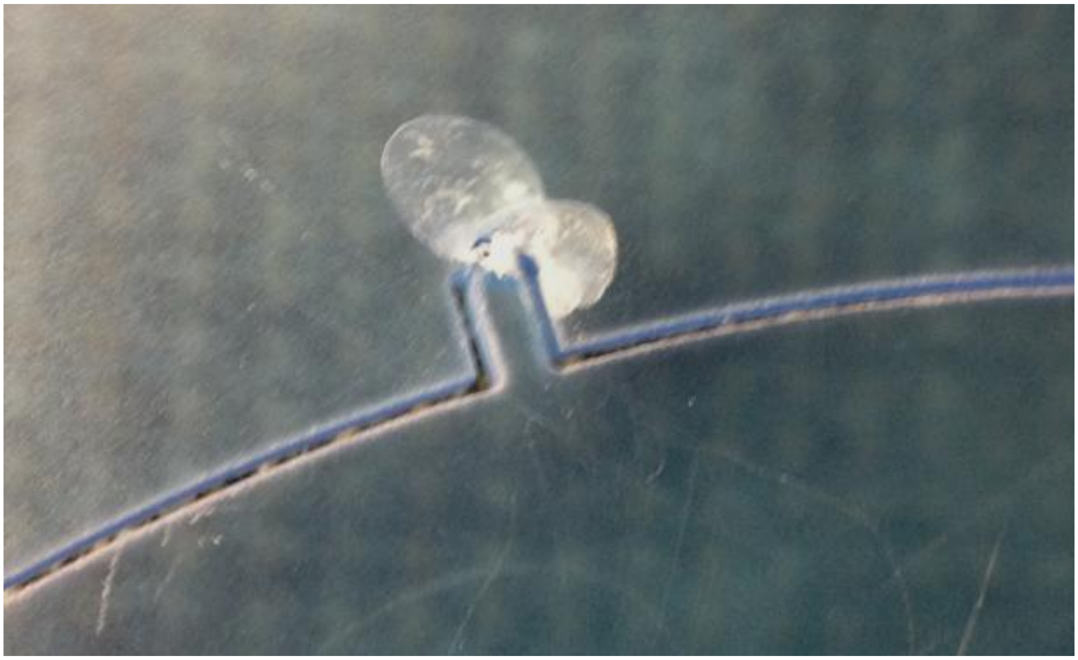


Figure 46. Example of Waterjet-Induced Bottom Blowout of 1/4" Tab

Prototype #2 Design

The Z-dimensional (thickness) tolerance of the geometry generated by layering uniform copolyester is determined by the slice resolution (i.e. the thickness of the sheets used). In this case the minimum available sheet thickness was nominal 1/8" (0.118" actual) or 3mm. Therefore, the z-dimensional tolerance of a laminated copolyester guitar body blank composed solely of 0.118" (3mm) sheets would be +/- 0.118" (3mm).

For example, if solely nominal 1/8" (3mm) sheets are used to generate a target guitar body blank thickness of 1.500" (38.1mm), 12 layers would generate a thickness of 1.416" (36mm) and 13 layers would generate a thickness of 1.534" (39mm). However, by combining nominal 5/32" (0.157" or 4mm) sheets with the nominal 1/8" (3mm) sheets, the z-dimensional tolerance is reduced to +/- nominal 1/32" (1mm). Six layers of nominal 1/8" (3mm) combined with five layers of nominal 5/32" (4mm) would generate a thickness of 1.496" (38mm).

Furthermore, nominal 1/4" (6mm) copolyester sheets can also be combined in order to reduce the total number of layers. Eleven layers would be required to generate a thickness of 1.496" (38mm) using just nominal 1/8" (3mm) and 5/32" (4mm) sheets. The same thickness can be generated in seven by combining five sheets of nominal 1/4" (6mm) with two sheets of nominal 5/32" (4mm).

The second prototype, as shown in Figure 47, used a combination of 3mm, 4mm, and 6mm layers to more accurately generate the three-dimensional data that comprised the laminated body. The standard thickness of a Gibson SG ranges from 1 5/16" to 1 3/8" (1.31" to 1.375"). The average of this range is 1.34" (34mm). Therefore, the targeted overall thickness of the second prototype laminated copolyester solid body electric guitar was 1.34" (34mm). Eight layers were required in order to achieve the targeted body thickness.

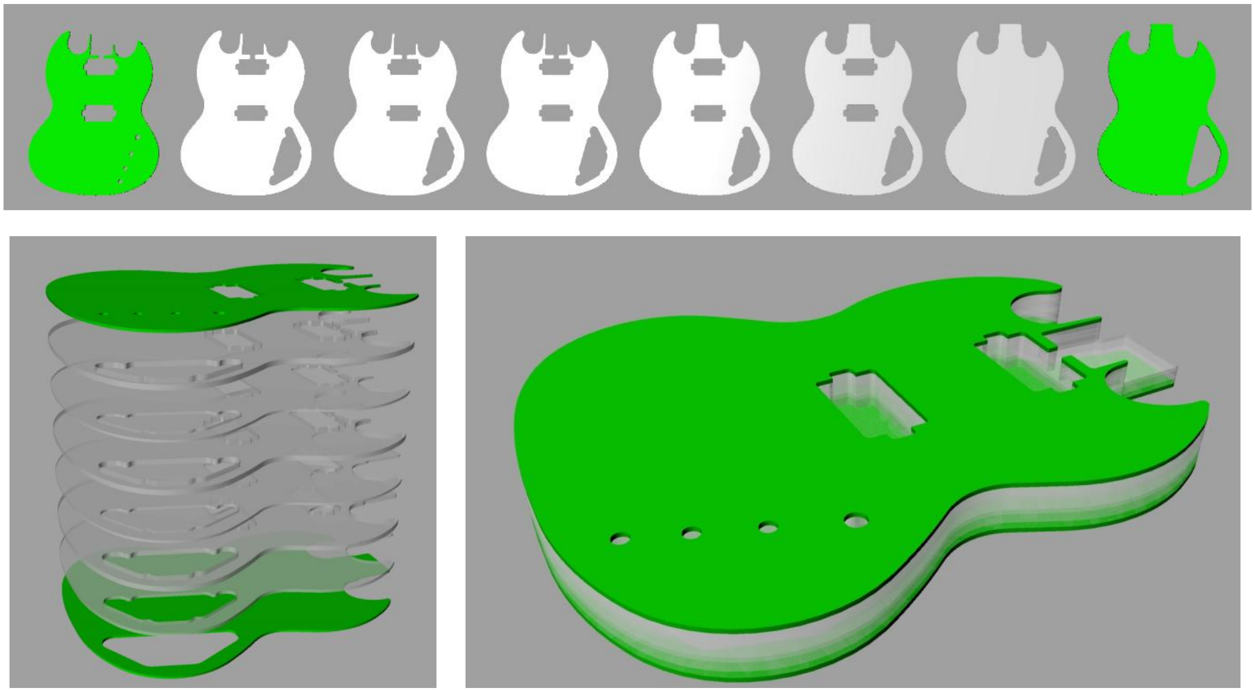


Figure 47. Second Prototype Design of Laminated Copolyester Solid Body Electric Guitar

The eight layers combined all three available thicknesses of copolyester sheet, which represented the two-dimensional geometric slices, were strategically layered with the purpose of producing three-dimensional guitar body features whose depths all fell within the acceptable ranges (shown in Table 3).

Table 3.

Acceptable Depths of Various Guitar Body Features

Acceptable Depths of Features	
Feature	**Depth**
Electronics Holes	.118" - .200" (3-5mm)
Neck Pocket	0.615" - .750" (16-19mm)
Humbucker Pocket	1.000" - 1.250" (26-31mm)
Electronics Cavity	1.000" - 1.125" (26-28mm)

Table 4 shows the thickness and features of each layer for the second laminated copolyester electric guitar prototype. Because the copolyester sheet provided by Eastman is available in nominal metric thicknesses, all layer calculations feature metric units.

Table 4.

Layer Specifications for Laminated Copolyester Electric Guitar Prototype #2

Laminated Copolyester Electric Guitar Prototype #2					
Layer	**Thickness**	**Features**	**Feature**	**Abbreviation**	**Depth**
1	3mm	E, N, H	Electronics Holes	E	3mm
2	6mm	N, H, C	Neck Pocket	N	18mm
3	3mm	N, H, C	Humbucker Pockets	H	27mm
4	6mm	N, H, C	Electronics Cavity	C	27mm
5	3mm	H, C	Cavity Ledge	L	3mm
6	6mm	H, C			
7	4mm	C			
8	3mm	L			

In order to conceal any visual defects inherent to the lamination process, the top and bottom layers of the guitar body were cut out of opaque, texturized green Spectar® copolyester sheet. Layers two through seven were cut out of clear Tritan® copolyester that were flame polished along the edges to create a semitransparent cross-section (as shown in Figure 48).

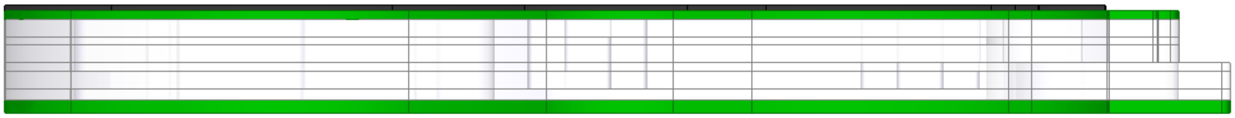


Figure 48. Cross-sectional View Depicting Layer Transparency

Prototype #2 Fabrication

Because blowout was unavoidable, the smaller geometric features such as small spotted mounting hole locations for hardware were eliminated from the CADD data. The waterjet was only used to generate the larger geometric features that included the guitar body edges and support tabs, tooling holes, electronics holes, neck pocket, humbucker pockets, and the electronics cavity. After the waterjet machining process, each layer could be mounted on the guitar tooling installed on the AXYZ CNC router so that any smaller hole geometry could be precisely located or spotted; the smaller holes were subsequently drilled out manually.

