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Production of a Banjo: Development of Manufacturing Processes for Banjo Resonators,Rims, and Necks.

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Production of a Banjo:

Development of Manufacturing Processes for Banjo Resonators, Rims and Necks

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Thesis submitted in partial fulfillment of Honors

by

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December 2012

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PRODUCTION OF A BANJO: DEVELOPMENT OF MANUFACTURING PROCESSES FOR BANJO RIMS, NECKS AND RESONATORS

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I would like to express my appreciation to my committee chair, William "Bill" Hemphill, who never failed to make smart remarks while I made mistakes; Mistakes from which I learned more than I ever would from any book of knowledge.

I would like to thank Mr. Sam Shafer and his relentless support and assistance during the development of the banjo neck tool path programs. I can not begin to count the hours spent in the machine tool lab during this process, nor do I wish to find out.

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PRODUCTION OF A BANJO: DEVELOPMENT OF MANUFACTURING PROCESSES FOR BANJO RIMS, NECKS AND RESONATORS

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ABSTRACT

This body of research focused on the development of prototype tooling and manufacturing processes to produce resonators, rims, and necks for building banjos. The resulting fixtures and manufacturing processes were designed for ease of use by a single employee in a small shop environment. This research required proficiency in interdisciplinary mediums (ie. 2D modeling, 3D modeling, centerline tool path program generation, 2D modeling, 3D modeling, rendering, design, and woodworking).

The resonator required development of a matching set of forming surfaces, a bending/gluing fixture, a work-holding fixture for utilizing a wood lathe, and a steam chamber required for bending strips of wood into the sides of the resonator. The rim was made using a block rim method and was made out of three laminations of staves, creating the necessary thickness for the rim. The same work-holding fixture was redesigned to accommodate the rim for turning. The goal for building banjo necks on the AXYZ CNC router was to produce a fully shaped neck out of a single piece of wood. The tall heel and angled headstock made this process difficult and resulted in more material being removed than if the neck had been shaped by hand utilizing shop equipment.

Three resonators were made, one using a non-turning method and two that utilized a redesigned gluing method for creating a scarf joint. While two rim blanks were made, the first was successfully turned, allowing the second to demonstrate how the rim was made. The banjo neck design required many prototypes, both in foam and poplar, and yielded a fully-shaped banjo neck out of maple. In October of 2012, after a year of effort, the three major wooden components were assembled with hardware, creating a working (i.e., playable) banjo.

INTRODUCTION

Background

Banjos, as they are recognized today, evolved from the stringed gourd instruments African slaves brought to America. Eventually innovators such as George C. Dobson and A.C. Fairbanks began modernizing the design and mechanical structure of the banjo (Linn, 1991). As the popularity of the banjo grew, the innovation expanded and resonators were added to banjo backs to amplify their sound (Siminoff, 1999). By the time the banjo became popular in bluegrass music, resonator banjos had three standard wooden components: the resonator, rim and neck as shown in Figure 1.

Figure 1. Parts of a Banjo. The rim is part of the pot assembly which all hardware, the resonator, and the neck are attached to.

While each manufacturer had their own variation on assembly, hardware, and especially tone chamber design, they all had to develop repeatable processes for manufacturing each part of their banjos. However, banjo manufacturers built these processes for large scale production, what kinds of manufacturing systems and processes would it take to enable one person to produce the wooden parts of a banjo? This is the question that led me to attempt this research. Recently, under the direction of Associate Professor William K. Hemphill, the engineering technology program has incorporated building electric guitars into the engineering technology curriculum. I was fortunate to be involved in the development process and also took the guitar building class. Although this course was quite complex, the manufacturing processes, the most challenging tasks, were already designed for the students. The realization that the design process can be taken one step further by designing a full system of tooling and CNC tool paths is just one more step in learning about the product development process. Since I play the banjo and will be graduating with a minor in Bluegrass, Old-time, and Country Music, I realized that the most rewarding research I could do would be to design the processes and fixtures necessary to make a banjo. Therefore, the purpose of this research was to develop a set of manufacturing processes and fixtures for producing rims resonators and necks for building banjos.

Development of the manufacturing processes began in the Fall of 2011and continued until October of 2012. While the rim and resonator, both round components, were turned on a lathe, the processes used to bring them to their "roughly round" shape were very different. The resonator required more processes and fixtures for development. The final goal of this development effort was to develop an automated process for fully shaping the banjo neck; this would be accomplished on the department's CNC router. However, since the department does not have access to Computer Aided Manufacturing (CAM) software that could generate tool-paths from 3D models, the tool-paths will have to be drawn in AutoCAD using 3D offsets from contours based on a standard banjo.

Review of Literature

The quantity of published literature available that focuses strictly on the practice of banjo building is limited. This is to be expected since banjo building is more of a niche market compared to guitar building. While many small shops and individual builders have posted their experiences online, one printed text by Roger Siminoff, *Constructing a 5-String Banjo: A Complete and Technical Guide,* has been instrumental in laying out the standard techniques for building banjos. This book covers each component of the banjo and gives detailed instruction on how to go about making each of them by hand. While these methods work well, the intent of this research is to create systems of robust tooling and fixtures that also yield a level of repeatability. Literature about the processes that larger banjo manufacturers use was scarce. Other resources researched covered basic woodworking processes such as forming and steam bending. Some sources were about building acoustic guitars, yet many of the techniques were applicable to banjo building and working with wood, such as volume 1 and 2 of *The Big Red Book of American Lutherie*.

METHODS

Resonator Development

The resonator of a banjo is necessary in order to amplify the sound from the sound chamber out toward the listener instead of toward the player's body. Banjo resonators are commonly made up of laminations of thin natural or manufactured wood strips forced into an expanding radial, forming the sides, which are then glued to a semi-spherical back (Siminoff, 1985). The resonator was a challenging component to make without using specific methods for bending and forming the wood into shape. First radiused forms for pressing the back of the resonator into shape were needed. Additionally, long strips of wood must be bent around a 12 and 3/4" circular form. To accomplish this, the wood must be steamed to make it flexible, which means a steam chamber must be made. Just to form and glue the resonator alone, at least three systems of tooling were required.

Forming the Resonator Back

Development of the resonator began in Spring 2012.The first task was to design and make concave and convex press forms to mold the back of the resonator into a nominal matching 42" radii. The initial 3D cutting paths were designed in Rhinoceros 4.0, a surface modeling software. This program was used over AutoCAD for 3D work because it is easier to create 3D arcs and line data in Rhinoceros. The first form data was a circular array of convex 3D arcs. The first prototype of this data was made out of laminated plywood and the outside edges were cut into a circle. The next step was to make the matching concave surface, which only required mirroring the convex data around the origin. However, when this data was sent to the CNC router, the 3D geometry was not read. Much of my time was consumed by attempting to troubleshoot problems with the CNC router reading the 3D arc data. After eliminating variables in how the data was created, it was found that the CNC router did not import DXF data from Rhino as clearly as it did DXF data from AutoCAD. Also, the CNC router read convex arcs differently than concave geometry. While the machine would move in the coordinate Z plane when reading the full length diameter arc in the convex part, it would run a straight line with no Z movement when running the concave geometry. After trying anything to try to get the machine to read the data, the arcs were split at their origin. When the arcs were split, the machine read the

Z data correctly and cut the circular geometry. The data incompatibility issue cost several weeks of development time. After finally cutting out the first set of forms, multiple plies of scrap veneer were laminated between the forms in order to test the design. Large metal weights were used to press the forms together. After drying, the veneer had taken shape, but the glue did not properly secure the sides of the material. This was because the veneers were cut into squares and the areas that were not covered separated. This prototype uncovered two problem areas that required redesigning of the forming process. First, more force was needed to properly form the plies of veneer. Second, the forms were redesigned to apply pressure to the entire 15"X15" square surface of the material.

The final design of the forms were cut out of laminated plywood, which exposed some voids within the surface. In order to fill in and waterproof the plywood, coats of two-part epoxy were applied and allowed to cure, as shown in Figure 2. The forms were then cut again to create a smooth surface. A twenty ton hydraulic press was purchased in order to apply more force to the laminating process.

Figure 2. Cutting the Convex Epoxy Surface. The convex surface was cut a second time after a coat of epoxy filled in some areas due to voids within the internal laminations.

The next issue was sourcing veneer material for laminating the resonator backs. After contacting many local suppliers with no luck, and receiving only tips to look online, it was decided to prototype the resonator press using 1/8" ply birch material purchased from a local woodworking supply retailer. The material was soaked in warm water for approximately one hour, then pressed between the matching forms using the hydraulic press (shown in Figure 3) and allowed to dry.

The initial concern with using plywood for forming was the chance that the plies would separate while being moistened for forming. However, the plywood held up during the process and showed no signs of deformation. After letting the plywood take to the form for twenty-four hours, the plywood was taken out of the form and appeared to conform well to the forming process. The plywood was compared to the form two weeks later and still held the form's geometry.

Figure 3. Using the Matching Radiused Forms. The 1/4" plywood material was pressed between the matched press forms for shaping.

Steam Chamber Design

The thought was given to using the CNC router to cut out the resonator, however, this method would have wasted a lot of material and would have produced a weak resonator because two sides would have been end grain while the other two would have been side grain (Siminoff, 1985). Over time, the natural growth pattern of the wood would warp the sides. So an alternative technique was needed. A common method to bend wood is to steam thin strips of wood until flexible enough to bend around a form (Woodworking, 1985). This method requires a steam source and a chamber to concentrate the steam into the wood pores. My design used 4" schedule 40 PVC pipe, an end cap, a threaded end cap, a grill thermometer, a wallpaper steamer rated up to nominally 200° F and a 2x4 saw horse for the chamber assembly to rest on as shown in Figure 4. The initial test of the chamber was successful, however improvements upon the design were needed if the unit were to be used multiple times. The schedule 40 PVC pipe was only rated up to 140° F, so it deformed vertically. The process needed to control water waste more efficiently. As the steam filled the chamber, condensation built up and began to rest upon the bottom of the pipe. once there was enough standing water, it would leak through the end caps. The water release was not detrimental to the function of the chamber, but prolonged water exposure on the 2X4 wooden frame could damage the frame.

