Inlay Carving with CNC– A Tutorial

By

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(Vers 1.1)

Introduction

CNC Inlay carving in wood is a technique intended to provide similar results to the traditional (manual) inlay and intarsia woodworking. Essentially it involves creating patterns using different woods (types, textures, colours) or other materials (bone, shell, metal) to form patterns on the surface of the finished object. While the thickness of the inlayed, or veneered, material may vary the principles are essentially the same. The CNC machine can be used for both preparing the substrate and the inlay material.

The manual approach requires considerable skill and much practice to achieve a quality result, reflected by the tightness of fit of the inlay pieces, and perhaps also the surface finish of the inlayed item. The use of CNC techniques offers some advantages, mainly relating to the accuracy of the required cutting, both for the inlay and substrate; but also the time it takes to complete the task.

There are, however, also some downsides. The application of CNC machining provides some challenges to achieve small and fine shape details, especially when sharp angled corners are required. There is also a need to avoid splintering, or tear out, on narrow sections of inlay. In addition, and for machining, the inlay pieces need to be held down securely, and this means that the size of the stock must be sufficiently large to be clamped. While various hold down techniques may be used (gluing, vacuum, etc) special care is required to ensure that the pieces of inlay stock are held firmly for machining.

This tutorial is primarily aimed at inlay tasks that involve the insertion of a single inlay material into a substrate. It does not fully address the issues associated with using multiple inlay materials (wood types, colours or textures) inlayed into single pockets in a mosaic pattern (as typical in intarsia). Such work deserves further discussion.

There are two different approaches for doing inlay work with a CNC router. They can be described, roughly as pocket inlay and V-carving inlay as shown in Figure 1.

(a) Pocket Inlay

(b) V-carve Inlay

Figure 1: CNC Inlay Types

The pocket inlay (a) is created by machining a vertical-sided pocket into the substrate to a depth just short of the thickness of the inlay material (or the required depth of the inlay). The inlay material is then cut out to the required shape using a profile machine operation (MOP). The inlay parts are then glued into place and the excess inlay material sanded (or machined) off to provide the finished surface. Providing that the inlay piece fits tightly (allowing for a fitting tolerance) then the result can be rather good. The machining operations are otherwise quite simple to set up and perform. The pocket inlay can also be used for quite thin inlay materials.

The V-carve inlay is done quite differently, and it is called V-carving as it uses a Vee-shaped router bit. The pocket in the substrate is machined with a sloping edge and the inlay stock must be machined with a matching (though mirrored) sloping edge. Those parts of the inlay stock that are not a part of the inlay must then be machined away using a pocketing operation. The inlay stock will need to be quite a bit thicker than the required inlay depth so that all the inlay pieces are held together for machining. With both the substrate and the inlay machined, the inlay stock is flipped over and glued (and clamped) into the substrate after carefully aligning the two parts. The fit can be quite precise.

Once the glue has dried then the top (excess) part of the inlay material is removed. This can be done by careful sawing (if the size of the item is not too large) or machined off with the CNC machine using a pocketing operation to remove all the excess inlay down to, or just below, the surface of the substrate.

The following table summarises the pluses and minuses of each approach.

Table 1: Comparison of Methods

Issue	**Pocket Inlay**		**V-carve Inlay**	
	Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Inlay stock thickness	Can be quite thin (less than 1mm) or thick			Must be quite thick, perhaps twice the inlay depth.
Sharp corners and fine detail		Limited by size of cutter used	Can be quite sharp and fine	

Stock tear out		Can occur, but may be controlled with slower machining and the use of down-cut spiral cutters.		Can occur on narrow sections of inlay
Surface durability	Can accommodate significant re-sanding without loss of detail			Can only accommodate limited re-sanding without loss of detail
Machining time	Shorter			Can be much longer
Data and CAM model preparation	Shorter and simpler			Much longer and can be complex
Suitable for Intarsia/mosaic work	With care			Probably not

The choice of method to use will depend on the inlay shapes to be made and also, perhaps, the available inlay stock material. In the following sections we will explore the theory of the two approaches then present two examples.

Both methods require some special capabilities from your CAD/CAM software. The pocket inlay requires some tools to correctly cater for sharp corners to match your cutter size. This might be done manually, by careful editing of the CAD file containing the inlay outline drawing, but requiring nothing special from your CAM package. Or, alternatively, CamBam provides a free plugin that will do this for you.

V-carve inlay work can be done using a propriety CAM package from Vectric (www.vetric.com) , for a price, and where the process is somewhat automated, but still requiring some attention to details and careful job planning. It can also be done with CamBam, that is much less expensive, but the procedures are probably more complex.

In the flowing sections the two methods will be explained by example using CamBam as the CAM tool.

Method for Pocket Inlay

The pocket inlay principles are simple. The original geometry defines the shapes to be inlayed, i.e. the pockets to be machined in the substrate and the inlay profile cut-outs that will be inserted (and glued) into these pockets. The substrate is machined using a Pocket MOP (one or more) and the inlay materials is machined with a Profile MOP (one or more).