As shown in Figure 49, various tab designs were used in order to determine an effective solution to the problematic occurrence of backside blowout. It was observed that some degree of blowout was inevitable when piercing copolyester with a 20k psi narrow stream of water. Assuming a waterjet traveling from right to left, the right-hand exit tab geometry could be shorter than the left-hand entry point (circled in red) for the next segment of the body outline.

Therefore the tab example labeled "D" in Figure 49 proved to be efficient and effectively isolated the blowout leaving the support tab intact.

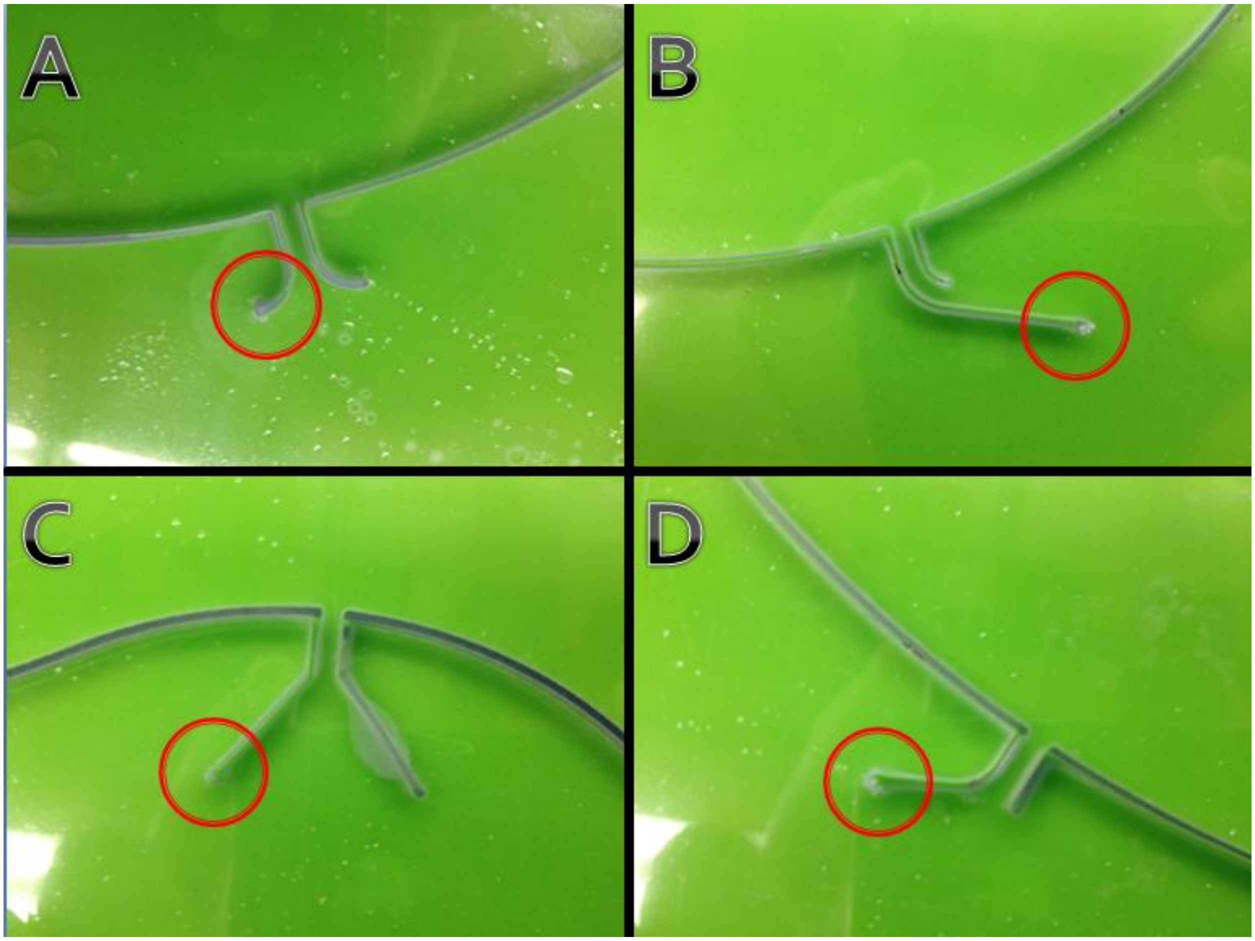


Figure 49. Anti-Blowout Support Tab Designs

One by one each of the layers was cut out using the OMAX 5555 JetMachining Center. For ease of machining, the larger copolyester sheets were precut into smaller sheets measuring approximately 24" x 16". The sheets, six of which are shown arrayed in Figure 50, were cut to the size of a standard wooden guitar blank that enabled the layers to be aligned and stacked on the AXYZ guitar tooling using the two precision-located 3/8” DIA alignment holes.

Figure 50. First 6 Layers Cut by the OMAX 5555 JetMachining Center

In the interest of exploring alternative fabrication methodologies, Layer 1 (the guitar top) was also cut out using a Universal Laser Systems ILS 12.75 Platform Series laser engraver-cutter (as shown in Figure 51). The setup procedures for this machine were far less complicated than those of the OMAX waterjet. Additionally, the laser was able to cut out the geometry in less than half the time and with no high pressure water-induced bottom side blowout.

Figure 51. Universal Laser Systems ILS 12.75 Platform Series Laser Cutter-Engraver

As shown in Figure 52, a considerable volume of nontoxic smoke accompanied by a pungent odor was produced during the laser cutting process. Although the system’s fume extraction system vented the smoke outside the building, it did not effectively eliminate the odor within the room.

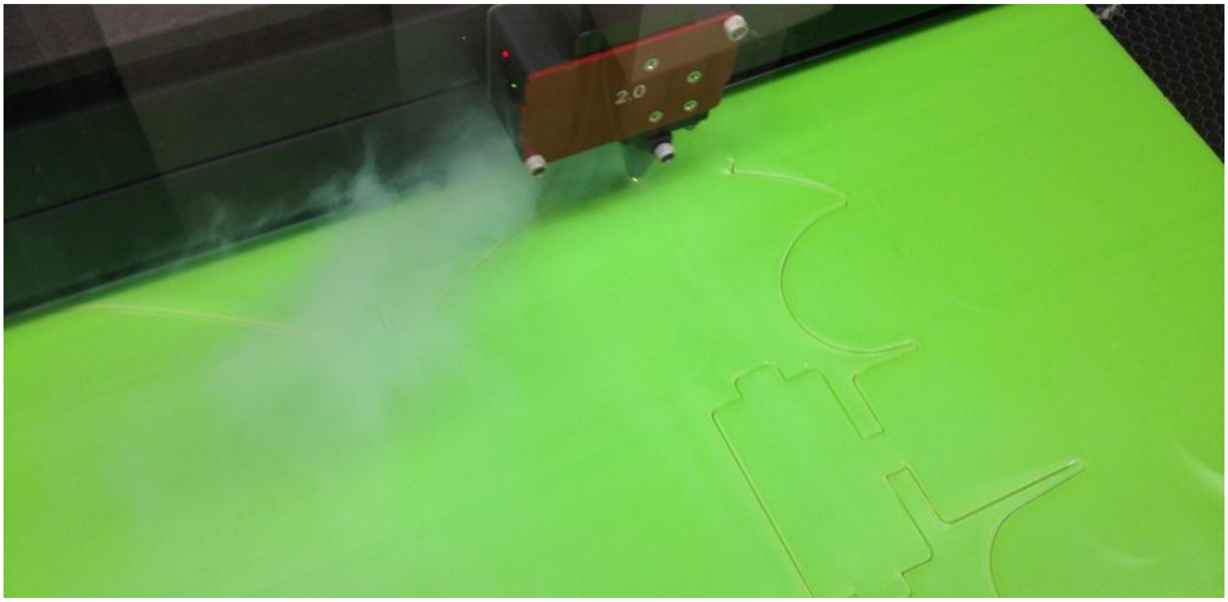


Figure 52. Laser Cutting Layer 1 of Prototype #2 from Nominal 1/8" (3mm) Copolyester

As shown in Figure 53, it was observed that the molten copolyester produced during the laser cutting process was splattered on to the material surface (top and bottom) by the force of the air-assisted flame extinguisher jet. This molten coplyester then cooled and solidified around the laser cut edges resulting in nonuniform top and bottom surfaces. These uneven surfaces would prevent surface-to-surface contact and preclude structurally sound bonding of the guitar body lamination.

