Choosing Material

There are a wide variety of millable materials to choose from and each has its advantages and disadvantages. Depending on the particular goals for the model or part you are making, some materials will be better suited to the task than others. Both the choice of material and its preparation can have a large impact on the quality of the model produced. If you are interested in using a material other than polystyrene foam, it is a good idea to talk to lab staff beforehand to understand how it affects the process and whether it makes sense for what you are trying to do.

Materials commonly used on the CNC router at the GSD are listed below. Some metals and plastics can be milled on the CNC vertical mill in the machine shop. Other materials are not appropriate for milling on any machine at the GSD because of the dust they create or simply due to the fact that they are not machinable. Materials that are NOT machinable at the GSD with the routers and mills include: concrete, stone, glass, plaster-based products, and others. However, many of these materials can be machined with the waterjet.

Keep in mind that the lab is staffed primarily by students whom are often learning the full depth of the process themselves. When spending money on more expensive or precious materials, consider the possibility that you may not get everything correct the first time and material and time might, ultimately, be considered be wasted as a model or part fails to meet expectations. There are no refunds for materials that are damaged or incorrectly processed in the lab. It is always best to become familiar with a material and process over time, rather than making a large investment in something you've never done before. When experimenting or trying something for the first time, be prepared to fail and take full responsibility for that failure (and learn from it). However, always experiment (and fail) safely.

Commonly Milled Materials

This material is recommended for people new to milling, for surface milling jobs, and for initial geometric prototypes. It comes in two forms: expanded and extruded. Expanded foam generally consists of a number of small spheres that are pressed together to form larger blocks which are then cut into smaller blocks and sheets. Extruded foam generally is generally available in board formats and has two faces that have skins on them, which can cause the board to change bow and change shape when milled. Both forms area available in a limited range of densities. The most commonly used density of expanded foam is 2 pound.

- **Advantages**: inexpensive, lightweight and transportable, mills quickly with inexpensive tools, paintable with gesso and water-based paints, forgiving as related to errors in the toolpath strategy, requires minimal preparation, available in a wide range of sizes, allows relatively deep cuts as longer cutting tools can be used
- **Disadvantages**: not very rigid, so may require additional support, some forms have strong colors that may desire painting, will not withstand significant wear and tear, stock available may not be of consistent width or precisely prepared
- **Sources**: available in 2’ and 4’ widths, up to 8’ length, and 2”, 3”, 4”, and 6” thicknesses from the GSD Lab Store; Also available locally at Insulation Technologies who can cut to requested sizes
- **Machines**: This material is most suitable for the two CNC routers (AXYZ and C.R.Onsrud), the Roland CNC mill, and the robots
This material was designed to be milled and so performs beautifully, producing better results than polystyrene foam. A wide variety of densities are available from manufacturers, from very soft materials to very hard and dense types. For most models and parts made at the GSD, the low-to-medium density range is sufficient, between 15 and 20 lb. densities.

- **Advantages:** dimensional stability, uniform color, homogenous material, mills relatively quickly, capable of being milled into relatively thin surfaces, requires minimal preparation, able to be sanded and painted, allows relatively deep cuts as longer cutting tools can be used
- **Disadvantages:** relatively expensive, moderately heavy when compared to other foam, specific densities are readily available in specific colors, which are not often attractive on their own
- **Sources:** Sold in GSD Lab Store in a limited range of sizes (4” thickness in blocks of 2’x4’, 4’x4’, or 4’x8’ size) of grey 20 lb foam. Other densities, colors, and sizes are available online from General Plastics, Freeman Supply
- **Machines:** This material is most suitable for the two CNC routers (AXYZ and C.R.Onsrud), the Roland CNC mill, and the robots

![Image of material](image)

This type of material comes in sheets ranging in thickness from about 1/8” to 1”. There are many different types of plywood and other laminated wood products. These types of products may have different grades of finished faces on one side only, on two sides, or on no sides. The inner core layers can also differ significantly. Some products have fewer, thicker layers that contain knots and voids, whereas other products will have equal thickness layers with no voids for all laminations. Some products are not laminated sheets, but laminated chips or strands of wood, instead. The adhesives used in all of these products are abrasive to the cutting tools.

Over time or during particularly long-running surface models, these tools will become dull, generating heat and degrading in their ability to cut well. In extreme cases, dull tools will cause the material to burn and potentially catch fire. Like wood, greater attention must be paid to the cutting tools and cutting parameters. Unlike foam, these materials have a greater likelihood of violently reacting to the milling process, so are less forgiving to work with. Incorrect settings are more likely to lead to broken tools, damage to the model, damage to the machine, and fire. For surface milling, we recommend marine grade Baltic birch plywood as it is made of many thin, higher quality layers than other grades of plywood. To achieve sufficient thickness, it may be necessary to glue multiple sheets of plywood together to form a block.