The issues that do need special consideration are:

- The accuracy of the two cuts (in the substrate and the inlay material) so that the pieces of inlay material fit tightly and easily into the cut pockets.
- The diameter of the end mill to be used and the impacts this has on the loss of detail in the inlay.

Consider the star shape in Figure 2 as shown by the green line. If this shape is pocketed with a 3 mm diameter cutter, then only the orange shape will be machined. There will be a small amount of material left uncut at each vertex; and more if the vertex angle is sharp. Since we must use a cutter with a finite size, we need to account for this problem by ensuring that both the substrate and the inlay is cut to the same edge, otherwise there will be gaps at the outer vertices and overlaps at the inner vertices.

The resolution to this problem requires that the original geometry (with sharp vertices) must be modified to suit the chosen cutter diameter, i.e. the (all) vertices must be filleted at the required radius. This can be done manually (either in your CAD package, on in CamBam using the Fillet plugin) or more automatically with the CamBam Inlay Toolpath plugin. This plugin produces the result as shown in Figure 2 as the orange shape. The resulting amount of adjustments depends on both the size of the cutter and the vertex angle.

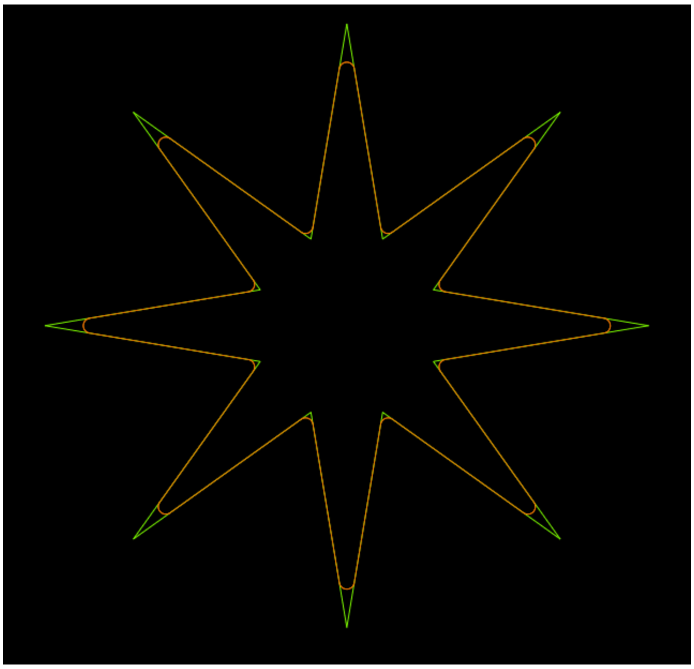


Figure 2: Preparing a drawing for Inlay pocketing

The result is, of course, a compromise so your judgement is required as to whether the results will be noticed and if they are acceptable.

The second consideration relates to the accuracy of the pocketing and profiles cut from the inlay material. Some things to consider are:

- The actual diameter of the cutter, as compared with its nominal diameter.
- The cutter runout caused by small eccentricities in the collet that will cause the actual cut to be wider than it might be expected.
- It may also be useful to use different cutters for the substrate and inlay materials. For example it is often useful to use a down-cut spiral cutter for the pocketing MOP for the substrate as it will minimise the surface tear out.

- While different cutters may be used for the substrate pocket and inlay profile they should have the same nominal diameter as the radii of the rounded vertices should be the same for both cuts.

Once you identify the cutters to be used then some test cuts are in order to ensure that the fit is just right. . The geometry is shown in Figure 3 where:

- Ds is the actual measured diameter of the end mill used for cutting the pocket in the substrate.
- Di is the actual measured diameter of the end mill to be used for the profile MOP to cut out the inlay sections.
- Ri is the Roughing Clearance (a CamBam parameter) to be used for the inlay, and
- Rs is the Roughing Clearance to be used for cutting the substrate. Both may need to be adjusted to give the required tight fit for Profile MOPs.