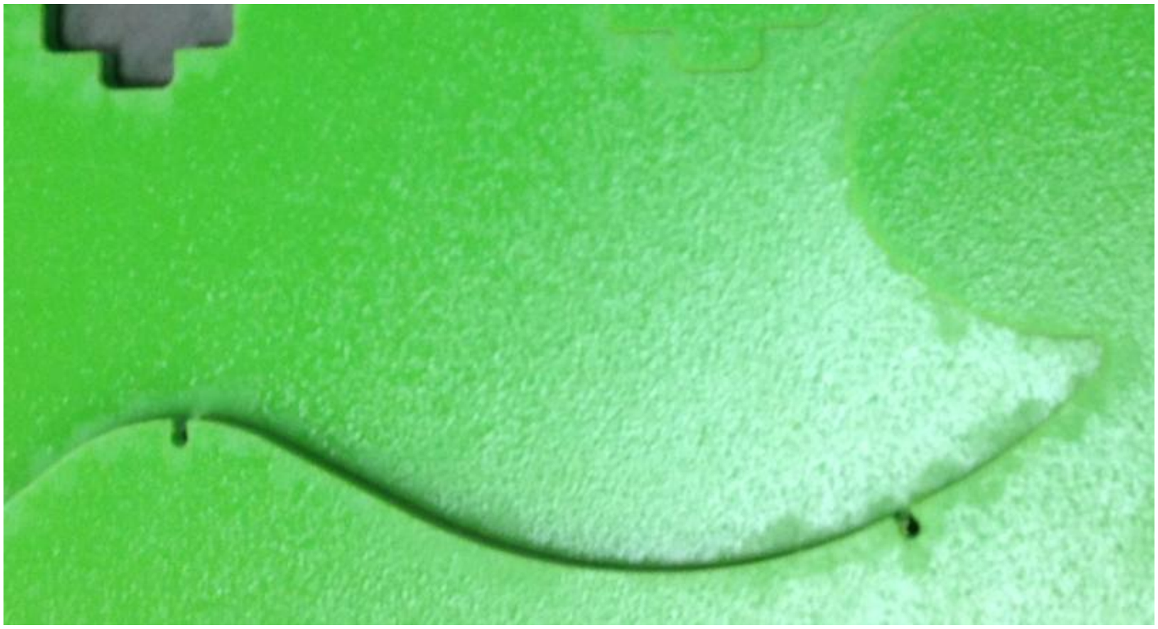


Figure 53. Example of Molten Copolyester Deposited Along Laser Cut Edges

It was later discovered that this problem could be eliminated by laser cutting the copolyester before removing the protective film from the sheet. Unfortunately, the nominal 1/8" (3mm) texturized green copolyester sheets used for the top and bottom layers of the laminated guitar body were provided by Eastman with protective film on only one side. As a result, the laser cutter was abandoned as a fabrication method in favor of the waterjet.

In order to test the alignment provided by the guitar tooling as well as the full scale bonding performance of the Loctite® spray adhesive, the laser-cut Layer 1 and a defective waterjet-cut Layer 5 were laminated together. After drilling out the support tabs, it was discovered that the neck pocket geometry of Layer 4 (identical to that of Layer 1) would fuse to Layer 5 and would not be removable after the lamination process (as shown in Figure 54).

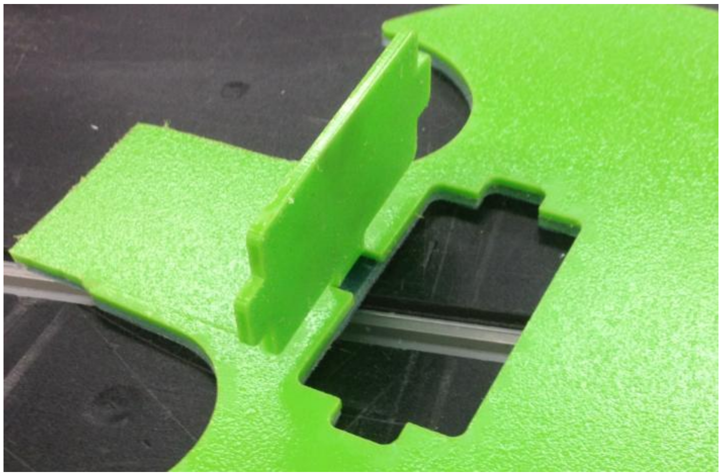


Figure 54. Example of Undesired Neck Pocket Bonding

As a result of this fortuitous test, it was determined that the neck pocket geometry (as indicated in Figure 55) of the first four layers had to be removed prior to the lamination process.

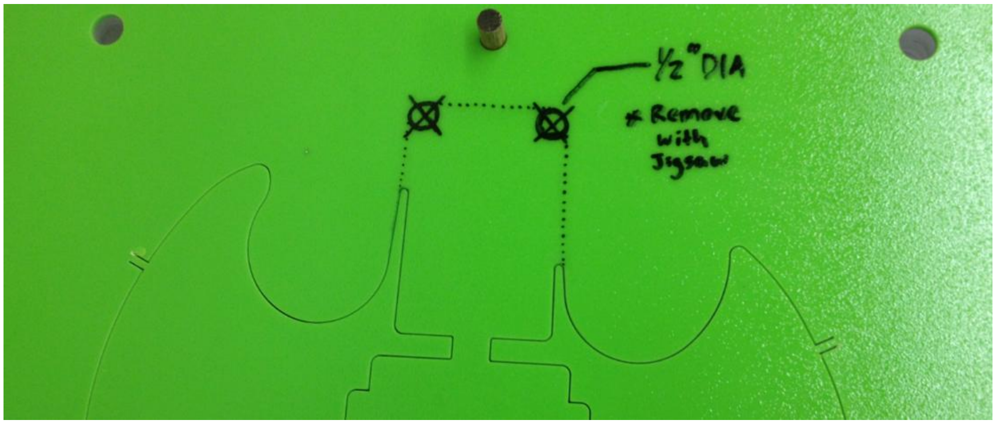


Figure 55. Modification of Neck Pocket Geometry Required for Layers 1-4

As shown in Figure 56, a jigsaw was used to individually remove the neck pocket geometry from Layers 1-4 prior to the lamination process. It should be noted that this was a inelegant solution to the problem in an effort to salvage the layers that had already been cut and conserve material.

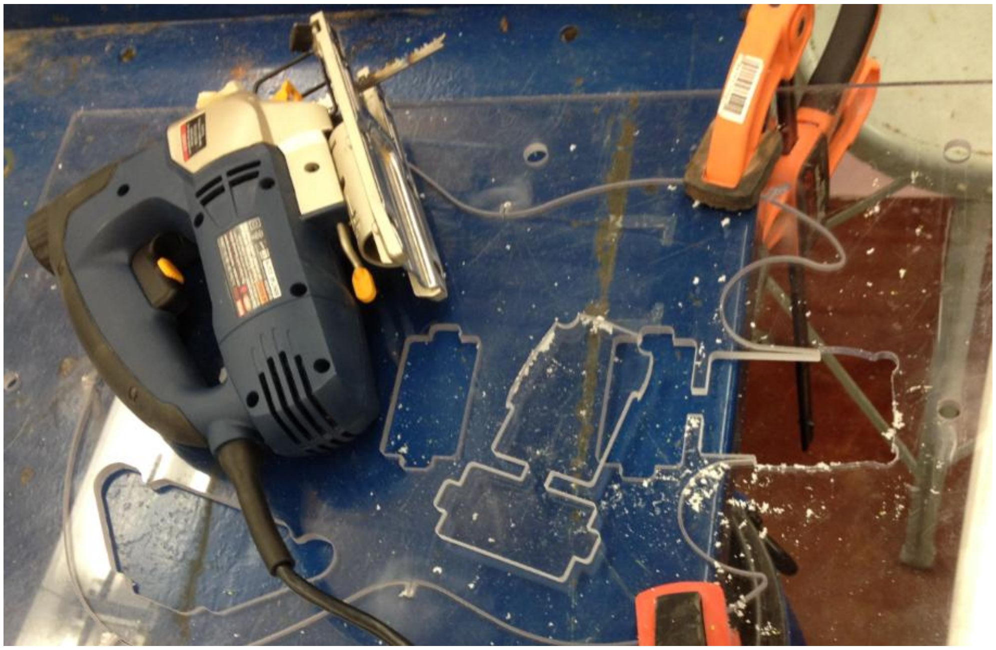


Figure 56. Jigsaw Removal of Neck Pocket Geometry

As shown in Figure 57, all eight layers were aligned on the lamination tooling to ensure proper fitment and clearance after the neck pocket geometry had been removed from Layers 1-4 with the jigsaw. It was concluded that the layers could now be correctly laminated.

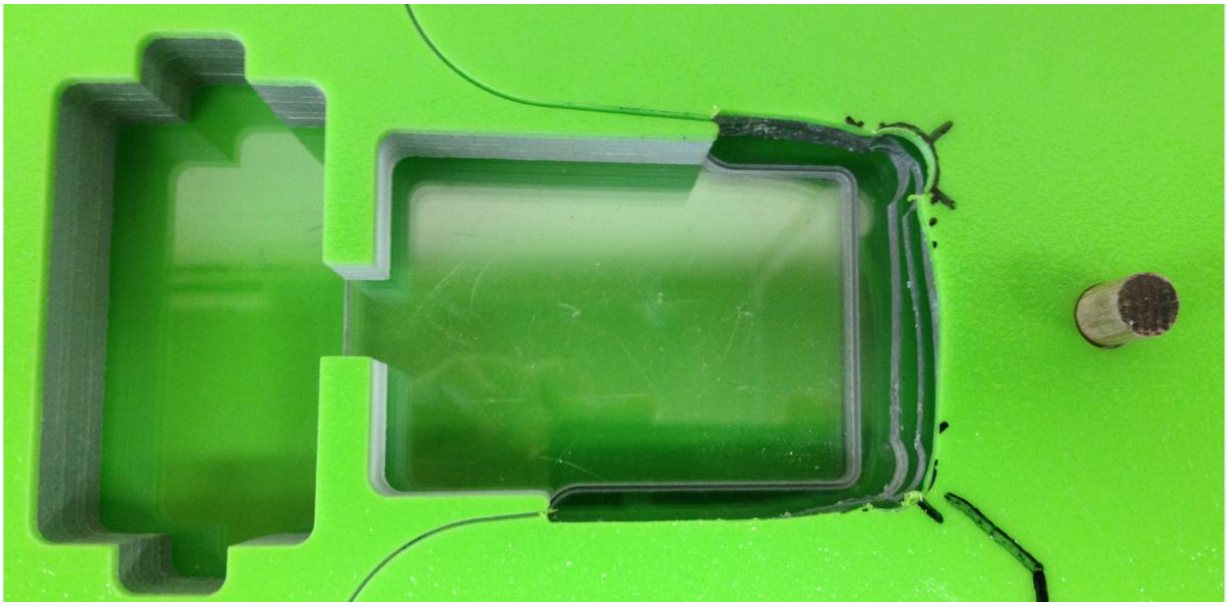


Figure 57. Fitment-Neck Pocket Clearance Test of Layers 1-8 on Lamination Tooling

As determined during the lamination experimentation phase, Loctite® Spray Adhesive High Performance Middleweight Bonding 200 was used to fuse the stack of layers together. Beginning at the bottom, the top side of Layer 8 was sprayed with an even, medium-thick coat of adhesive and placed on the alignment pins of the guitar tooling. T mating, or bottom surface of Layer 7 was then quickly sprayed with a coat of Loctite®, allowed 1 minute to dry, and carefully placed above Layer 7 using the 3/8" diameter alignment pins (as shown in Figure 58).