Material will vary slightly +/- in thickness, affecting the fit of joints and pockets. 3/4” plywood is a nominal size and may be closer to 0.715”, so double check measurements with your drawings where it will affect fit and finish. Measure several locations along the edge and use the largest dimension. Additional room (~0.005”) may be needed in pockets and joints to allow for expansion and adhesives.

Please review the information on compression spirals for best results when performing 2D contour and pocket cuts.

- **Advantages:** withstands wear and tear, layers create interesting effect (but often distracting), dimensionally stable, can be sanded and painted
- **Disadvantages:** potentially expensive, depending on grade chosen, may require specialized cutting tools, layers may be of different quality and contain knots, heavy, cannot make deep narrow cuts as cutting tools cannot be as long as those that can be used with foam, requires preparation to form thicker blocks from sheets, milling time is longer than that for foam
- **Sources:** available locally at Boulter Plywood and Home Depot
- **Machines:** This material is most suitable for the two CNC routers (AXYZ and C.R.Onsrud), and in limited applications, for the Roland CNC mill and the robots
Medium Density Fiberboard (MDF) and Low Density Fiberboard (LDF) are most commonly available in sheet-based form similar to plywood, but it is possible to buy blocks from specialty vendors (Freeman Supply). These products are made of wood pulp that is pressed and bonded with adhesives. The adhesives used in all of these products are abrasive to the cutting tools. Over time or during particularly long-running surface models, these tools will become dull, generating heat and degrading in their ability to cut well. In extreme cases, dull tools will cause the material to burn and potentially catch fire.

When milled these materials create a fine dust, which is a nuisance to lab staff as it makes equipment maintenance, room cleaning, and managing a healthy work environment more difficult. Compared to foams, plywood, and most hardwoods, MDF is also more demanding on generic cutting tools. Specialty endmills are better in terms of maintaining a sharp tool and extending tool life. When available, LDF that is made with non-formaldehyde resins is preferred over other types.

If you are gluing up a large multi-ply stock, consider generating a contour model and roughing out your blanks on the bandsaw before assembly. This can save huge amounts of time when milling and the contour stock geometry can be imported into MasterCAM and used to create more optimized tool paths. Use plenty of glue, spread evenly to avoid dry spots and poor adhesion between layers which will impact the end result.

- **Advantages:** uniform color, homogenous material, can be milled to be very smooth, more dimensionally stable than hardwood, generally less expensive than plywood, hardwood, or HD foam, can be sanded and painted
- **Disadvantages:** requires expensive cutting tools, creates fine dust, heavy, cannot make deep narrow cuts as cutting tools cannot be as long as those that can be used with foam, requires preparation to form thicker blocks from sheets, milling time is longer than that for foam
- **Sources:** available locally at Boulter Plywood and Home Depot, specialty sizes available online through Freeman supply
- **Machines:** This material is most suitable for the C.R. Onsrud CNC router, and in limited applications for the AXYZ CNC Router, the Roland CNC mill, and the robots
Solid wood materials come in a range of hardnesses with varying grain qualities, making some varieties easier to work with than others. Generally, we work with hardwoods, rather than softwoods. Commonly used hardwoods include Maple, Walnut, Ash, Basswood, Poplar, Mahogany, and Cherry. As this material is literally a slice of a tree, there are limits to the size of stock that is available. Sold in boards at fine lumber purveyors, this material may be rough sawn or finished or 2 or all 4 faces. To prepare this material for milling, a substantial amount of work will need to take place in the woodshop first, using equipment that requires advanced training.

Not all pieces of lumber are suitable to being made into relatively flat and stable workpieces. Material may have environmental or drying stresses built in that will react badly when it is machined. Time to acclimate to the shop and surfacing (to flatten and stress relieve) in the wood shop may help, but it is not a guarantee. It is best if you know what you are looking for when you go to purchase this material as you could end up with a piece that turns into a pretzel when you start to cut into it on the router. When a piece of hardwood wants to start moving or changing shape, there is very little that you can do to stop it. Trying to mount it to a more stable sacrificial board to hold it flat will simply not work. There is no good way to hold a non-flat piece of material to the vacuum bed of the large CNC router. Talk to Fabrication Lab staff before you proceed down this route and while you prepare your file and material.