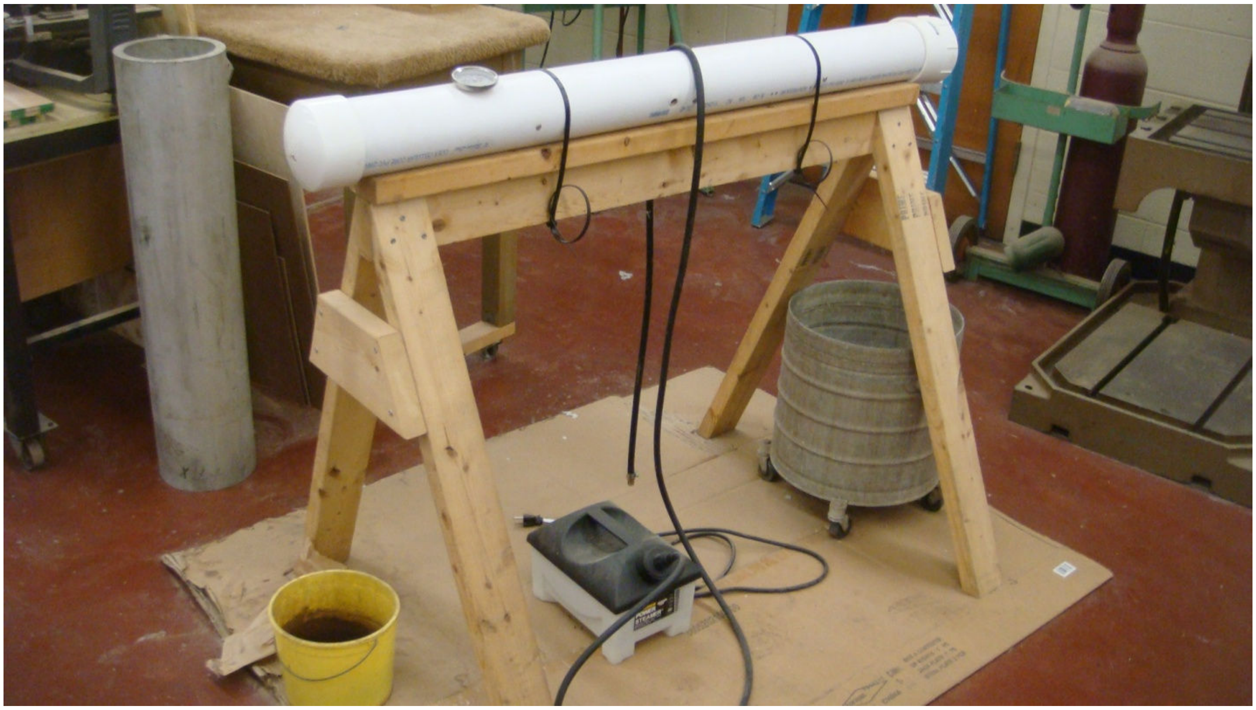

Figure 4. A Look at the Steam Chamber. The steam chamber softened the wood strips so the pliable strips could be bent to be bent.

Creating a Steam Bending Process and Form for Resonator Sides

Once the back of the resonator was completed, focus shifted to making a process to bend the sides of the resonator. The method Siminoff outlined did not require turning the sides on a lathe if the sides were cut to final dimensions and scarf jointed together during the bending process. Using this method, the sides of a resonator are made up of two 1/4" thick strips of maple bent around a circular form 12-3/4" in diameter. Once steamed, the strips were wrapped around the form and tightened by a ratchet strap clamp, as well as multiple sliding "D" clamps. After the wood dries, it keeps its shape and the scarf joints must be cut in order to make the strips fit together (1985). Because the inner strip was molded around a 12 3/4" form, it required a circumference of 40.035" and the outside strip 41.605". This led to both strips being rough cut to 45" long and 1/4" thick strips prior to the bending process. Using Siminoff's method for making the lip that cradles the resonator, one strip was 1-1/8" tall and the other 1-3/8" tall. The strips were then steamed and the bending process began.

Prior to bending the strips of wood, a bending form had to be designed and prototyped. The first design had a 12-3/4 diameter center attached to a plywood base and two rectangular plywood clamps that would fit around the center. In theory, the wood strips would be wrapped around the center and then the clamping blocks would be pressed together to clamp the strips together. After the prototype was finished, some strips were steamed. However, this design proved to be difficult to use because the strips could not be bent and clamped at the same time. Finally, the clamping blocks were abandoned and a ratchet strap was used to clamp the strips together.

Several of the first attempts at bending failed due to fractures caused by the material drying before the bending process was complete. Once the first strip was fully bent, the ends had to be cut to match. the first method used was to cut matching 45° angles on the band saw. When they were clamped tight, the joint was not tight. The ends were then cut into matching scarf joints in the band saw and sanded smooth. The ends matched better, however, the process had to be repeated two more times for the ends of the second strip. These strips were clamped and allowed to dry overnight and were glued together the following day. After drying, the sides had a roughly circular shape, however, it was not uniform and the scarf joints were flat. Although it was not perfect, the resonator side was glued to the resonator back which made the first prototype resonator. This prototype revealed the need for a more efficient and ergonomic bending process as well as a more controlled process for cutting the scarf joints.

The decision was made to address the scarf joint issue first to see if fixing this issue would improve the shape of the resonator. Therefore, a jig that cradled the wood and left excess wood outside the jig to be cut with a flush cut saw or a hand router was designed. The purpose was to insure that the proper angle and length for the scarf joint was always made precisely. The jig housed both the inside and outside pieces even though the lengths had to be different. One length angled across the top of the wood while the longer length angled across the bottom. The first prototype was made out of a 6' X 4" X 4" piece of pressure treated wood (as this was the only economical material large enough that did not require gluing up). After machining the prototype tooling, it was used by inserting a 1/4" strip of maple in the slot and using a table router to flush cut the strip. While the principle of trimming off the excess wood seemed like a simple process, more of the strip chipped out than was cut by the router bit.

This failed tooling design led to the idea of creating a form that takes cutting the scarf joint out of the bending and gluing processes. The redesigned form cradled the end of the strip and allowed the other end to overlap the beginning of the strip to create the scarf joint as shown in Figure 5. This design allowed the person bending the material to focus on eliminating gaps in the joint. Since the resonator sides would need to be turned on a wood lathe to produce a more uniform circular surface, the sides could then be turned to final dimensions. However, this meant having to either add a third ply into the side lamination process or to make each of the two plies thicker in order to be turned down to final dimensions. The strip must dry before gluing the outer strip. After the inside strip is glued and dry, the outer strip is first trimmed to create a butt joint with the first strip and then worked slowly around the form while continuously applying steam to facilitate bending. This process created plenty of material for turning down on the lathe and created a successful way to create accurate scarf joints.

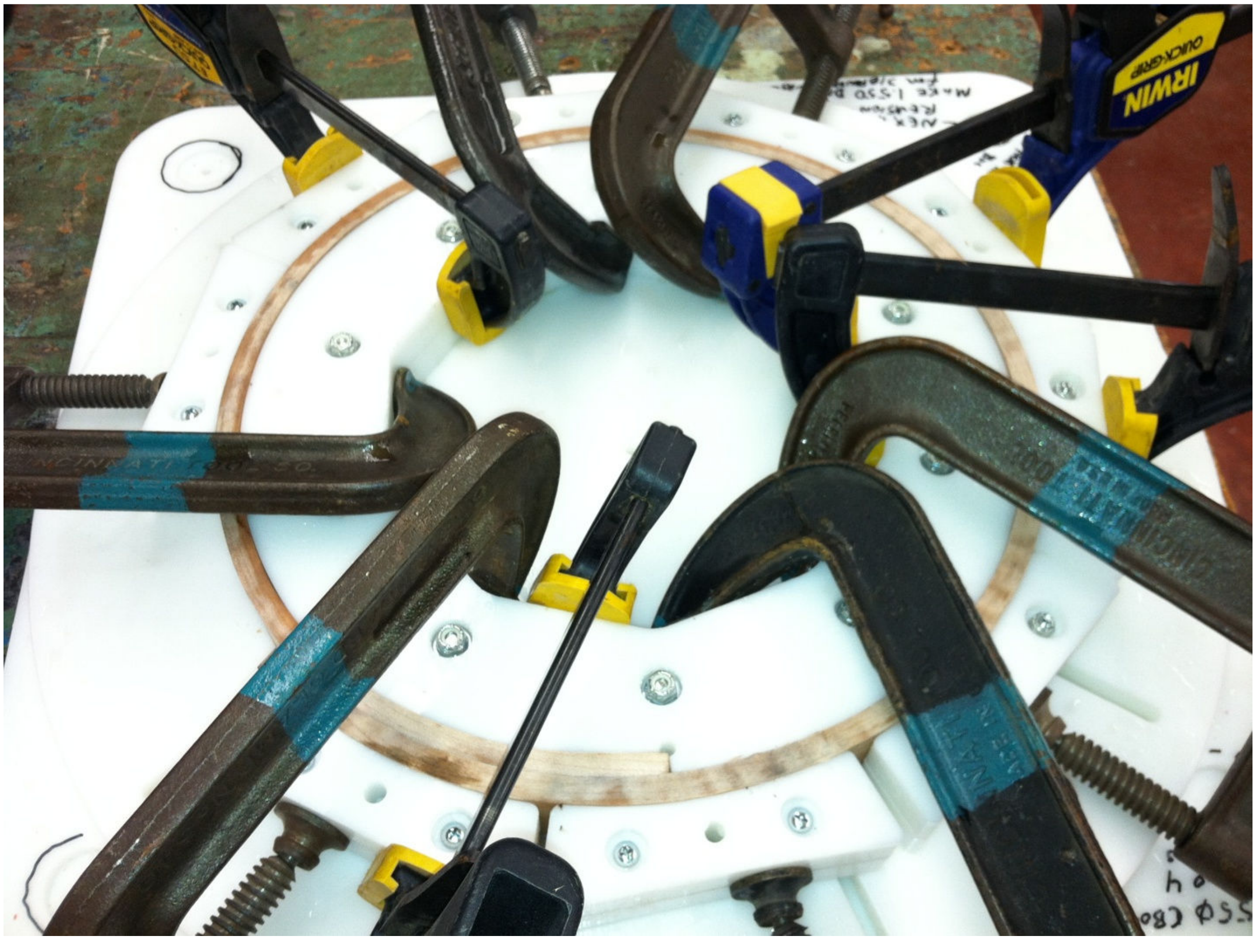

Figure 5. Bending Using the Redesigned UHMW Tooling. The Resonator form allows both strips of wood to be bent and glued on the same form.

The initial tooling for bending and gluing resonator sides was made out of 3/4" plywood. A major issue with this material during the bending and gluing process was avoiding gluing the strips to the plywood tooling. Wax paper was used to prevent this, however, it led to an important aspect of the redesigned tooling. The material chosen for the redesigned tooling was ultra high molecular weight polyethylene (UHMW). This material was non-porous and resisted glue adhesion. After drying, excess glue could be removed easily. Another issue with the previous design was that the form had to be rotated as the clamps were attached around the work-piece. This made the entire form difficult to work with. In order to "bring the work" to the operator, it was suggested "lazy susan" style bearing system to allow the form tooling to rotate. By allowing the form to rotate on a base, once a section was clamped, it was rotated out of the way. This improved the rate of bending and allowed the long piece of laminate to extend off the tooling in only one direction simplifying shop layout and increasing space utilization.

The last improvement to the bending process came after the redesigned tooling was completed. While the new tooling made the bending process faster, the strips were still becoming too dry by the end of the process to finish bending a strip. During one of the bending procedures, the steam hose was removed from the steam chamber and, using insulated gloves, was used to steam the strips during the operation. This allowed the operator to focus on making tight joints between the laminations.

Lathe Cole Jaw Extension Design

Once a resonator side blank was successfully created, the next issue was how to fasten it onto a lathe for turning. The blank size of the resonator exceeded the 15" between centers acceptable on the available wood lathe; this meant that the resonator would have to be turned as an outboard operation (ie. rotating the lathe and chuck to avoid the limits of the inboard area). In order to secure the resonator sides, a set of Cole jaw extensions were needed. However, a set of extensions large enough to hold the part was not available for purchase. Due to this, the best course of action seemed to be to retrofit a 10" Cole jaw set designed to fit the Nova II chuck system installed on the lathe.