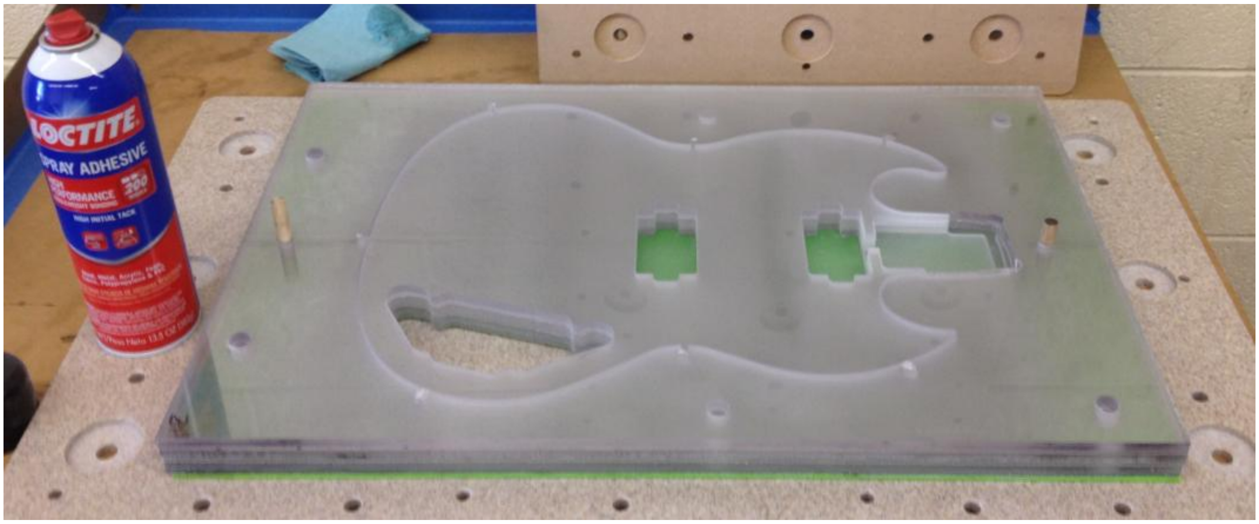


Figure 58. Tooling Used for Alignment During Loctite® Lamination

The air was squeezed from between the two mating surfaces as the layers were pressed together The topside of Layer 7 was then sprayed with Loctite®, and the process was repeated for the remaining six layers to create the finished 1.40" laminated copolyester guitar blank shown in Figure 59.

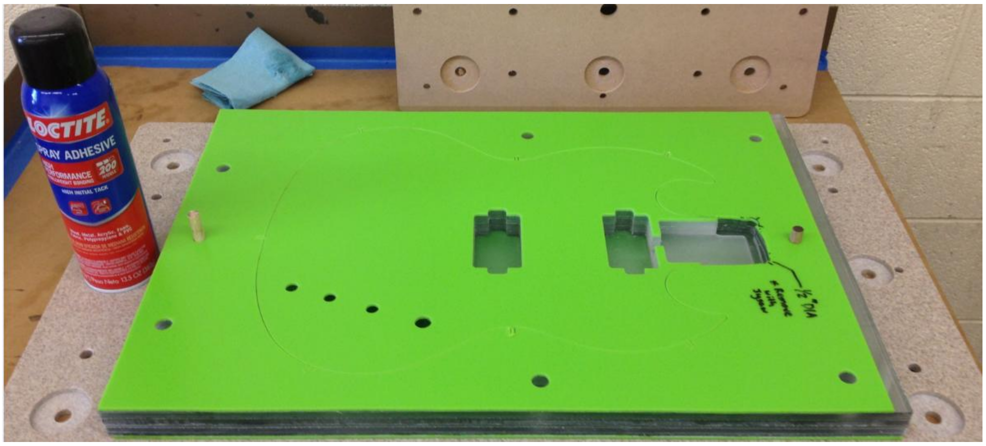


Figure 59. All Eight (8) Layers Aligned and Bonded Together

To ensure a maximum strength bond between layers, approximately 100 pounds of compressive force was applied to the stack (as shown in Figure 60). After a period of 24 hours the adhesive had fully cured and the weights were removed. As expected, the individual layers had been bonded into one solid slab.

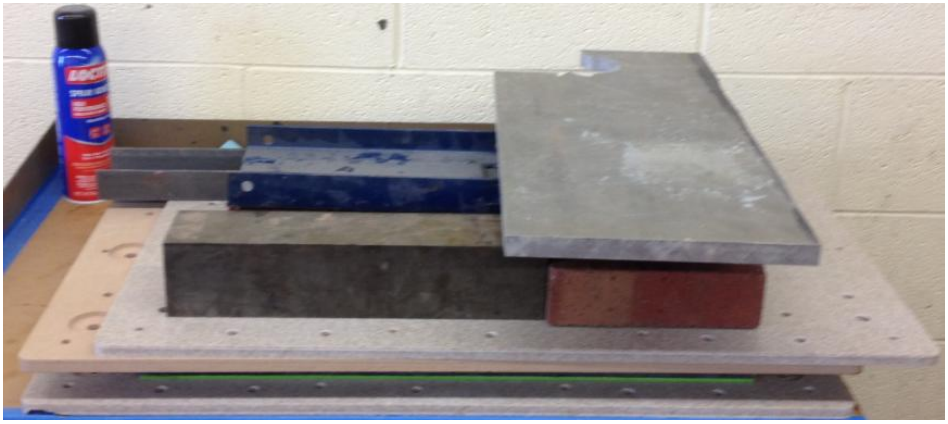


Figure 60. Compressive Force Applied to Laminated Guitar Blank

As shown in Figure 61, the laminated guitar body was then placed on the AXYZ CNC router to accurately spot drill the small geometry that could not be generated using the waterjet without backside blowout.

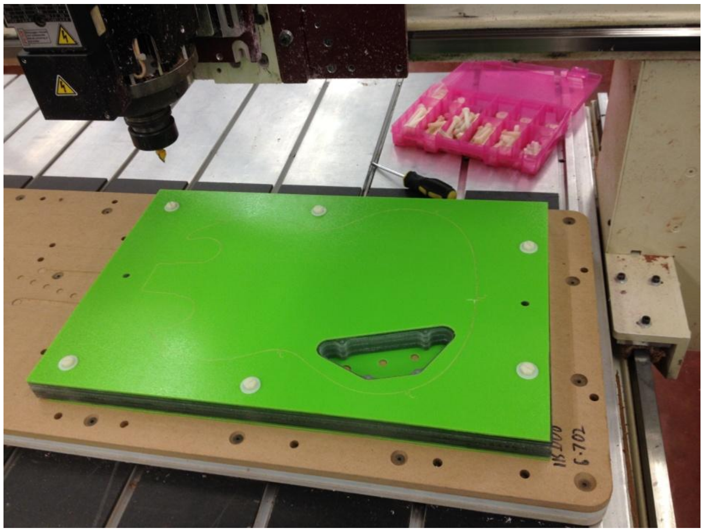


Figure 61. Reference Spotting on the AXYZ CNC Router

First, the ferrule holes and the cavity cover and neck mounting screws were accurately spot drilled on the bottom side of the laminated guitar body blank. Then, the blank was unbolted from the AXYZ CNC guitar tooling, flipped over, and bolted back onto the tooling so that the string holes and the bridge and humbucker mounting screws could be accurately spot drilled on the top side. After removing the blank from the guitar tooling, the support tabs were manually located and drilled using a 1/2" diameter bit on the drill press (as shown in Figure 62).

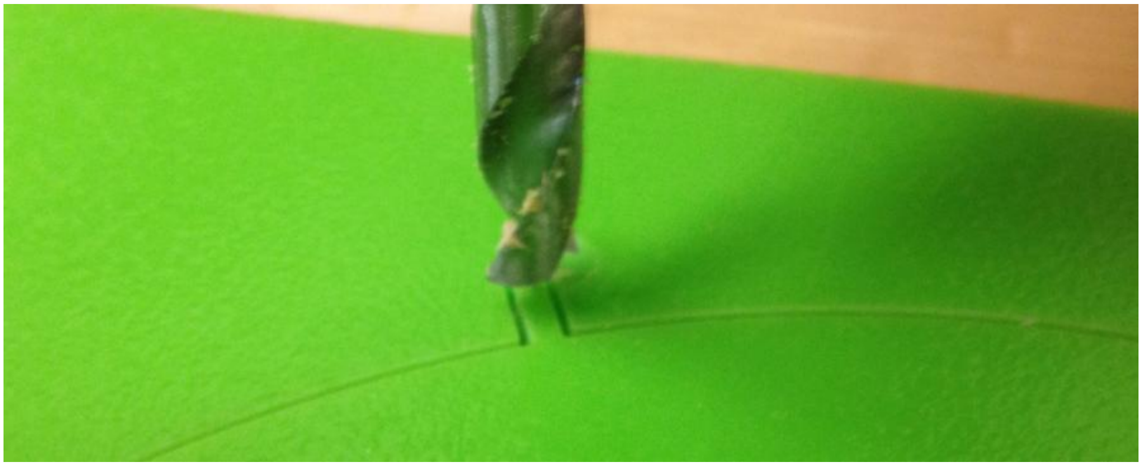


Figure 62. Drilling Out the Support Tabs

As shown in Figure 63, drilling out the support tabs separated the laminated copolyester guitar body from the rest of the blank.