- **Advantages:** looks nice, will withstand wear and tear
- **Disadvantages:** can be expensive, not dimensionally stable, limited sizes, may require expensive cutting tools, milling time is longer than that for foam
- **Sources:** available locally at Boulter Plywood, Anderson McQuaid, Longleaf Lumber, Rockler and Home Depot.
- **Machines:** This material is most suitable for the C.R. Onsrud CNC router, and in limited applications for the AXYZ CNC Router, the Roland CNC mill, and the robots.

**Machinable Wax** is a special wax designed to be cut by mills for a variety of purposes. It is able to hold high resolution and be cut with small diameter endmills. It is dimensionally stable and relatively easy on cutting tools. Machinable waxes allow parts to be prototyped and checked for size and fit before then machining them from metal. Some types have melting temperatures that allow the material to be used in the lost wax casting process. It is a suitable material for making molds for other casting and forming operations as it releases well without the need for additional sealants and release agents. Multiple blocks can be glued together with cyanoacrylate to form a larger block. For many of the above reasons, it is a popular choice for engineering school machine shops. It comes in block and rod form in a variety of colors, and can be ordered online from a number of vendors. The shavings from this material can be recycled by re-melting them and forming them into new blocks.

- **Advantages:** Very versatile material for prototyping, casting, and mold-making. Dimensionally stable. Comes in block form.
- **Disadvantages:** Colors are particularly strong and the material does not receive paint well. May be more expensive than foam if making prototypes where precision is not important. Limited stock volume (under 2 square feet).
- **Sources:** This material is available online from a number of vendors, one of them being MachinableWax.com, another is freeman supply.
- **Machines:** This material is most suitable for the Prototrak CNC Knee mill and the Roland CNC mill due to typical part size, but it could also be used on any of the other routers provided there is a provision to secure it to the machine.
A wide variety of machinable plastics are available, including cast and extruded acrylic, polypropylene, HDPE, and PVC. Plastics themselves can vary significantly in terms of how well they are cut with an endmill. Specialty tools are made for different hardness of plastic and particular toolpath settings are needed for different types of plastics. Plastics can generally be obtained in sheet or block form from a variety of vendors. These materials are often best cut with the addition of compressed air to aid in chip removal, and sometimes with the addition of lubricant. Neither of these additions are supported adequately on the CNC routers, making the use of specialty tools more important to aid in proper chip removal.

- **Advantages:** unique qualities are achievable (transparency, flexibility), may not require any material preparation
- **Disadvantages:** requires specialty tools, milling time is longer than that for foam, difficult to make deep narrow cuts as cutting tools cannot be as long as those that can be used with foam, file preparation requires more attention to detail
- **Sources:** some types of plastic are available locally from Altec Plastics, online from McMaster-Carr and others
- **Machines:** CNC Routers, Vertical Mill, limited applications for Roland, Robots
There are different types of aluminum, alloys 2007, 2011, and 6020 are the most machinable, being more brittle than other types of aluminum. Aluminum can be purchased in sheets, plates, or blocks. Like plastics, it is important to use specialty tools when machining this material without the aid of compressed air and lubricant/coolant. When routing thin sheets on the router, there is a great potential for the sheet to be lifted up by the machine and cause damage to the part, machine, tool, or you. Special tools that help to hold the material down while being cut may be necessary. Small parts from block material are best done on the knee mill where a mist of coolant can be applied and the operator can freely add lubricant. This material presents its own challenges that are much different than those encountered when working with wood. A considerable amount of attention will need to be placed in preparing a Mastercam file. Chips produced when cutting this material cannot be collected in the dust collector attached to the CNC routers. Talk to Fabrication Lab staff if this is a material that you need to use.

- **Advantages:** best for use where the material properties of aluminum are required for the project (conductivity, strength)
- **Disadvantages:** specialized tooling, chip removal/collection, heat dissipation/chip welding
- **Sources:**
- **Machines:** Knee Mill (limited sizes), limited applications on CNC routers, machining thin stock is possible on the Zund which has lubrication and chip collection built into it's router spindle

There are a few more considerations when milling Graphite. The material must be fully dried before milling—any moisture that remains will damage the tools used when milling. Because graphite dust is electrically conductive, the material cannot be milled on the larger routers. Chips produced when cutting this material cannot be collected in the dust collector attached to the CNC routers. Considerable attention must be paid to the order and direction of toolpaths when using graphite to avoid chip out and dust getting caught in the material. Talk to Fabrication Lab staff if this is a material that you need to use.

- **Advantages:** Great for mold making where heat is necessary in the molding process
- **Disadvantages:** Difficult to mill, requires custom tools
- **Sources:**
- **Machines:** Knee Mill (limited sizes)
Preparing Material

Cut Material

- If you will be using the C.R. Onsrud router and will be employing its vacuum hold-down, you can usually cut your stock material to the final size of the model and not leave any extra around the edges.