After modeling the Cole jaw set, development of the four (4) extensions began. In the initial design, each attachment was made out of 3/4" thick medium density fiberboard (MDF). The extensions were routed out to a 1/2" thick where the Cole jaw set met the extensions in order to help balance them. Each extension houses two blocks that match the geometry of the resonator

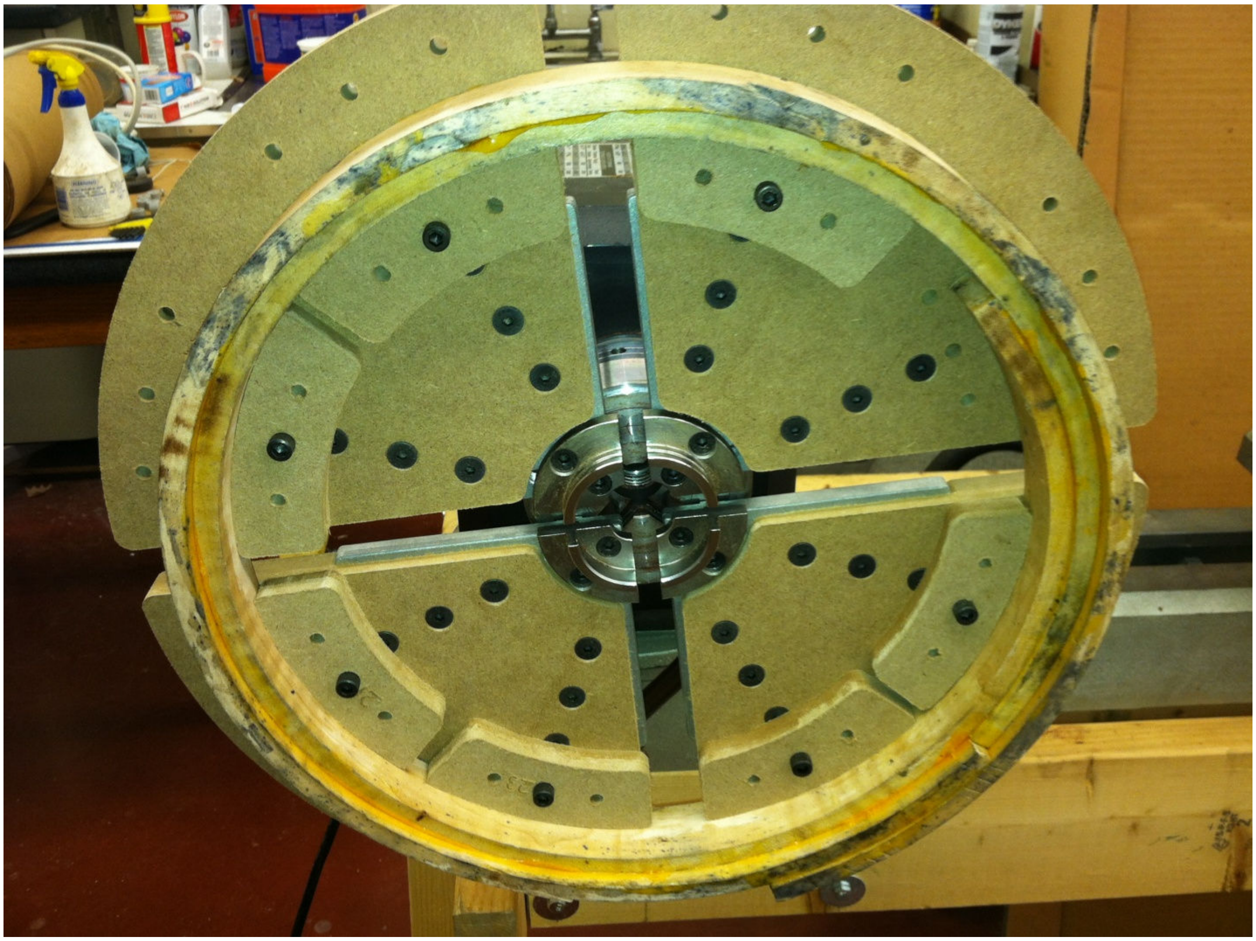

Figure 6. Turning with the Cole Jaw Extensions. The Cole jaw extensions apply force to the inside of the resonator blank and center it for turning.

blank in order to apply uniform force against the blank. The blocks cradle the overlap in the resonator and center the work-piece because of its unbalanced shape. It took about four modifications until the correct spacing was found to match the manufactured Cole jaw set. Once correct, the extensions were attached to the Nova chuck and tested. The initial test showed an acceptable balance and centered the resonator blank well. The last modification to the design was to combine the two blocks on each extension into a single block. This design cut down on the amount of blocks that had to be produced for holding. Since the resonator had to be held from the inside as well as the outside, two sets of blocks were made, an internal holding set of eight and an external holding set of eight as shown in Figure 6, in practice only seven (7) of the internal blocks were used to accommodate the starting geometry of the laminating form tooling. While the initial tooling was prototyped out of MDF as proof-of-concept, it was sufficiently strong and robust enough to last during the production of three (3) turned pieces.

Rim Development

A large wooden ring, known as the "rim" acts as the heart of the "pot" assembly which is made up of over 35 pieces of hardware as shown in Figure 1. The rim is instrumental in creating the infamous "twang" that banjos are known for. Not only does the rim act as a sound chamber for carrying the string vibrations from the bridge out to the resonator, it also acts as a mechanical system for applying force to tighten the drum head. Realistically, a banjo rim can be made out of numerous materials. Some more affordable banjos are made with metal rims, however, hardware is more readily available for wooden rims. Since the rim is round in shape, the most practical method of cutting it would be turning it on a wood lathe. Rims must not be cut out of single pieces of wood due to their vulnerability to humidity and warping. Because of this, manufacturers have standardized several processes to make the rims and conserve material.

Traditionally, two popular methods have been used for making wooden banjo rims. One method is to bend wide strips of wood into a circle and laminate them. While this method was my choice for making the resonator, wider strips would be harder to bend as well as more likely to introduce gaps between the joints caused by natural defects in the wood.

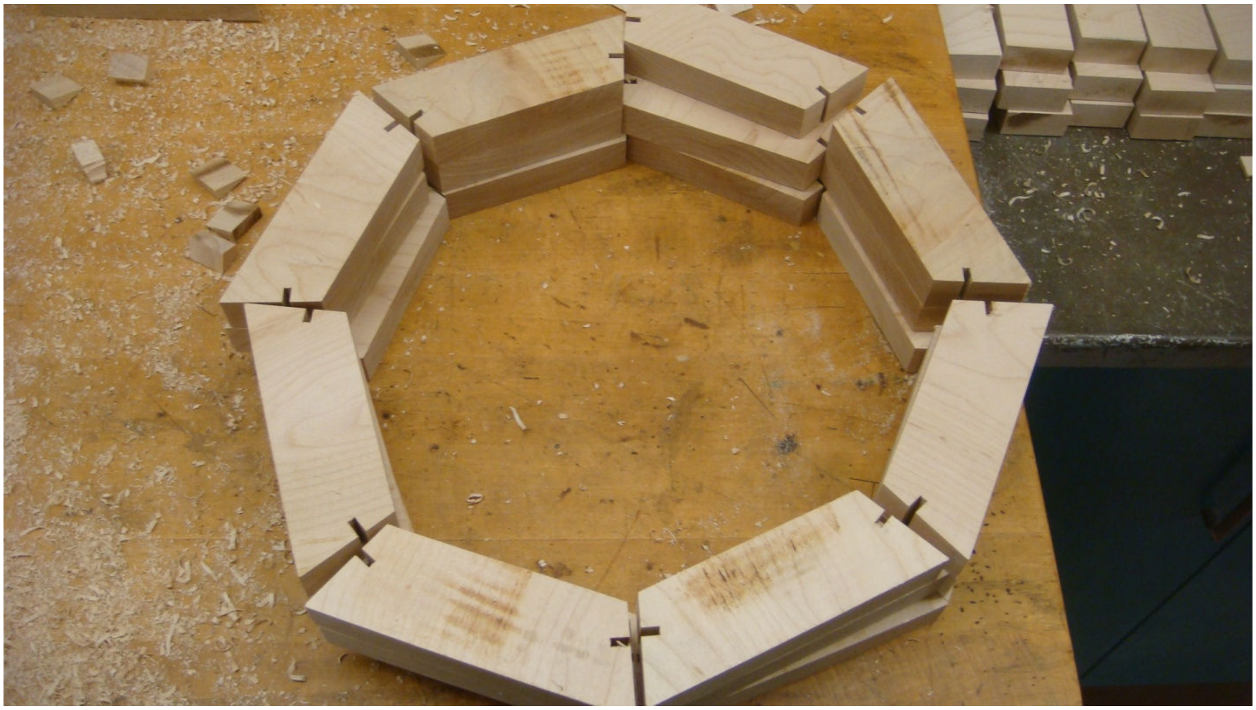

Figure 7. Block Rim Before Gluing. Blocks after they have been cut at 22.5 degrees on both sides prior to staggering the center row.

The second method for building up the rim is to cut staves that make up three stacked and staggered octagons. This method is known as a block rim (Luthiers, 2001) and is shown below in Figures 7 and 8. By stacking three octagons and gluing them together, the necessary thickness is created (Siminoff, 1985). The diameter of the finished rim is 11"; the rim's thickness must be nominally 3/4" before being turned down to final dimensions. Therefore, the staves must be large enough to accommodate the circular shape of the rim yet small enough to minimize waste material. The staves were cut into 1-1/2" wide by 4-3/4" long by 3/4" thick strips. The edges of the strips were then cut at 22.5° using a miter saw. The rim required three of the octagon shapes vertically laminated together with the middle laminate rotated 22.5° to reinforce the joints. As with the resonator, the challenge was finding the optimum method for clamping the material together to prevent gaps in the joints. While the first attempt of a rim was usable, the angled edges did not join well. On the second attempt, large stainless steel hose clamps were used on the outside of all of the rims which pulled the edges together well as shown in Figure 8. Then the three octagons were forced together on the 20 ton hydraulic press. After the lamination was complete, all the was left was to figure out how to hold the wood blank for shaping.