Figure 63. Removal of the Laminated Guitar Body

The sides of the guitar body were sanded using a Rigid® Belt/Spindle Sander as shown in Figure 64. This process removed the remainder of the support tabs as well as any minor layer misalignment.

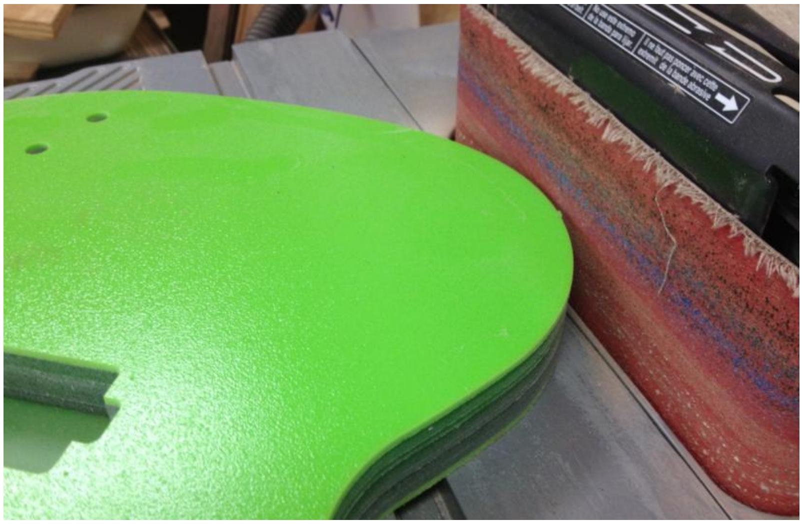


Figure 64. Removal of Support Tabs with Belt Sander

The sides were then sanded by hand using progressively higher grits of sandpaper (up to 3000 grit) until they could be flame polished with a MAPP gas torch to achieve maximum transparency (as shown in Figure 65).

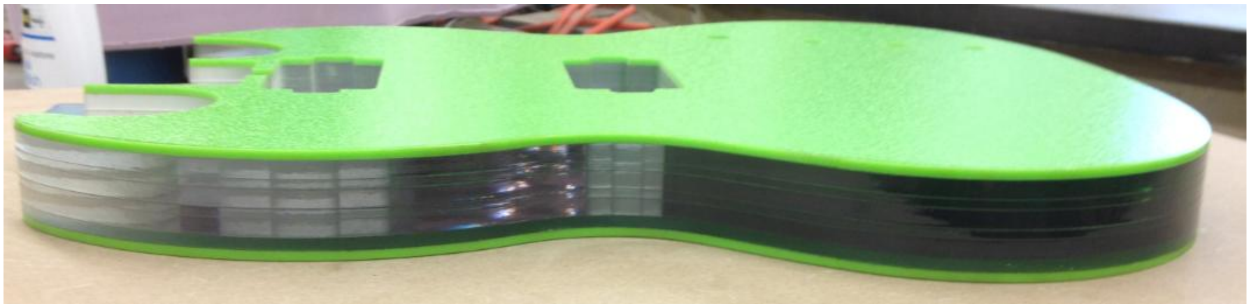


Figure 65. Flame Polished Sides of Guitar Body

While attempting to flame polish the inside of the electronics cavity, the surface of Layer 1 was inadvertently deformed by the radiant heat of the MAPP gas torch. To hide this deformity, an integrated faceplate-pickguard was designed (as shown in Figure 66) and fabricated out of black 2mm copolyester sheet.

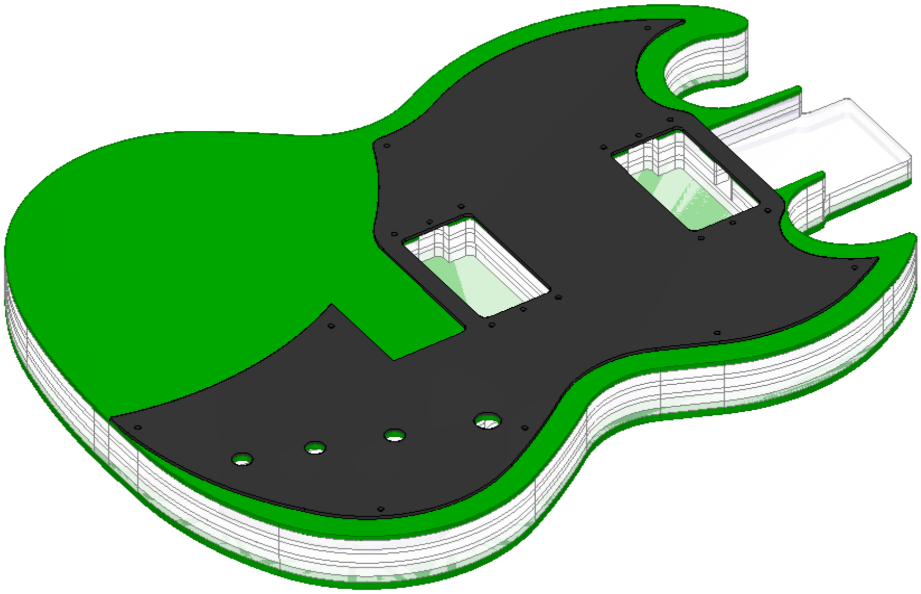


Figure 66. 2mm Black Copolyester Faceplate-Pickguard Design

In addition to the faceplate-pickguard for the top of the laminated guitar body, a cover for the electronics cavity was also fabricated from the 2mm sheet of black copolyester using the laser system (as shown in Figure 67).

Figure 67. Faceplate-Pickguard and Cavity Cover Laser-cut from 2mm Black Copolyester

The holes in the faceplate-pickguard were then countersunk on the drill press in order to flush-mount the heads of the mounting screws. The faceplate-pickguard, bridge, humbuckers, and electronics were then installed as shown in Figure 68.

Figure 68. Faceplate-Pickguard and Hardware Installation

The electronics package chosen for this guitar included two humbucking pickups, a 500kΩ audio taper volume potentiometer, a 500kΩ audio taper tone potentiometer with a .047μF capacitor, a three-way pickup selector switch, and a 1/4" output jack. Copper tape was applied to the "bottom" of the electronics cavity to establish a ground plane for the electronics. The installed and soldered three-way switch, two potentiometers, and 1/4" output jack are shown in Figure 69.

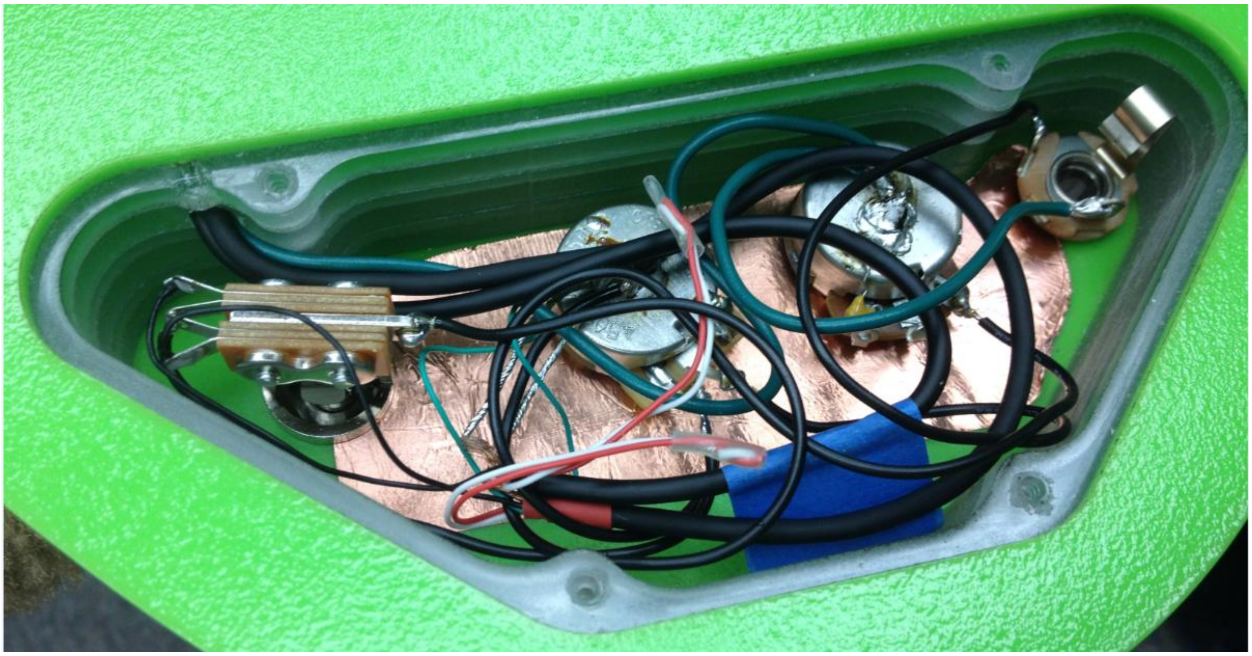


Figure 69. Installed and Soldered Components in the Electronics Pocket

An open-source designed 21 fret maple neck with 3 x 3 headstock was selected for this guitar. These necks used in the guitar building project are all based upon the geometry released in Summer 2012 for 21 fret, 25.5" string length solid body electric guitar design from the NSF-sponsored guitarbuilding.org site. The design of the guitars (especially the critical neck geometry) is open-source and available from following URL: http://www.guitarbuilding.org/current-guitar-models-design-files/.

The neck was fitted with a 21 fret/25.5" string length maple fretboard with ebony fret dots. To accommodate the "as built" geometry of the laminated guitar body's bridge placement, the fretboard was shifted as necessary in order to maintain the proper 25.5" string length between the plastic nut and bridge necessary for intonation. The fretboard was contoured to a 12" radius; medium fret wires were used to create the finished neck shown in Figure 70.