- For flip-milling or making a part on the AXYZ router, include extra material around the extents of your model or part when cutting your material to size (about 2 inches in at least two opposite directions to allow for screw placement). Be sure to include this larger stock size when setting up the stock in Mastercam.

Depending on which machine is used and the geometry of the part, it may be necessary to secure the material to the router table with screws. In this case, it is best to plan for extra material around the area that is to be milled. The finished product can be later removed with an additional milling operation or with another method in the wood shop.

As routers and many of the shop machines are limited in the depth they can cut, it’s generally best to cut material to size before gluing it up into a thicker block.

Flatten Material

In general, it is necessary for at least one face of your material to be absolutely flat in order to secure it to the machine and mill it. Most often, this is the bottom face. For low-density soft materials like foam, there is some flexibility with this as the material may be able to be held flat by the machine or other fastening devices. Depending on the machine you are using, the options available are different. Consult a TA to better understand the options for your particular material and geometry.

Some general pointers:

- Depending on the material you are using, you may have to flatten the material in multiple steps, including before the material is cut to size and after gluing up a larger block. This is especially true when gluing up hardwood. Consult wood shop staff about the best approach.
• To reduce warping (low dimensional stability) in the extruded blue polystyrene foam, the top and bottom faces of the blue foam can be sanded to relieve surface tension. The white expanded polystyrene foam is less prone to warping.
• When using vacuum for hold-down (most jobs on the C.R. Onsrud router) it is especially important that there not be any large voids on the bottom of the material that lead to its edge as this would compromise the vacuum seal and the part would not be securely held.
• Keep in mind that hardwood is a natural product of our friends, the trees. It will change in size and shape with slight changes in humidity and as moisture from within it moves in and out. Due to this, it can be rather difficult (and sometimes impossible) for even experienced wood workers to prepare hardwood stock so that it lies flat and remains flat after being cut.

Glue Material

In general, two different types of glues are used to create larger blocks of material from sheets, wood glue for wood-based products, and expanding polyurethane glue (Gorilla glue) for foam. Regardless of the glue or material type, keep the following in mind:

- Allow enough time for the adhesive to dry completely before milling.
- Use adequate amounts of glue and expect to see squeeze out between layers. No squeeze out means you did not use enough glue.
- Adhesive that is not dried or cured can cause damage to the cutting tool and machine, and can also result in a damaged model.
- Be sure to clamp all material to achieve a good bond between layers.
- Be sure to clean surfaces that will be glued such that they are free of dust, wax, and oils.
- Always follow the directions on the glue bottle.
- Always consult the MSDS for the glue you are using.

Wood Glue:
- Check the label for the specific glue’s working time. Some will allow only 5 minutes to put materials together and clamp, others 20 minutes, etc. A longer working time is probably better than a shorter one, especially for large parts, or parts that will be made of several layers.
- If wood glue dries before the part is clamped, the part may delaminate during the milling process as wood glue will not bond to dried wood glue. If there is dried wood glue on a surface, it will need to be removed prior to gluing.
- Some wood surfaces may require sanding or planing.

Gorilla Glue:
- Gorilla glue is most often used with polystyrene foam, but can be used with other materials as well.
- It requires 24 hours to fully cure.
- This adhesive cures rather than dries, and requires water to be present for the reaction to occur. Both surfaces to be glued should be misted with water to aid the curing process.
- Gorilla glue expands as it cures, so be sure to sufficiently clamp your material.
- Gorilla glue can also be used to mount a single layer of foam to a more rigid material such as MDF or plywood to create a more stable part.

Clamp Material

To ensure a clean-looking and continuous bond between materials, it is necessary to adequately clamp and/or weight your work while the glue is drying or curing. Some adhesives expand when curing, separating the material with a large, low density glue line. If not done properly, a laminated stack of plywood can fly apart on the mill, wasting time and money, and increasing hazard. Talk to Burton or a woodshop TA about how to do properly clamp the material you are using.

Pressure must be applied to the edges as well as the center of the material. To accomplish this, there are several strategies:

- sandbags or heavy weighted items may be placed in the center of the work (see image below)
- long pieces of plywood or wood may be laid across the material on edge across and clamped on either end to more evenly distribute the load across the face of the material (see image below)
- the vacuum clamp may be used for parts that will fit within it
- deep-throated cam clamps may be used for some smaller parts, where the depth of the clamp can reach the center of the material from the edge

(Make a better image/photo of this)