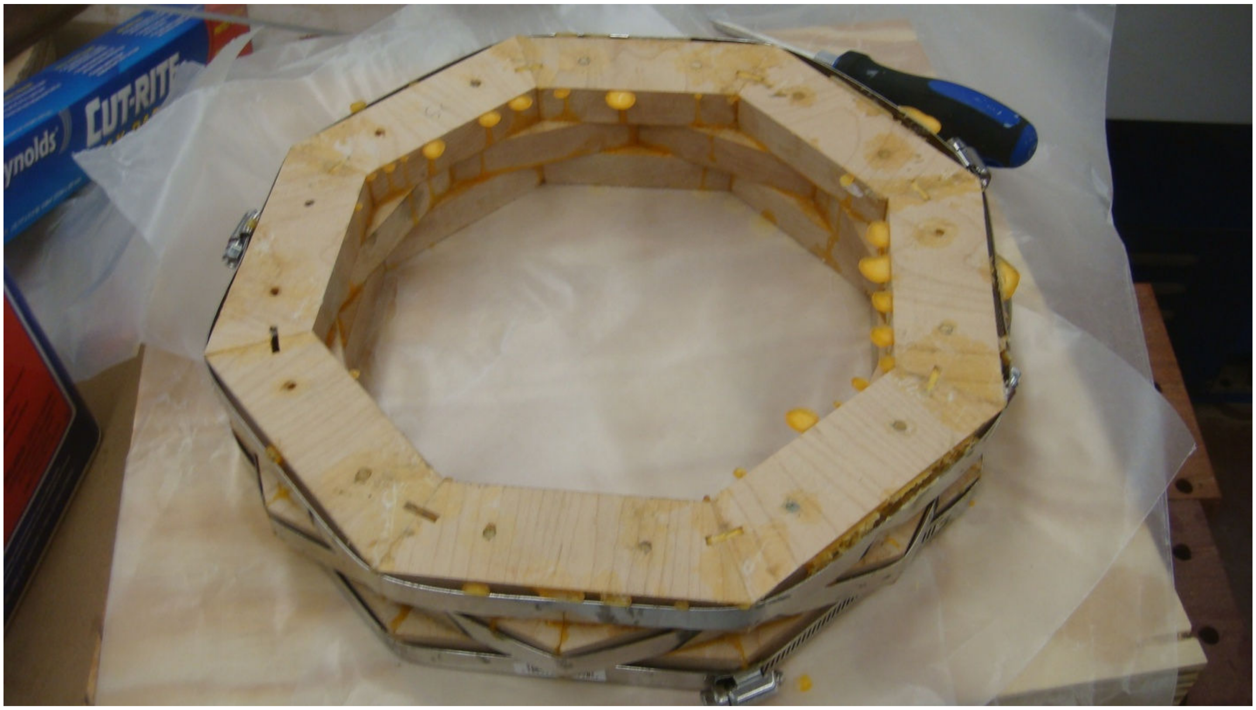

Figure 8. Fully Glued Block Rim. The second lamination's joints were much tighter, yielding better results with the hose clamps.

Adapting the Cole Jaw Set for Rim Turning

Early in this project, the CNC router had been considered to cutting out the rims for precision. However, after designing the Cole-jaw set extenders for turning the resonator, the idea arose to design the appropriate stops to clamp to the inside of the rim that attach the rim to the jaw extenders. The adapters to accommodate the rim were designed by using offsets of the rim's edges using AutoCAD. They were then trimmed to fit onto the extenders. An additional set of locating holes were added to attach the adaptor plate. After a final redesign of the jaw extender fixtures, they easily accommodated the rim, even with its octagonal shape. Once the glued laminated assembly was held securely onto the lathe, turning the rim was not a difficult process. Although I had not had much experience using the hand tools associated with the wood lathe, within a short while, the first rim was turned down to thickness as shown in Figure 9. Finally, the hardware assembly was fitted onto the rim.

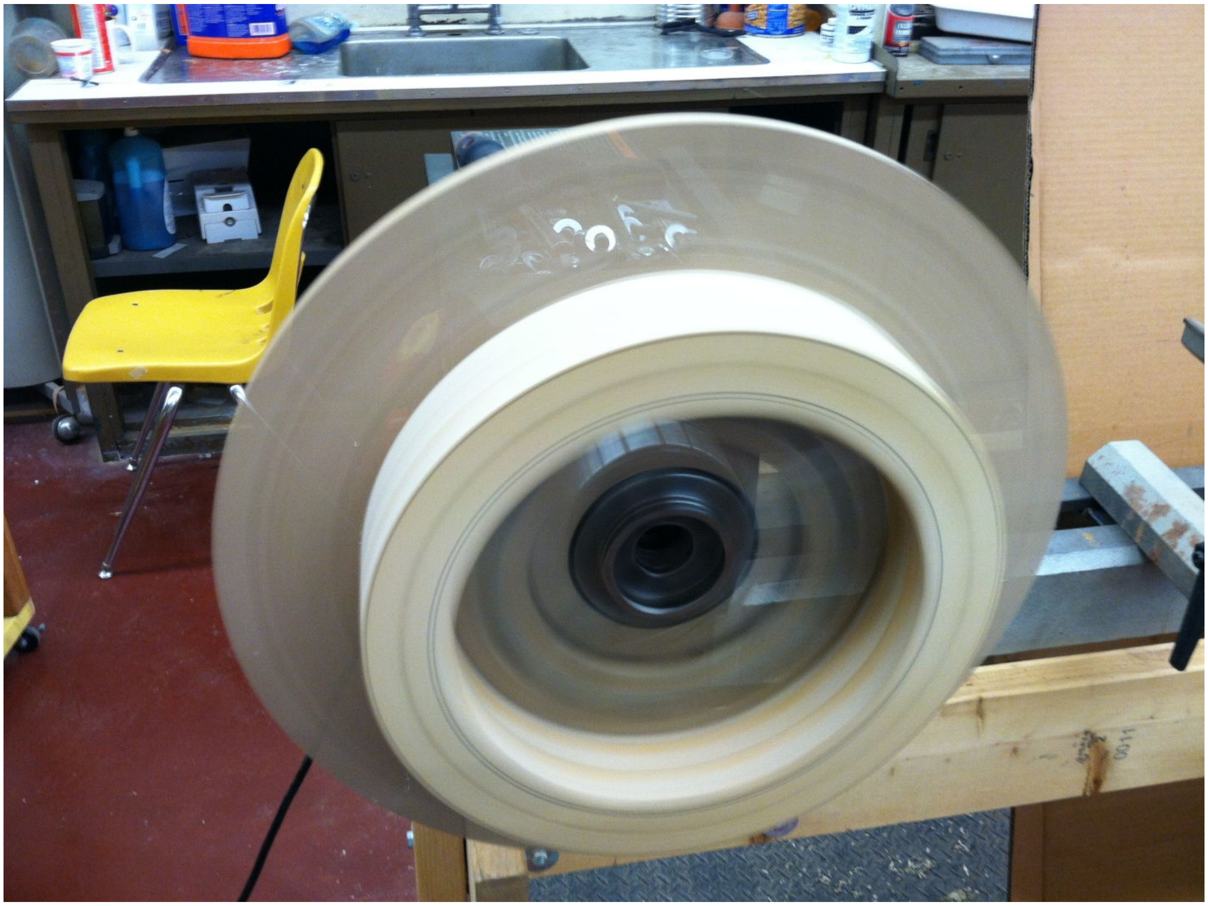

Figure 9. Block Rim Being Turned. After modifying the Cole adapter set to accept the rim, the rim was able to be held securely by the extensions and turned to final shape using hand tools.

Banjo Neck Development

The neck of a banjo is unique and distinguishes it from many other stringed instruments. A banjo neck has a fifth string that starts at the fifth fret on the neck. The purpose of this string is to act as a drone, which gives the banjo part of its unique sound and playing style. Designing the neck proved to be the most challenging parts to design because of its complex curves and angled centerline (Siminoff, Constructing a 5-String Banjo: A Complete Technical Guide, 1985). The bottom of the neck was designed over the Fall 2011and completed with the top in the Fall of 2012.

Banjo Neck Bottom Shaping Design

Development of the banjo neck began with taking measurements from various banjo necks available. Using the measurements, a 2D set of edges of the banjo dimensions was created in order to create the tool-paths for use on the CNC router. Each section of the neck was broken into separate centerline tool paths including a planing path, the heel, the neck, and the headstock.

Rough Shaping Tool-path

The first step in the program was to remove enough material to allow the finish cutters to shape the neck. The purpose of the rough shaping tool-path was to establish the angle of the headstock and the height of the neck and heel while roughing out enough material to allow the finishing paths to contour the neck. While this method produces a lot of waste, the purpose was to avoid making a scarf joint at the headstock and to safely secure the part on the router table. This method takes some extra time, but produces excellent results. The final design of this tool-path replaced the heel roughing pass and the headstock roughing pass by stepping down at 1/8" intervals, revealing the rough shape of the heel and the headstock. This program establishes a flat surface to allow four (4) bolts to help hold the neck in place during the next operations as shown in Figure 10.

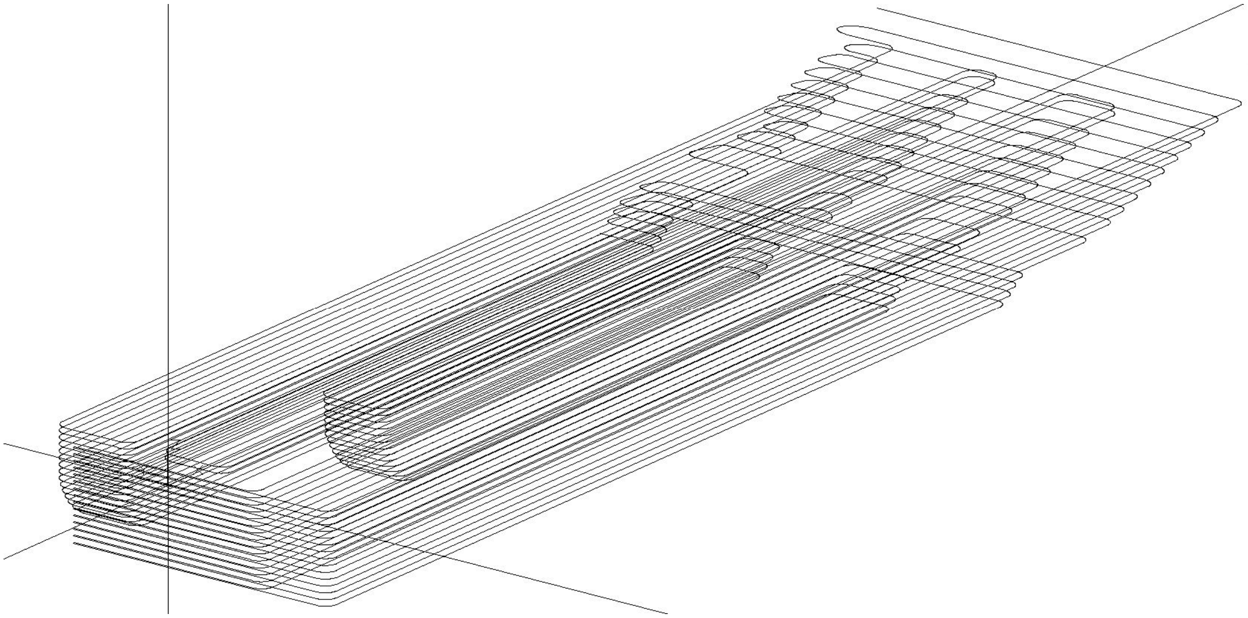

Figure 10. Rough Shaping Tool Path. The rough shaping path establishes a rough outline of the headstock, heel, and the surface of the neck.

Headstock Shaping

The headstock shaping tool-path cuts the bottom of the headstock to a finished surface. This tool-path is unique because it transitions from cutting a 3D line to cutting a 3D curve and contains a total of 120 3D curves. This geometry establishes the curve of the volute, which strengthens the neck where it transitions into the headstock. This tool path first plunges and then takes small cuts as it moves from start to finish, as shown in Figure 11. As the tool reaches the end of one line, it curves into the next line to take off more material. Each path is offset each 32nd of an inch to insure a uniform surface.