Figure 70. Modified Guitarbuilding.org Maple Neck with Custom Maple Fretboard

The neck was subsequently fitted into the laminated guitar body neck pock and secured using four #8 screws through a standard nominal 2" x 2.5" steel neck plate.

The completed and assembled guitar is shown in Figure 71 (front view) and Figure 72 (back view). Following assembly, the string heights (action) over the fretboard were adjusted and the six bridge saddles individually adjusted in a process called intonation to ensure that the guitar could play in tune.

Delightfully, the finished guitar could be played and sounded like any solid body electric guitar. The development effort was, in that regard, a success: a playable solid body electric guitar had been created using laminated sheets of copolyester in the guitar body.

Figure 71. Finished Guitar (Front)

Figure 72. Finished Guitar (Back)

CHAPTER 4

RESULTS

Metrics of Success

In order to determine the metrics for success of this project, it is important to define the performance characteristics of the proof-of-principle laminated copolyester solid body electric guitar that was evaluated. Two key performance points that characterize the overall quality of an electric guitar include sustain and playability. Each of these performance characteristics was measured and analyzed in order to provide quantitative data for comparison to conventional, wooden electric guitars.

Sustain Comparison

The sustain of the copolyester electric guitar was evaluated against three other electric guitars with 25.5" string lengths. The objective was to determine the duration of string vibration at different frequencies for each of the four guitars to see how their sustains compared. A series of 20-second instrument audio tests were conducted on the four guitars at three frequencies. The signal profiles were arrayed for visual comparison.

A quick comparison of the component materials (see Table 5) showed that all four test guitars featured a maple neck. Three of the test guitars had solid body designs (J, K, & S). Two of the three solid body guitars featured a maple fretboard (J & S). Therefore, the key variable affecting the sustain of test guitars J and S was the body material. There were of course numerous differences between the guitars' hardware and electronics, but the difference in sustain of the two guitars was predicted to be minimal.

Table 5.

Summary of Guitars, Materials, and Designs for Testing Sustain

Feature	Guitar			
	J	K	L	S
Body Material	Laminated Copolyester	Basswood	Walnut & Spalted Maple	Unknown
Neck Material	Maple	Maple	Maple	Maple
Fretboard Material	Maple	Bloodwood	Walnut	Maple
Body Type	Solid Body	Solid Body	Semi-hollow Body	Solid Body
Neck Type	21 Fret, NCME	21 Fret, NCME	21 Fret, NCME	21 Fret, Fender

An early guitar design created during this project was informally given the working name of “S-Jet” as it was being fabricated using waterjet technology. Accordingly, this guitar has been designated “J.”

The guitar designated "K" was a FireX style of solid body electric guitar of ETSU design based on the 2012 Summer release of the Guitarbuilding.org open-source CADD data provided through the National Center for Manufacturing Education (NCME). The body of guitar "K" is longitudinally-laminated basswood. The 21 fret maple neck is topped with a bloodwood fretboard.

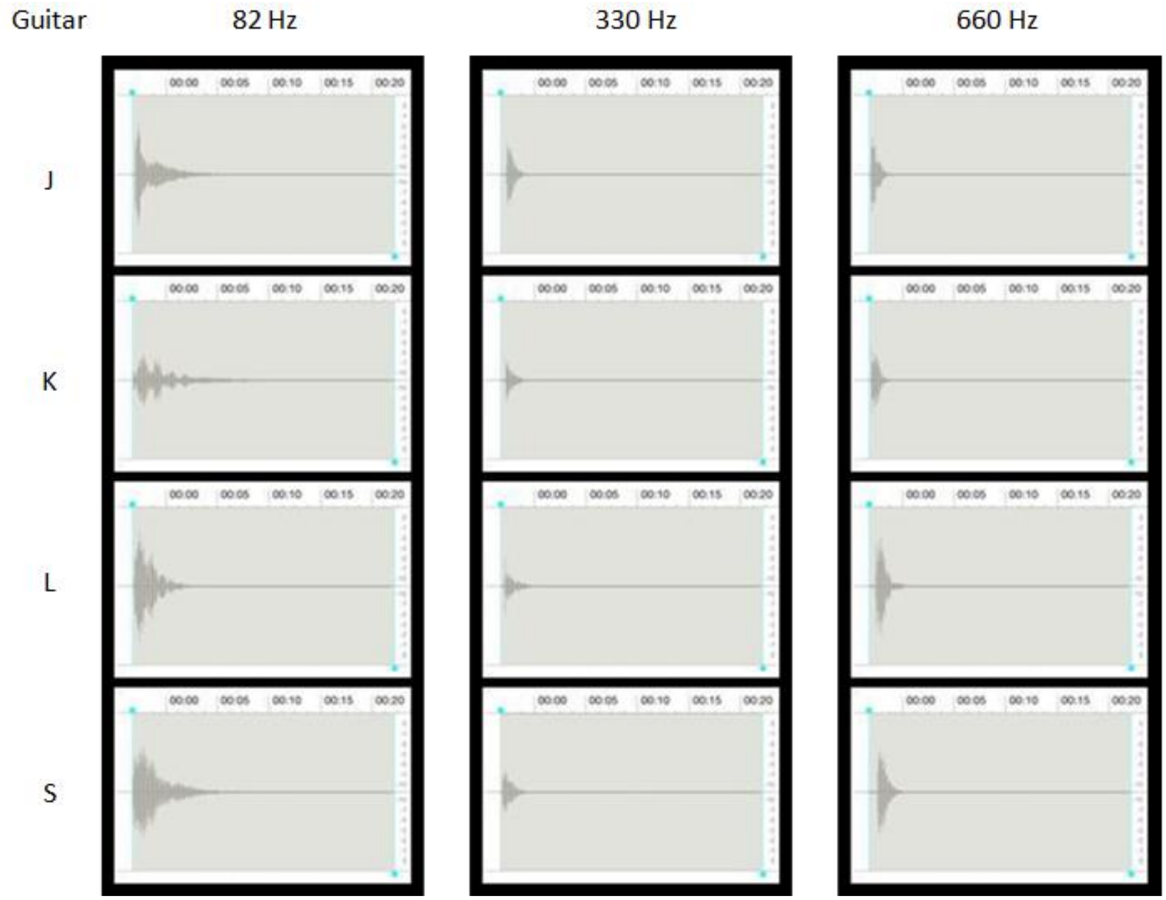
The guitar designated "L" was a Lucy-style semihollow body electric guitar designed and fabricated at ETSU to the same 2012 Summer release of the Guitarbuilding.org open-source CADD data provided through NCME. The body of guitar "L" is longitudinally-laminated hardwood: a nominal 4" wide core of walnut with sides of spalted maple. The 21 fret maple neck is topped with a walnut fretboard.

The guitar designated "S" was a high-end, factory built, solid body guitar patterned after the Fender Stratocaster. The body is compromised of an unknown wood (possibly swamp ash or maple) and painted dark blue. The 21 fret maple neck is topped with a maple fretboard.

As shown in Table 6, the signal profile of the copolyester guitar did not stand out as unique among the raw recording data. This conveyed that the sustain of the copolyester electric guitar was within the acceptable range for electric guitar sustain.

Table 6.

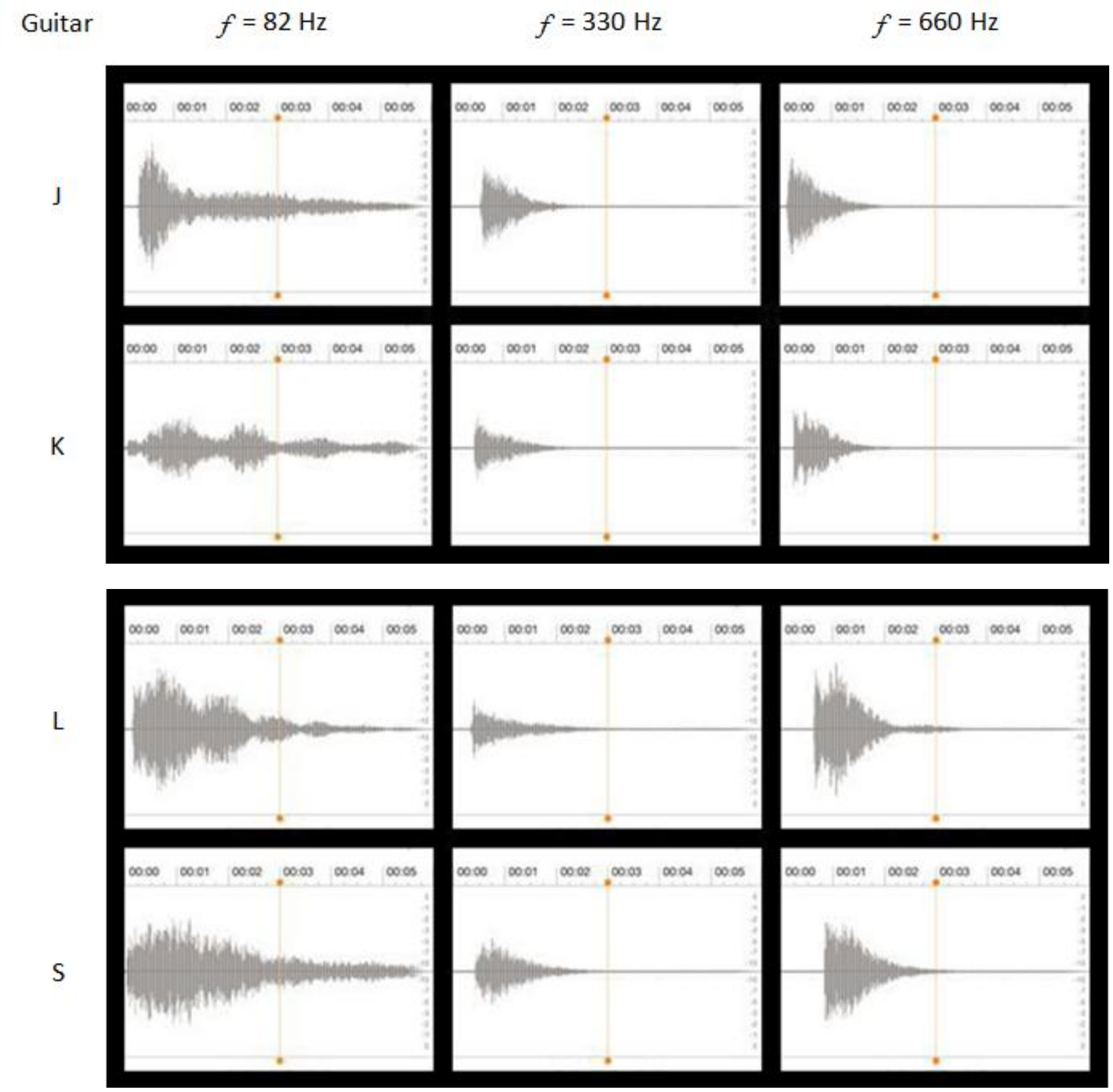
Signal Profiles of 20-Second Sustain Tests of Four Guitars at Three Frequencies



In order to determine the actual sustain values for each guitar at each frequency, the recording data were trimmed down to the first 6 seconds. This was possible because the magnitude of the wave for all tests had dropped below 10% by the 6-second mark. As shown in Table 7, by condensing the data the sustain could be more accurately measured and compared.