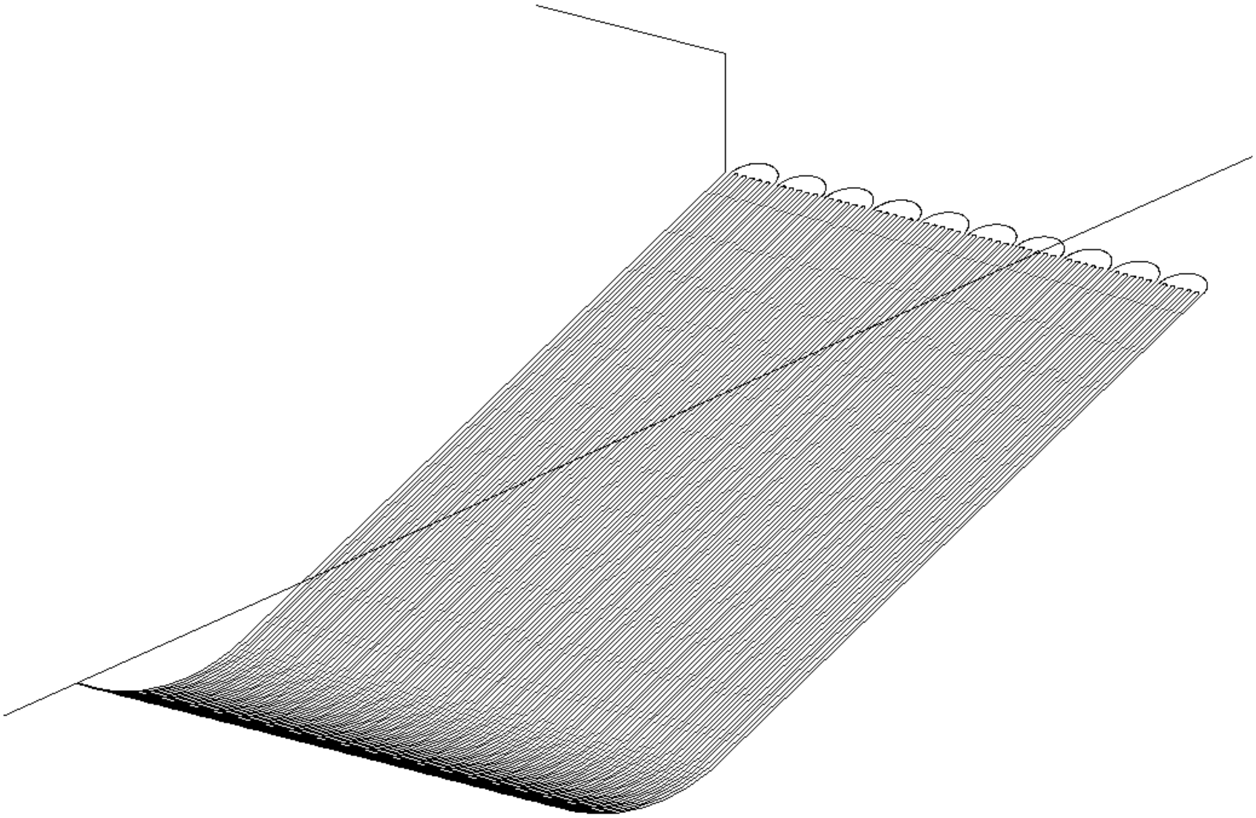

Figure 11. Headstock Shaping Tool Path. The angled bottom of the headstock and the curve of the volute are established by this tool-path.

Heel-Rim Radiusing

The heel of the banjo has to seat properly to the rim and attached hardware. The bottom part of the heel is the section below the slotting cut that rests against the lowest, wooden part of the rim. The top heel cutting file shapes half of the heel while this path shapes the bottom. The centerline tool paths for these cuts are shown in Figure 12.

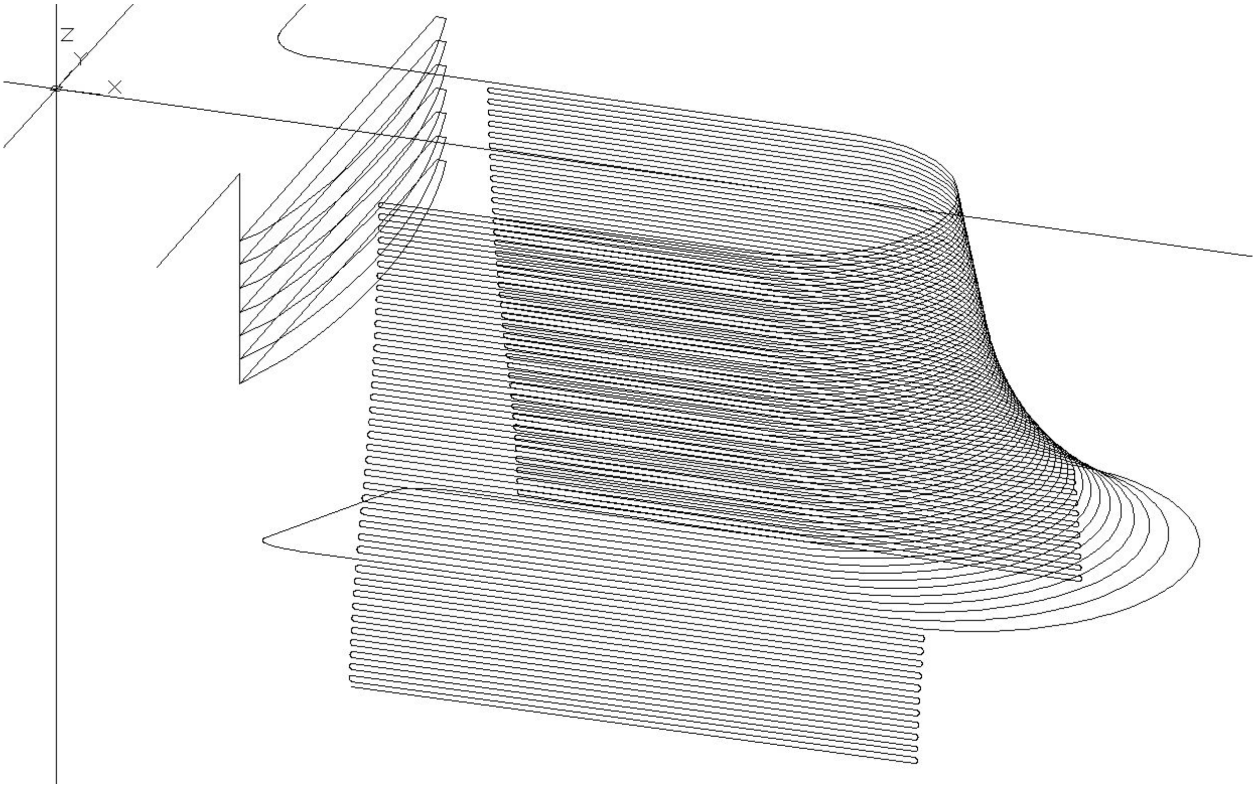

Figure 12. Heel-Rim Radiusing Tool Path. This tool-path insures that the heel of the banjo neck fits properly against the pot.

Heel Slotting

One of the more challenging parts of the neck to cut is the geometry that allows the heel to seat onto the rim. More specifically, the flange requires a radiused taper under a flat groove. This geometry could not be cut by a regular spiral shaped cylindrically cutting tool. This operation requires a tool that cuts from the side, known as a slotting bit. The slotting bit is held onto an arbor which allows it to be loaded into the router.

The first tool path design was a series of loops that would circle in and out, notching out material from left to right. The slotting bit was necessary for cutting out a 1/4" diameter curve underneath the initial slot. As the cutter finished one path, it moved out and down to start the next cutting path in order to cut the radius. While this initial design worked, it was slower than necessary and the placement was off. A second design replaced the loops with a series of deeper and deeper passes that established the radius of the notches. As each pass finished, the cutter stepped out and moved to the starting point of the next deepest path. This redesign, shown in Figures 13 and 14, managed to reduce the run time of this operation.

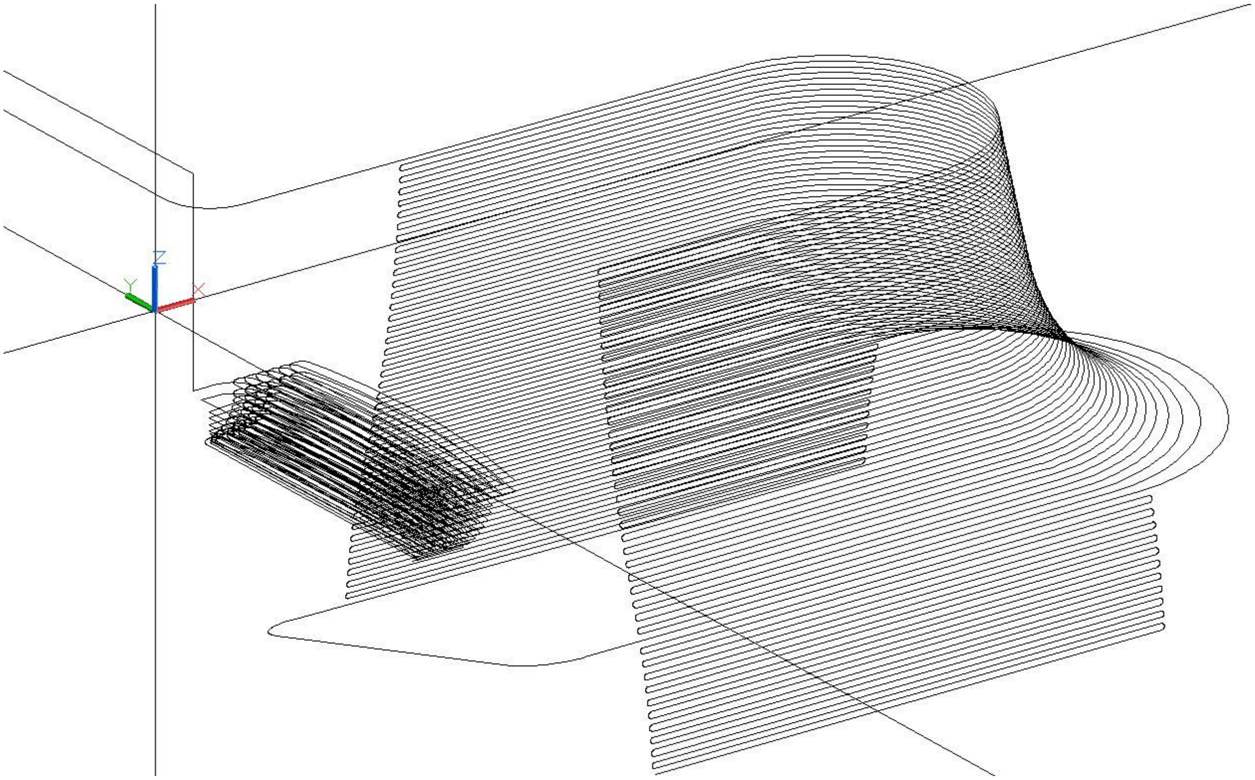

Figure 13. Heel Slotting Tool Path. The 2" diameter Slotting Bit cuts a groove and steps down and out to establish a radiused cut to match the contour of the one-piece flange.