Table 7.

Signal Profiles of 6-Second Sustain Comparison of Four Guitars at Three Frequencies



In order to determine the sustain of each guitar at each frequency, the time at which the wave reached its peak magnitude was subtracted from the time at which the magnitude of the wave dropped below the audible amplitude threshold set at 10% of the maximum signal. The absolute value of the resulting difference, from peak to inaudible (measured in seconds), was a measurement of the duration of an audible vibrating string, or sustain. The three sustain values for the three frequencies for each guitar were averaged to compare the overall sustain of the four electric guitars (as shown in Table 8).

Table 8.

Comparison of Sustain Value Test Results for Four Guitars

Guitar	f = 82 Hz		f = 330 Hz		f = 660 Hz		Average	
	Sustain (sec)	% of Longest	Sustain (sec)	% of Longest	Sustain (sec)	% of Longest	Sustain (sec)	% of Longest
J	4.00	80	1.10	73	1.30	76	2.13	82
K	4.30	86	1.00	67	1.00	59	2.10	81
L	3.20	64	1.50	100	0.90	56	1.87	72
S	5.00	100	1.10	73	1.70	100	2.60	100

At 82 Hz, the copolyester guitar ("J") had sustain lasting at least 4.00 seconds − a difference of 1.00 second (or 80%) from guitar "S" that had sustain lasting at least 5.00 seconds. At 330 Hz the copolyester guitar ("J") had sustain lasting at least 1.10 seconds − a difference of 0.40 seconds (or 73%) from guitar "L" that had sustain lasting at least 1.50 seconds. At 660 Hz, the copolyester guitar ("J") had sustain lasting at least 1.30 seconds − a difference of 0.40 seconds (or 76%) from guitar "S" that had sustain lasting at least 1.70 seconds. The copolyester guitar ("J") had an average sustain lasting at least 2.13 seconds − a difference of 0.47 seconds (82%) from guitar "S" that had an average sustain lasting at least 2.60 seconds.

When compared to the high-end, factory built guitar ("S"), the copolyester guitar's ("J") sustain never measured below 75%. As the sustain of the copolyester guitar ("J") compared favorably to all three guitars, the copolyester guitar ("J") successfully fulfilled one of the primary objectives of the project that was to achieve sustain and playability comparable to traditionally constructed wooden electric guitars.

Playability

String Action

At a thickness of only 16mm (.630"), copolyester neck pocket ledge proved too flexible to withstand the force of the tuned string tension. The D'Addario EXL110 Nickel Wound, Regular Light, 10-46 gauge strings used on this guitar imposed a calculated combined string tension of 105.52 lbs when "standard E tuned" on a 25.5" scale (D'Addario, 2008).

As shown in Figure 73, when the copolyester guitar was tuned to "standard E tuning," the 6th string (Low E) caused a deflection of 0.156" (3.57°) and the 1st string (High E) caused a deflection of .188" (4.30°). The asymmetry of the neck pocket, having more support on the Low E side, resulted in a twisting deflection of .031" (0.84°).

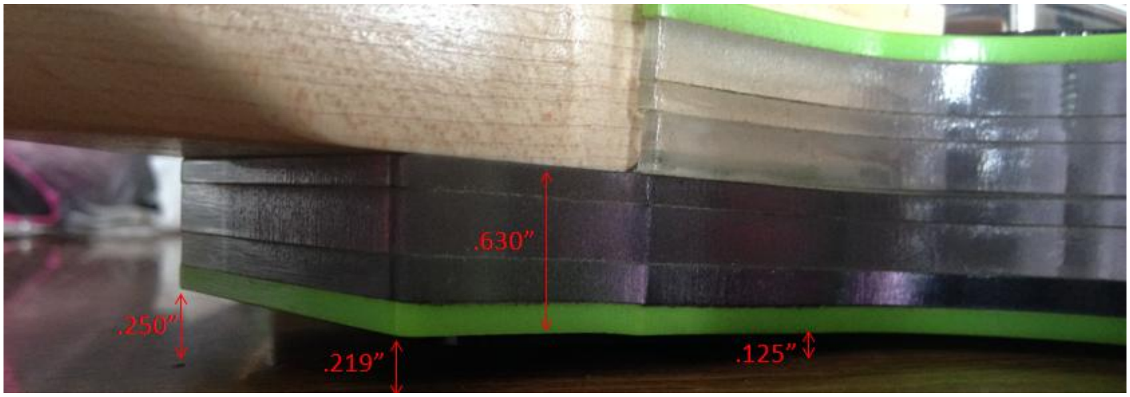


Figure 73. Neck Deflection from String Tension

The deflection and subsequent twisting rotation of the neck (and the neck pocket area) resulted in extremely high string action. Measured above the 12th fret, typical string heights for an electric guitar are 0.093" (2.362mm) on the bass side (E, A, D) and 0.062" (1.575mm) on the treble side (G, B, e). As shown in Figure 74, the string heights on this guitar averaged 0.172" (4.369mm) on the bass side and 0.141" (3.581mm) on the treble side. The neck deflection raised the string action by a nominal 0.08" (2.03mm)

Figure 74. High String Action Due to Neck Pocket Twisting and Subsequent Deflection

Weight

Fully assembled, the combined weight of the 1.34" (34mm) laminated copolyester body, neck, electronics, and hardware was measured at 14.5 lbs. For comparison, a typical Gibson SG weighs between six and eight pounds. This copolyester SG is therefore nominally twice as heavy as a similarly sized wooden guitar. Even the hefty solid body Gibson Les Paul has a maximum weight of 11 pounds. Thus, a solid copolyester guitar is an ergonomics nightmare. Even with the support of a strap, the weight of the laminated copolyester guitar body would make extended playing an uncomfortable experience to most guitar players.

Suitability of Copolyester for Electric Guitar Bodies

Copolyester, whether laminated in sheets or as a solid cast part, is simply too soft and flexible for use in production scale electric guitars. To prevent neck deflection due to string tension, a copolyester electric guitar body would require some type of reinforcement. One method of reinforcement would be the addition of copolyester laminations. Unfortunately, not only would this result in additional, undesirable weight, but, given the inherent plasticity and ductility of the material, the copolyester neck pocket would still tend to flex to an undesired degree if the thickness were increased by the nominal 3/8" (9.5mm) that would bring the guitar to the nominal thickness of a standard commercially produced solid body electric guitar. By reinforcing the guitar with another material such as metal, the properties exhibited by the guitar could no longer be claimed as the result of using copolyester as the body material.

This thesis has been an investigation of realistically accessible fabrication and assembly methodologies employed in the development of a proof-of-principle prototype electric guitar composed of laminated copolyester sheets. It is, by no means, meant to be a best practices guide or an endorsement of the use of copolyester for production-scale electric guitars. It has been an attempt to answer to the question: "Can a playable electric guitar body be constructed of laminated sheets of copolyester?" This thesis has proved that it is indeed possible. The completion of this proof-of-principle prototype now presents the follow-up question: "Should production electric guitars be constructed of laminated sheets of copolyester?" The answer is more nuanced: "While laminated copolyester is not an ideal guitar body material for production guitars, the material offers unique possibilities for highly customize and unique solid and/or hollow body electric guitars.

CHAPTER 5

POSSIBILITIES FOR FUTURE RESEARCH

Lamination

While Loctite® 200 series spray adhesive was not the ideal adhesive for bonding the copolyester sheets, it was selected primarily because it was a cost effective, commercially available product. Cyanoacrylate may have been another possible bonding method to test. Unfortunately, because of the large surface areas in contact (nominal 2,352 in^2), it was too expensive in the quantity required. Cyanoacrylate (CA Thin) would be applicable if the guitar body were pocketed for weight reduction. The bonding areas would have smaller surface areas, which would allow the CA Thin to be wicked into the joints via capillary action.

The same method of capillary action for small area bonds would also work with MEK. In experiments for this project, MEK's solvent bonding action actually produced the strongest bond between layers. Once the MEK had evaporated, the copolyester was fused into one piece. The issues with solvent laking, or liquid entrapment between large surfaces, would be nonexistent when bonding nominal 1/2" wide strips of copolyester. In fact, if the layers were pocketed for weight reduction (as shown in Figure 75), a combination of MEK and CA Thin would be ideal. MEK could be brushed onto the center strip, and the edges could be fused with CA Thin. A pickguard and back-plate could cover any visual defects in the MEK bonds.