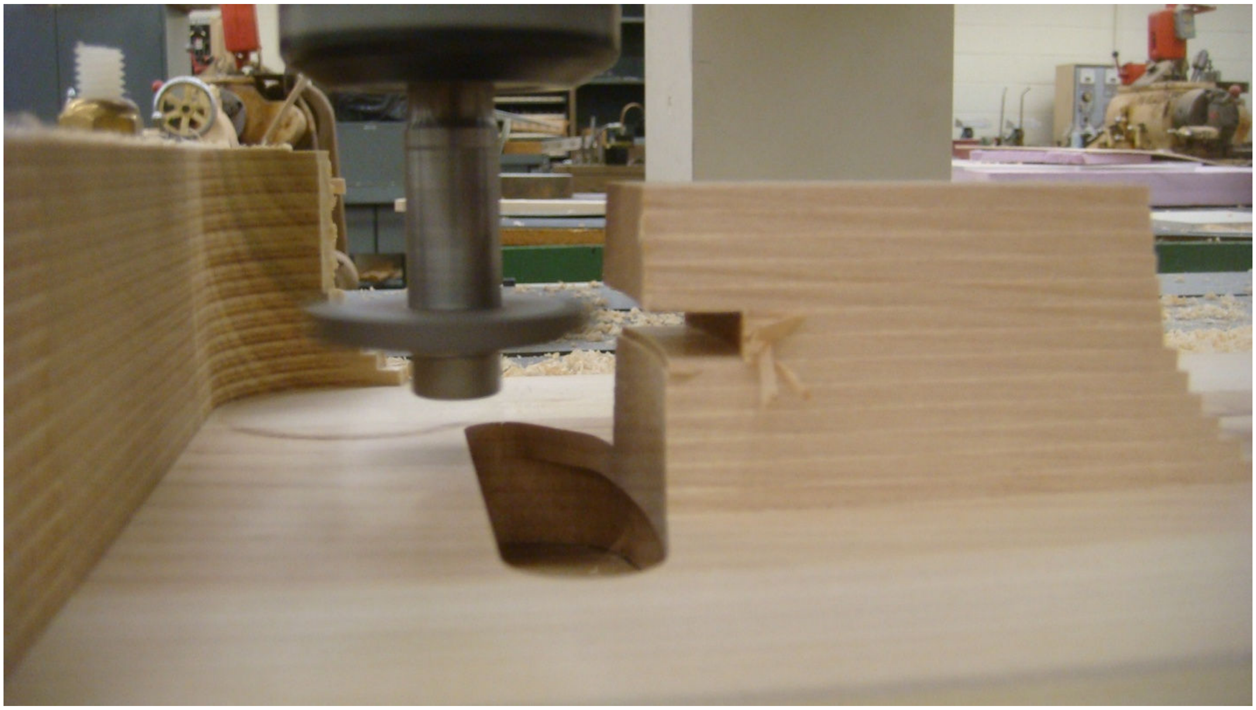

Figure 14. Heel-Slotting Path Application. The slot cutting bit created the slot to allow the heel to fit properly to the pot assembly.

Heel Shaping

The heel of the banjo is made up of a compound radius that transitions from the neck to the bottom of the heel. During the initial design, the heel shaping path cleared out the area for the final shaping. This feature was removed after the rough shaping pass was redesigned to taper the sides of the heel as it removed most of the material on the wood blank. It was difficult to transition from the tapered sides into the heel curve on every pass. This was accomplished by initially creating the profile of the sides of the heel, then drawing arcs that start on the lines and go through the midpoint of the heel profile line. As each arc was drawn, the general shape began to take form. At this point in the program, the neck had not been shaped yet, but it was important to insure that enough material was left to hold the heel and the neck in place. If the heel was cut out entirely, the neck would no longer be secured to the work-piece after the neck was shaped. To insure that the neck would be secured for the headstock cutout program, 1/4" tabs were left on each side of the heel. These tabs were sanded flush to the rest of the neck by a sanding process using an oscillating spindle sander during the assemble and fabrication of the neck and fret board. This tool path is shown in Figure 15.

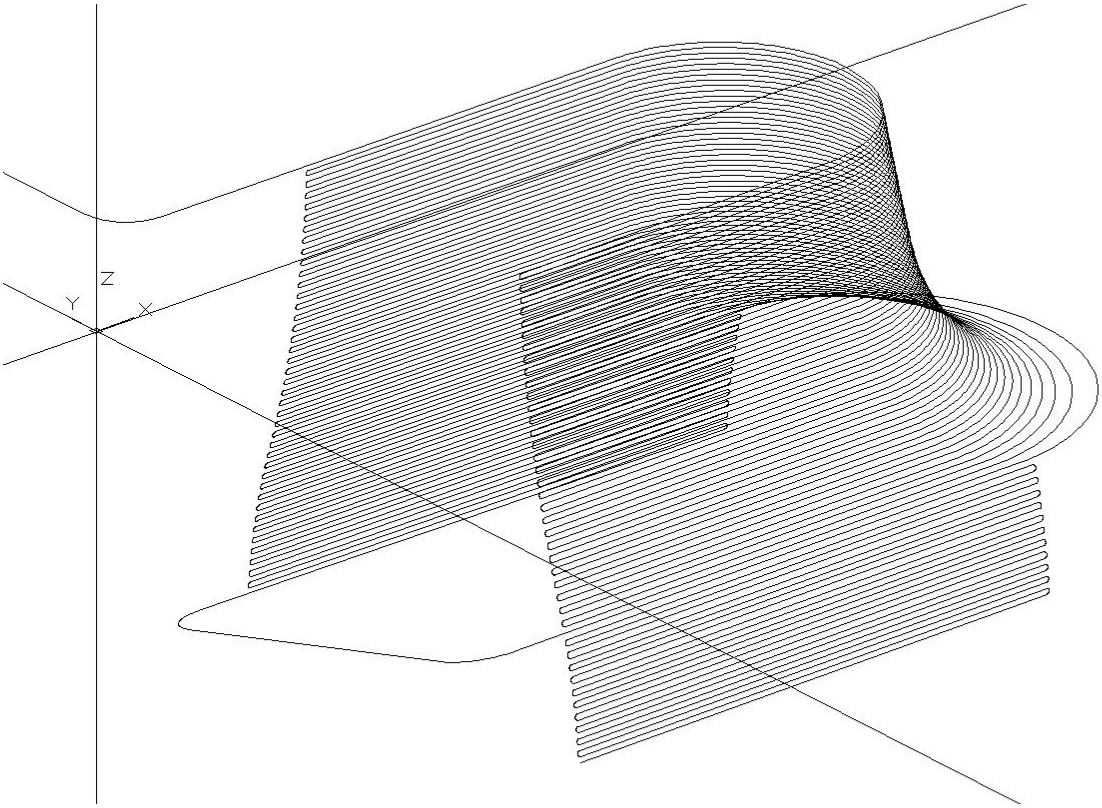

Figure 15. Heel Shaping Tool Path. The heel shaping tool-path establishes the sides and the radius of the heel that transitions into the neck. As the tool follows the u-shaped path, it steps down and begins the next.

Neck Shaping

The neck shaping pass took the most development time. This tool-path was difficult to develop because of the constantly changing taper of the non-symmetric neck. On banjo necks, one side has a protrusion where the fifth string tuner attaches and the fifth string runs over the fret-board towards the bridge, while the other side is a continuous taper. Because of this non-symmetrical geometry, the tool-paths could not be mirrored. The changing tapers also meant that multiple sections of arcs and arrays would have to be created at the beginning and end of the section in order to generate the cutting paths.

In the earliest development stages, the neck shaping program consisted of a roughing pass using the 1/2" diameter cutter followed by a 1/4" diameter ball end cutter. What made this program take so much development time was trying to make the offsets correctly. When the 1/2" diameter cutter would start at the top of the neck it would be cutting with the bottom of the tool. However, as it would follow the curve, the cutting surface became the edge of the cutter. The final design utilized only the 1/2" diameter cutter, increasing step size as it stepped down towards the bottom of the blank. As shown in Figure 16, the offsets were generated by creating an arc that had no offset at the top of the arc and transitions to a 1/4" offset at the bottom.

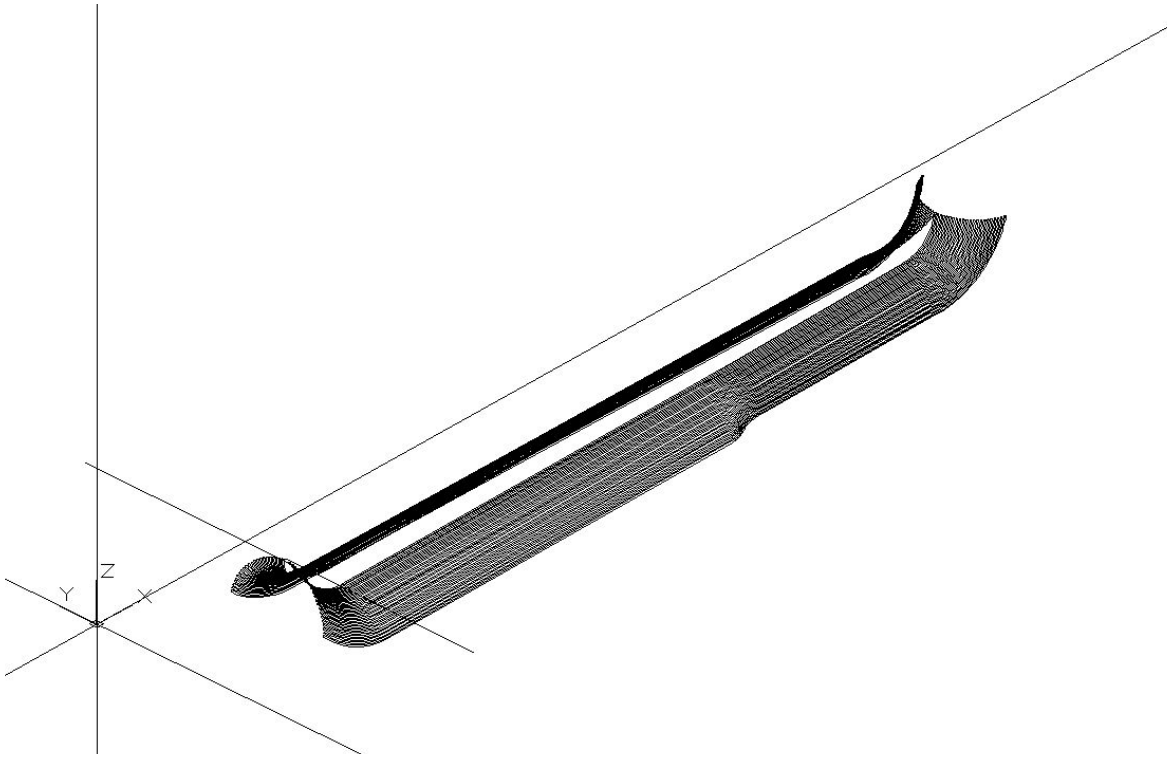

Figure 16. Neck Shaping Tool Path. A 3D view of the neck shaping tool-path shows how the fifth string contour transitions from four strings to five.