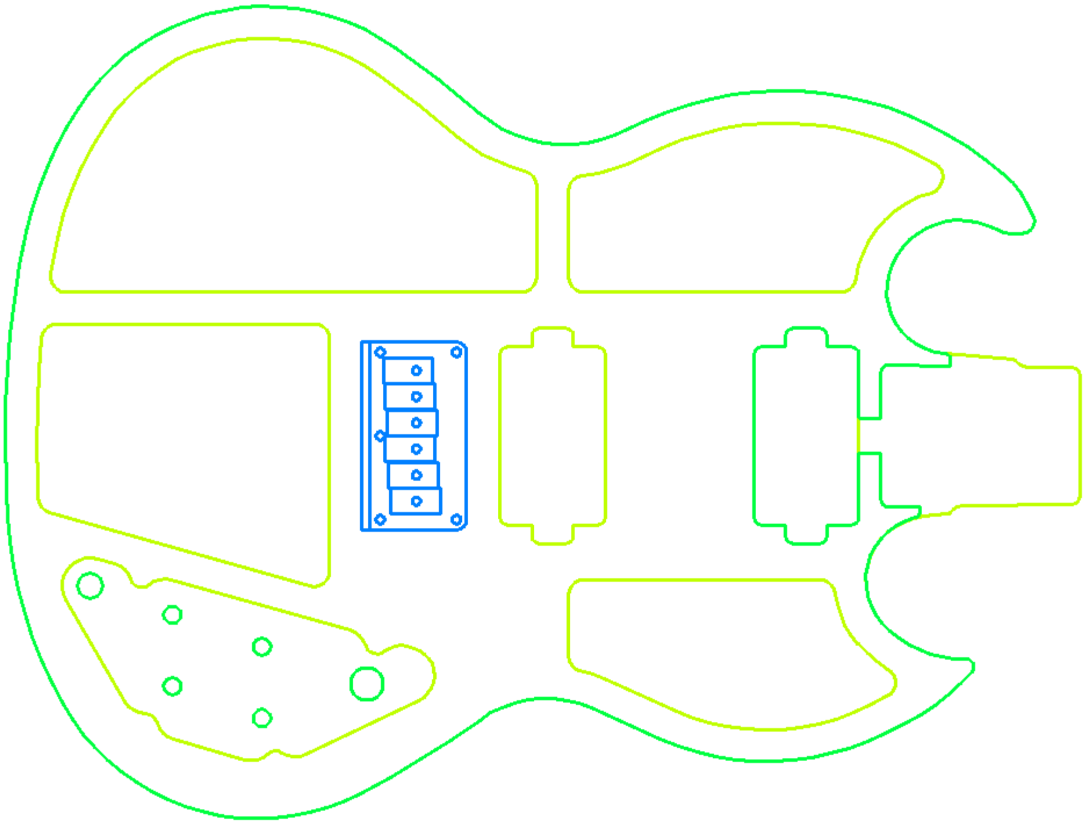


Figure 75. Example of a Laminated Guitar Body with Weight Reduction Pocketing

Fabrication

In order to prevent neck deflection due to string tension, the copolyester could be reinforced with a metal plate. The plate would extend from the bridge to the edge of the neck pocket eliminating the neck plate. A set of bolts would extend from the bridge through the body to secure the bottom of the plate. The top of the plate would be secured by the standard neck mounting screws. A plate cut from 0.188" aluminum would most likely prevent any deflection. A back-plate for reinforcing the neck joint would certainly also be necessary when material is removed by implementing weight reduction pockets. The additional stiffness supplied by the plate will compensate for the potential sustain loss due to reduction of body mass. The completed prototype laminated copolyester guitar has a nominal volume of 180 in^3 and a total weight of 8.3 lbs. With an estimated volume of 130 in^3, the future prototype laminated copolyester guitar pocketed for weight reduction would have a total estimated weight of 6.0 lbs. The removal of 50 in^3 of copolyester will reduce the total weight by an estimated 2.3 lbs (27.8%).

A future prototype guitar body will feature modifications to the bridge and humbucker locations for optimized sustain and harmonics. The length of the neck pocket supports may be reduced for better lamination. The body will also contain several large weight reduction pockets. In addition to reducing the weight of the guitar body, it will also reduce the laminated surface area. The completed prototype has a nominal laminated surface area of 1,088 in^2. A future prototype pocketed for weight reduction will have a nominal laminated surface area of only 735 in^2 for a total reduction of nominally 353 in^2 (32.4%).

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APPENDICES

Appendix A

Flame Polishing Results

As shown in Figure 76, a prismatic effect was observed as natural light passed through the flame polished edges of the laminated copolyester guitar body.

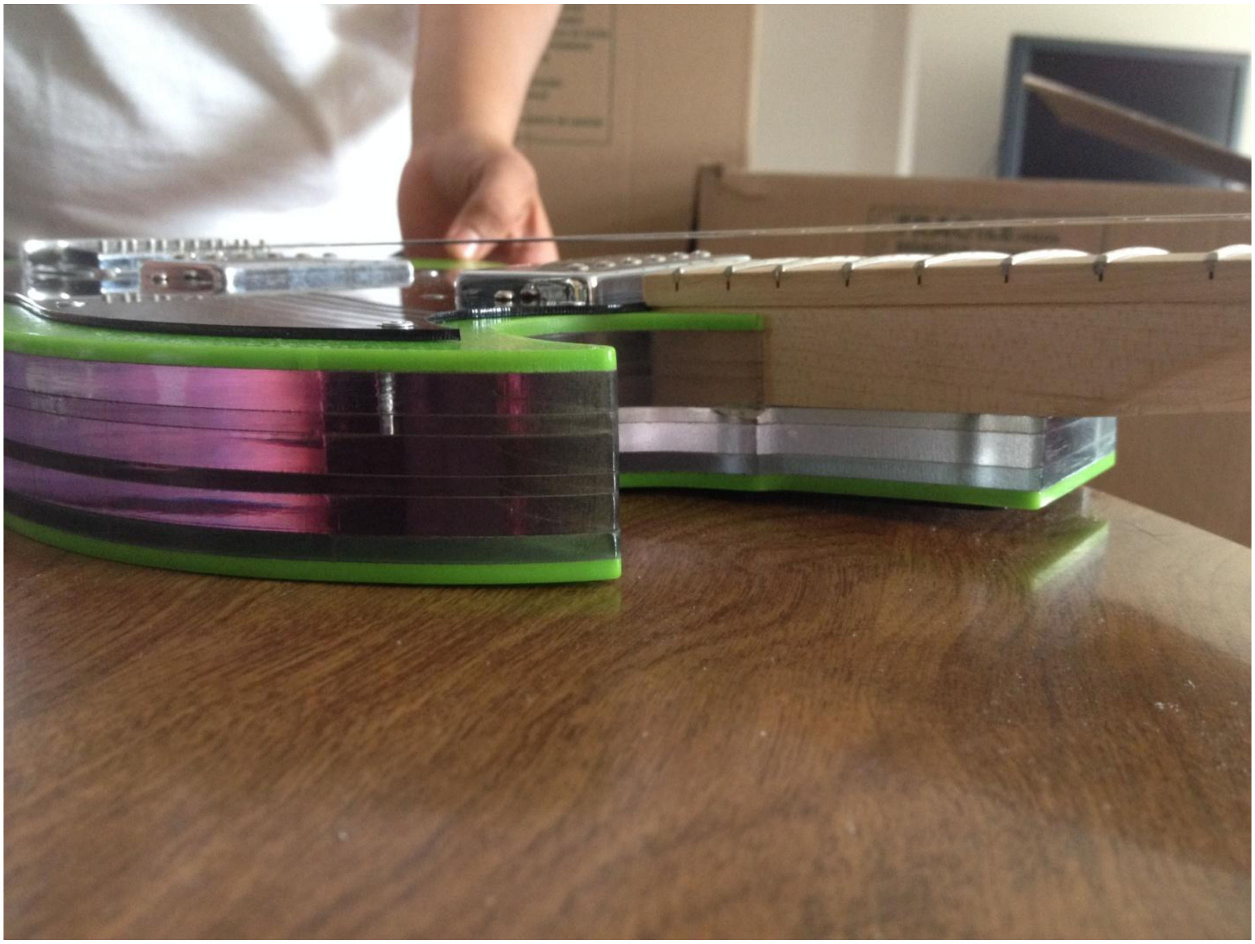

Figure 76. Observed Prismatic Effect of Light Passing Through the Flame Polished Edges

Appendix B

Test Guitars "J" and "L"

Figure 77 shows the completed copolyester guitar along with one of the test guitars ("L") and the Fender Mustang I amplifier used for the sustain comparison test.

Figure 77. Copolyester Prototype with Test Guitar "L" and Fender Mustang I Amplifier

APPENDIX C

Neck Close-up

Figure 78 provides a closer look at the completed 3 x 3 maple on maple neck that was used with the prototype laminated copolyester solid body electric guitar.

Figure 78. A Closer Look at the Completed 3 x 3 Maple on Maple Neck

VITA

ADDISON SCOTT KARNES

Education:	Independence High School, Thompson's Station, TN 2008 B.S. Engineering Technology, Concentration in Product Development (Honors-in-Discipline), East Tennessee State University, Johnson City, TN 2012 M.S. Technology, Concentration in Engineering Technology, East Tennessee State University, Johnson City, TN 2014
Professional Experience:	Engineering Intern, Massey Systems Industrial Design; Nashville, Tennessee, 2011 Engineering Intern, Solid State Lighting Services; Johnson City, Tennessee, 2012 Graduate Assistant, East Tennessee State University, College of Technology and Geomatics, 2012 - 2014 R&D Intern, SVHEC R&D Center for Advanced Manufacturing and Energy Efficiency; South Boston, VA, 2014
Honors and Awards:	Honors-in-Discipline Scholar, East Tennessee State University 2008 - 2012 Graduated Magna Cum Laude, East Tennessee State University 2012