Headstock Cutout

The headstock cutout program cut the outline of the headstock into an original headstock design. While the first headstock design that was used throughout the development stages was a nice design, it did not allow the tuners to be installed flush with the surface. Therefore, after the first poplar prototype was cut, a new headstock shown in Figure 17, was designed based on more traditional styles. The main modification was to remove more of the material around the volute and to shift the holes for the tuning pegs further up the headstock in order to seat them properly.

Figure 17. Headstock Cutout Tool Path. Redesigned headstock followed traditional banjo headstock designs.

Banjo Neck Top Shaping Design

The series of programs that cut the top of the banjo neck were not developed until the Fall of 2012 after the more complex bottom programs were nearly finalized. The top files consist of tool-paths that rough out the headstock area for final shaping, the final shaping, a heel shaping file that cuts the heel matching radiuses to the rim, and a slot for the truss rod to fit into. These geometries were not a difficult to generate because most of the cutting would be done from a 2D point of view.

Headstock Roughing and Finishing

The programs that rough out the material for the headstock consist of a program that uses a 2" diameter fly cutter, as well as the 1/2" diameter cutter. Once the 2" diameter cutter removed most of the material, the 1/2" diameter cutter established the angle of the headstock and cleared out enough material to allow the headstock to be cut in 3D. The finishing pass uses the edge of 1/2" diameter tool to remove the remaining material. Because the edge of the tool is doing the cutting, the resulting shape is radiused. In an attempt to avoid creating pits and to make a more uniform surface, the 3D tool-paths take a pass across the headstock every 1/16th of an inch, as shown in Figure 18 The final pass is actually two layers deep in order to smooth out the steps that were left over by the roughing passes.

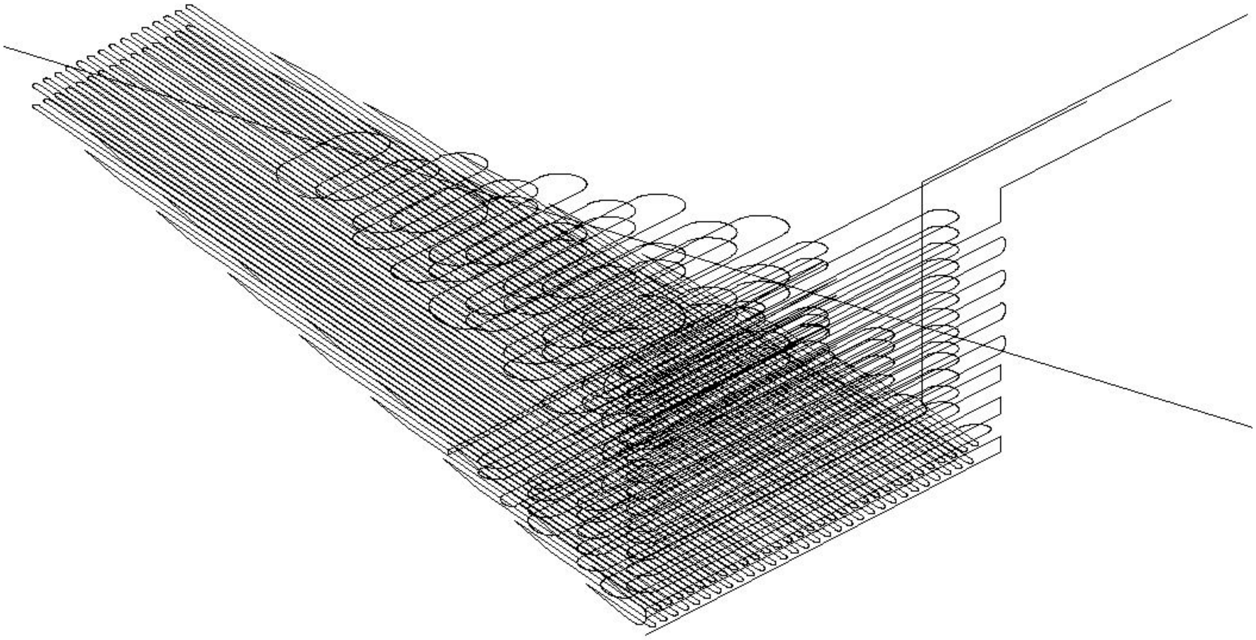

Figure 18. Headstock Roughing and Finishing Tool Paths. The screen shot above shows the three tool-paths for roughing and finishing the top angled headstock surface.

Heel Radiusing

The heel radiusing tool-path creates the surfaces that fit against the rim and the pot assembly. The wider cut at the top is where the neck meets the tension hoop. The shallower, deeper passes create the area that rests on the tone ring and roughs out the area that is cut for the flange during the bottom program. These passes, shown in Figure 19, could only be cut from this side because they are farther in on the neck than the shape cut on the bottom passes.

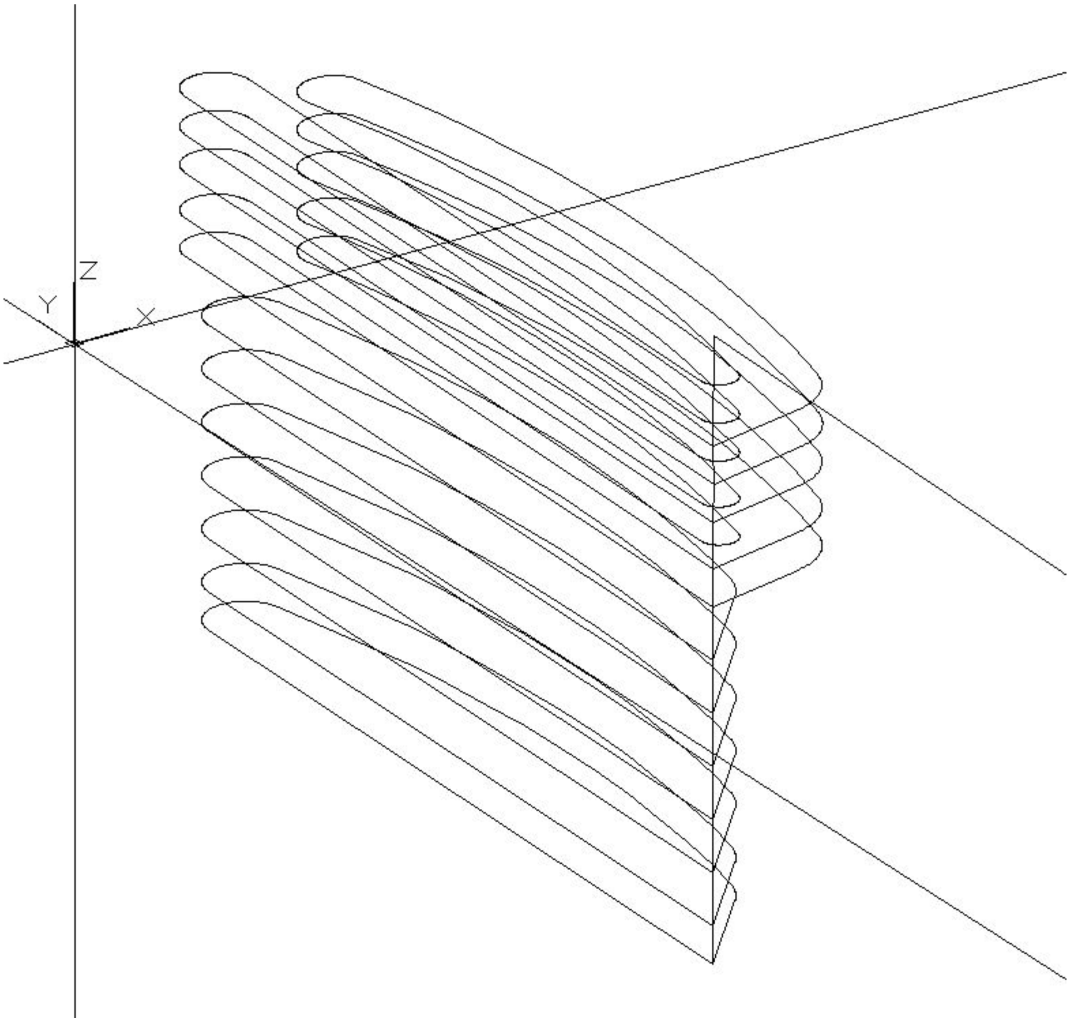

Figure 19. Heel Radiusing Tool Path. The heel shaping path shapes the top and mid section of the heel to meet the rim.

Truss Rod Slot

The truss rod slot- a 1/2" deep by nominally 1/4" wide pocket milled into the top of the neck- allows an 18" two way truss rod to be inserted underneath the fret-board. Truss rods are used to reduce bowing and warping of the neck. The two way truss rod commonly used in banjos allows the neck to be adjusted with the degree of "upbow" or "backbow" as needed to straighten the neck when under string tension (Siminoff, 1985). Without the truss rod, adjustment to the playing action would have to be more invasive, such as sanding or re-leveling the fret-board. The second part of the truss rod program is the data that clears out the area for accessing the truss rod adjustment. This tool path, shown in Figure 20, cuts into the angled headstock to allow an allen wrench for adjustment of the truss rod.

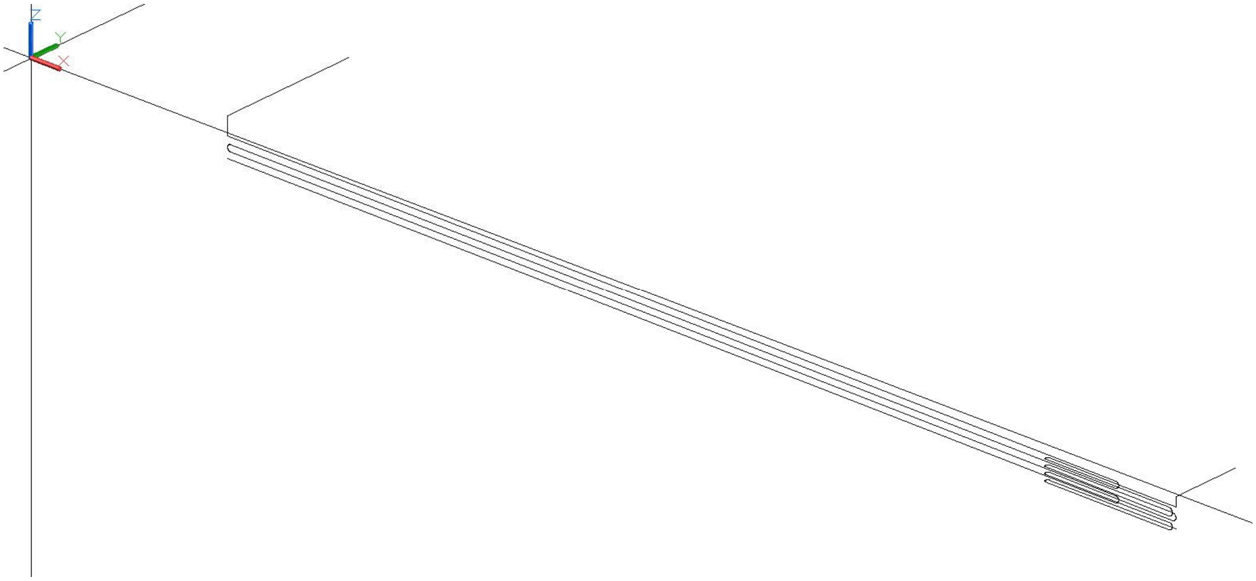

Figure 20. Truss Rod Slot Tool Path. The truss rod program cuts a slot along the centerline of the neck to accept an 18" two-way truss rod.

RESULTS

Resonator

The first resonator that was completed using the initial tooling design had multiple gaps between the joints in the side walls. Because it was not turned, the outside of the side walls were not entirely circular. The area of the handmade scarf joint also looked very flat. When compared to the flange of the pot assembly, the sides appeared wavy or rippled. These results were caused by relying on the bending process to create a perfectly circular shape. While the bending process appears to make the strips uniformly circular, the sides needed to be turned. This is why the second bending/gluing fixture focused on eliminating the need to cut the scarf joint by hand and over-sizing the thickness of the strips to allow the lathe to bring the sides down to thickness. The redesigned fixture's tapered groove allowed the material to overlap and create a turned scarf joint that eliminated variability in the manual process. The second resonator was significantly more uniform because of the turning process. While the butt joint needed to be mated tighter, the laminates showed tighter joints with less gaps between them. This second resonator assembly was accidentally turned to the wrong dimensions, so a third resonator was made to the correct dimensions for fitting around the flange. The third resonator had a better butt joint and only one gap in the side joints, this was the resonator chosen for the final build and is shown in Figure 21. While the redesigned process reduced the number of imperfections in the resulting resonator, they were not eliminated entirely. In order to fully control the lamination process a more mechanized and automated system should be implemented.

Figure 21. Resonator after Finishing. The third resonator after walnut veneer was applied and finished with Truoil.

Rim

The first rim was glued up using the block rim method and biscuit joints. The biscuit joints helped align the staves together on each individual section, but did not help align all three laminations. The result of this method was that when load was put on the laminations, they tended to slide because of the glue and that the joints between the blocks were not accurate. This meant that a better method of alignment as well as adding side load during the vertical lamination process. The second method of aligning the staves was to insert 1/8th" dowel rods to act as a locating method for each block. Also, large hose clamps were purchased in order to draw the joints together. The second rim had few gaps in the joints because when the vertical load was applied, the hose clamps kept the joints tight and the locating dowels kept the laminates from sliding. After turning the second rim down to thickness, the tone ring fit very snug, which is very important in the quality of the tone generation . A loose rim to tone ring fit would cut down on the number of vibrations (Siminoff, 1999). The rim assembly is shown in Figure 22.

Figure 22. Assembled Rim and Pot Assembly. The rim after pot assembly and the neck was installed.

Neck

The neck was developed in rigid foam insulation material because it allowed for cheap and rapid prototyping. While the 3D tool-paths were cut initially in foam, all of the depths of cut and roughing passes were designed to work in wood. Therefore, when the first wooden prototype was made on October 4th out of poplar, there was proof of concept that the tool-paths would be appropriate and safe for use in harder woods. The first wooden banjo neck was successful even though there were some issues because it uncovered some problems that were overlooked in the foam prototypes. Problems in two different cutting areas were discovered. First, the heel radiuses were not centered and the bottom part of the heel was too long. These issues caused the heel not to attach to the rim. Second, the headstock design would not allow the tuners to be put on because the area where the bottom two tuners attach was radiused. This issue was solved by redesigning the headstock and assuring that the area was flat, this also allowed the transition from the neck to the headstock to be feel more natural to the hand. After these issues were resolved, a neck as shown in Figure 23 was finally cut out of maple.

Figure 23. Top, Side, and bottom View of Finished Neck. The finished maple neck is shown after a coat of Truoil was applied.

DISCUSSION

Analysis of Results

The results above represent a successful integration of the manufacturing processes and fixtures because each process produced at least one working part within tolerance. The steam chamber, bending jig, Cole jaw set extensions, and 42" radiused forms performed their operations well and produced the necessary parts for forming a uniform resonator. The final resonator side bending jig improved the quality of the joints between the two strips of wood as well as allowed the sides to be turned on a lathe. Modification of the Cole jaw set extensions prevented the need for a separate holding fixture for the rim turning process. The top and bottom neck cutting programs took a long time to develop, but the resulting maple neck was more than satisfactory.

The results of this research demonstrate the practicality of a luthier with a small shop to set up the necessary manufacturing processes and tooling for building dimensionally accurate and structurally sufficient resonators, rims, and necks. With the appropriate resources, a small shop could be set up to build banjos in a minimal amount of time. The final banjo assembly is shown in Figure 24.

Figure 24. Final Banjo Assembly Side View. Finally, the components were assembled to create a playable banjo.

Future Research

While the results above show that each process has been fully developed and reached a satisfactory conclusion in regards to the scope of this project, some aspects of the processes could be improved in future research. The steam bending process worked for the purposes of this research, but should be redesigned to eliminate handling of the steam hose for safer use. After the initial steaming of the wood strip, it was taken out of the chamber to be bent on the bending jig. Once the wood is removed from the steam chamber, it immediately begins the lose flexibility. With the current method of clamping on the tooling, it took more time to bend than the original steaming allowed; which made it necessary to remove the steam hose from the chamber and actively be steaming the wood. This method improved the results of the bending process and prevented breaks and failures due to dryness. By following this line of thought, a method of active steaming built into the bending jig would allow the operator to use both hands to clamp the work-piece. Another concern with the current bending jig is that water tends not to evaporate quick enough on the wood surface that bends against the tooling. This applied also to the time it took for the glue to set up. If air flow to this area could be increased and a suitable dehumidifying environment could be created, the production time of the resonator could be greatly reduced.

Expenses

While there was no preliminary budget outlined during the early stages of this research, the results generated far outweigh the expenses that were necessary to develop the manufacturing processes. While Table 1 shows a detailed bill of materials, there was an abundant amount of departmental materials used during development process. The machine tool lab keeps various thicknesses of insulation foam and MDF sheets in stock for student prototyping. Two inch thick foam was used extensively for prototyping the neck tool-paths and 3/4 inch thick MDF was used for making the set of Cole jaw extensions. The ultra high molecular weight (UHMW) sheet material used for the resonator bending form for the resonator was also material available in the lab. Using these materials helped to cut down on the cost of development. Table 1 shows that the cost of the materials for this project was just over $1000.00. While this number grew faster than expected, it was necessary to provide materials when they were needed in order to keep the project on track for completion. It is possible that extensive planning prior to beginning the research could have helped to reduce the costs involved, it is nearly impossible to plan the correct amount of resources without having previous experience in a similar circumstance. The chart shows that the most expensive processes were the resonator and the neck. While the neck required some higher priced tools, the resonator building process required more fixtures.

	Bill of Materials		
	Description	**Supplier**	**Total Cost w/tax**
	Wood Materials: Plywood, Hardwood, Veneer	Woodcraft, Lowes	372.19
	20 Ton Shop Press	Harbor Freight	218.99
	Tools and Hardware: Wing Slot Cutter, Flush Router, Easy Rougher	Woodcraft	318.06
	Finishing Supplies: Veneer Glue, Titebond II, Truoil, Respirator	Woodcraft, Lowes, Auto Zone	81.01
		Total w/tax	$990.25

Table 1. Bill of Materials. The table below shows an overall view of the expenses of the development process.

Another large cost to the research was the hardware that was required for assembly of the banjo once the components were built. Banjos require several expensive metal pieces of hardware which quickly causes the costs of building a banjo to rise. An initial estimate of the hardware costs was around $600. Considering the fact that banjo manufacturers price their average instruments anywhere from $1200 to $3500, the cost of building a banjo using the methods in this research would be much less than the price of buying a banjo at retail . Table 2 quickly reveals that hardware is the largest cost of building a banjo. Of course, this estimate is strictly from a retail supplier and buying each individual component outright. Even from the same supplier prices would be cheaper if the parts were bought in bulk. More research into a more cost effective parts supplier would be critical to a small banjo manufacturing operation.

Resonator Banjo Hardware Cost

Part Number	Quantity	Part Name	Supplier	Cost
0822	1	Five-Star Flathead Tone Ring	Stewart-MacDonald	$ 245.75
0995	1	Resonator One-Piece Flange	Stewart-MacDonald	$ 85.97
5014	1	Five-Star Banjo Tuning Pegs (4)	Stewart-MacDonald	$ 73.33
0250	1	Five-Star Notched Tension Hoop	Stewart-MacDonald	$ 48.98
0960	1	Banjo Resonator Hardware Set	Stewart-MacDonald	$ 42.36
0916	1	Kershner Banjo Tailpiece	Stewart-MacDonald	$ 34.53
0280	1	Banjo Coordinator Rod Set	Stewart-MacDonald	$ 25.56
0100	1	Frosted Five-Star Drum Head	Stewart-MacDonald	$ 20.95
0140	1	Five-Star Banjo Strings-Light	Stewart-MacDonald	$ 5.92
0124	1	Resonator Bracket	Stewart-MacDonald	$ 5.35
0266	1	5/8 height 5 String Banjo Bridge	Stewart-MacDonald	$ 3.09
5307	1	5th String Capo Spikes	Stewart-MacDonald	$ 0.99
Total w/tax				$ 592.78

Table 2. Resonator Banjo Hardware Cost. Estimated cost of hardware for resonator banjos, prices taken from Stewart-MacDonald catalog.

CONCLUSION

In conclusion, this research project demonstrated the development of fixtures and manufacturing processes for producing banjo resonators, rims and necks. Through this research, a finished rim, resonator, and neck were made. The resonator was the first component to be finished. For its development a steam chamber was built to steam wooden strips for bending. These strips made the sides of the resonator. Once the sides were made, they had to be turned on a lathe. This required the design of a set of extensions for a Cole jaw set in order to hold the resonator blank. The back of the resonator was made up of 1/4" birch plywood that was press formed into a 42" spherical radius. Once these two components were glued together and trimmed flush, a fully shaped resonator was formed. The rim was made using the block rim method. This required blocks to be cut on both sides at 22.5 degrees in order to form an octagon. Three of these octagons were oriented and glued together to form a roughly circular shape that was then turned on a lathe using the modified Cole jaw set extensions designed to hold the resonator. Once turned, the hardware was assembled on the rim to make the pot assembly. The neck had the longest development time because of making separate and complex CNC centerline tool paths for cutting each section. Although the development process was long, by the time the first wooden prototype was created, most of the major issues had been solved in the foam prototypes. After a few adjustments and redesigning the headstock cutting program to accommodate the tuners, the neck cutting programs were finished. Finally a fully shaped neck was routed out of a single piece of maple. These fixtures, tool-paths and manufacturing processes were successful in producing the three wooden components that this research set out to develop. While many would think the cost of this research was excessive, it is surprising that such a complicated process could be completed for around $1600. This research was very rewarding and the results exceeded my expectations considering the time and budget that was available.

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