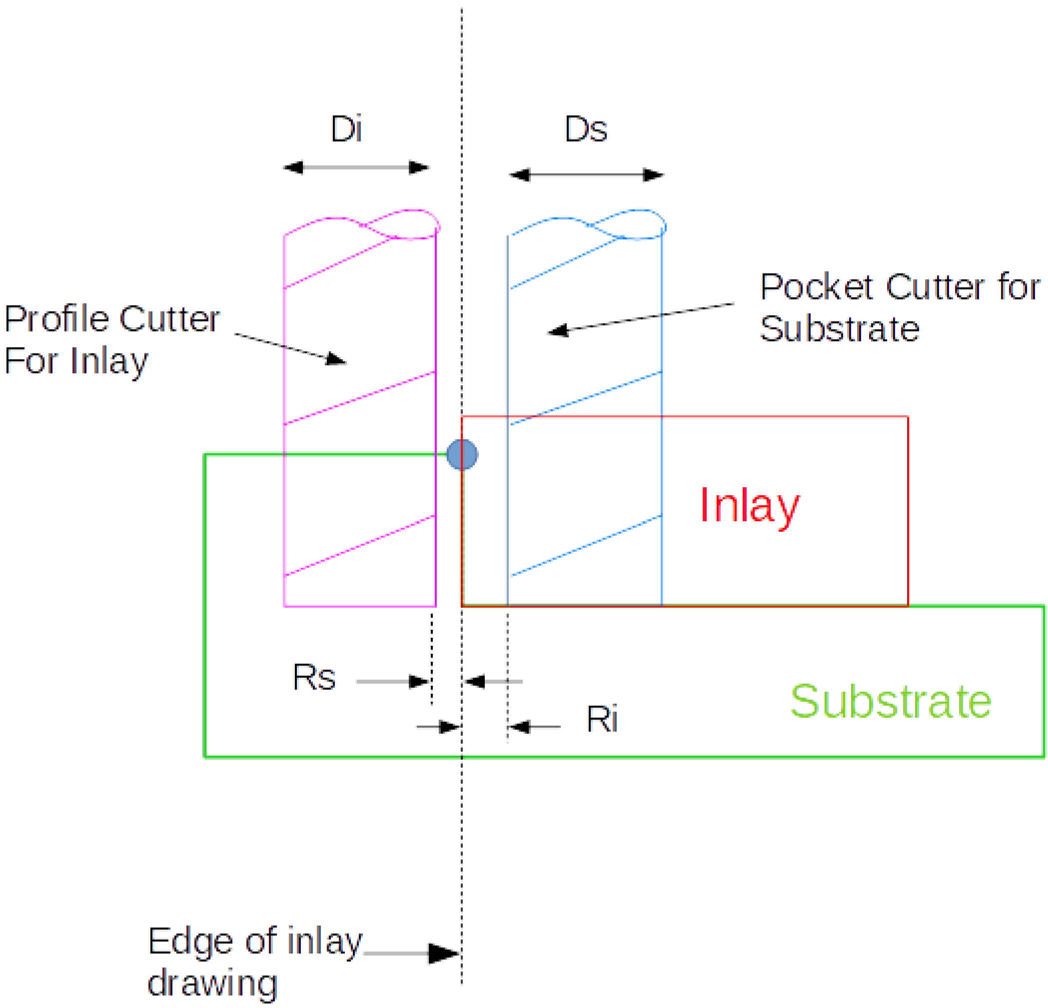


Figure 3: Geometry of Pocket Inlay

The strategy for a fine adjustment of the pocket and profiles uses the Roughing Clearance parameter, in the respective MOPs. This parameter sets a distance for the cutter to under, or over, cut the required shapes.

A suggested strategy is as follows:

1. Create a sample drawing (a simple circle or rectangle will do) that will be used for the both substrate and the inlay test cuts.
2. Cut a sample inlay section using a profile MOP using the measured diameter of the cutter used.
3. Measure (with a Vernier calliper) the actual dimensions of the cut piece and estimate the required Roughing Offset, by halving the difference.
4. Update the Roughing Clearance for the Profile MOP.
5. Repeat from step (2) until the actual dimensions of the inlay sample are close enough to the required dimensions (less than 0.1 mm difference)
6. Cut a matching pocket using a pocket MOP in a substrate material sample using the measured diameter of the cutter.
7. Test the sample inlay piece for fit quality.
8. If the fit is not perfect then measure the actual width of this pocket to estimate the error then adjust the required Roughing Offset, and repeat from step (6).

A number of trials might be necessary to get the required result, but once good fit is found it should be consistent for the entire inlay job. It may also be the case that to achieve a perfect fit then some small gap is required so allow the inlay pieces to slide into place.

Once the optimal cutting parameters are found then the substrate and the inlay can be machined, glued, then the top surface sanded to the required finish.

Method for V-carve Inlay

The V-carve method is more complex, and it is necessary to understand something of the required geometry (and mathematics) of how the inlay fits into the substrate. The geometry is shown in Figure 4 as a cross section view of one edge of a section of inlay. In this figure the substrate is shown with the green outline and the inlay with the red outline. The blue triangle (pointing down) shows the Vee cutter at the edge of the substrate cut, and then inverted (as a dotted blue line) at the matching edge of the inlay stock. The inlay must be machined top-down, so to achieve this the pattern must be mirrored (flipped over) to prepare the MOPs for the inlay machining.

The method described here has been developed by Bob Mackay (http://bobmackay.com) and published in the CamBam Forum (http://www.cambam.co.uk/forum/index.php?topic=4065.0).

There are a number of key parameters to consider:

- T: the angle of the Vee cutter
- I: the required finished inlay thickness
- G: the glue allowance that provides a small gap between the inlay material and the bottom of the substrate pocket. This provides a small space for glue as well as a small allowance for the inlay material to fit tightly into the substrate pocket without bottoming out.
- A: the air gap that leaves a small gap between the top of the substrate and the bottom of the inlay pocket, again to prevent the two surfaces coming together and otherwise preventing a tight fit along the edges of the inlay.

- S: The sanding allowance to allow for final finishing of the top surface of the substrate after removal of the excess inlay material.

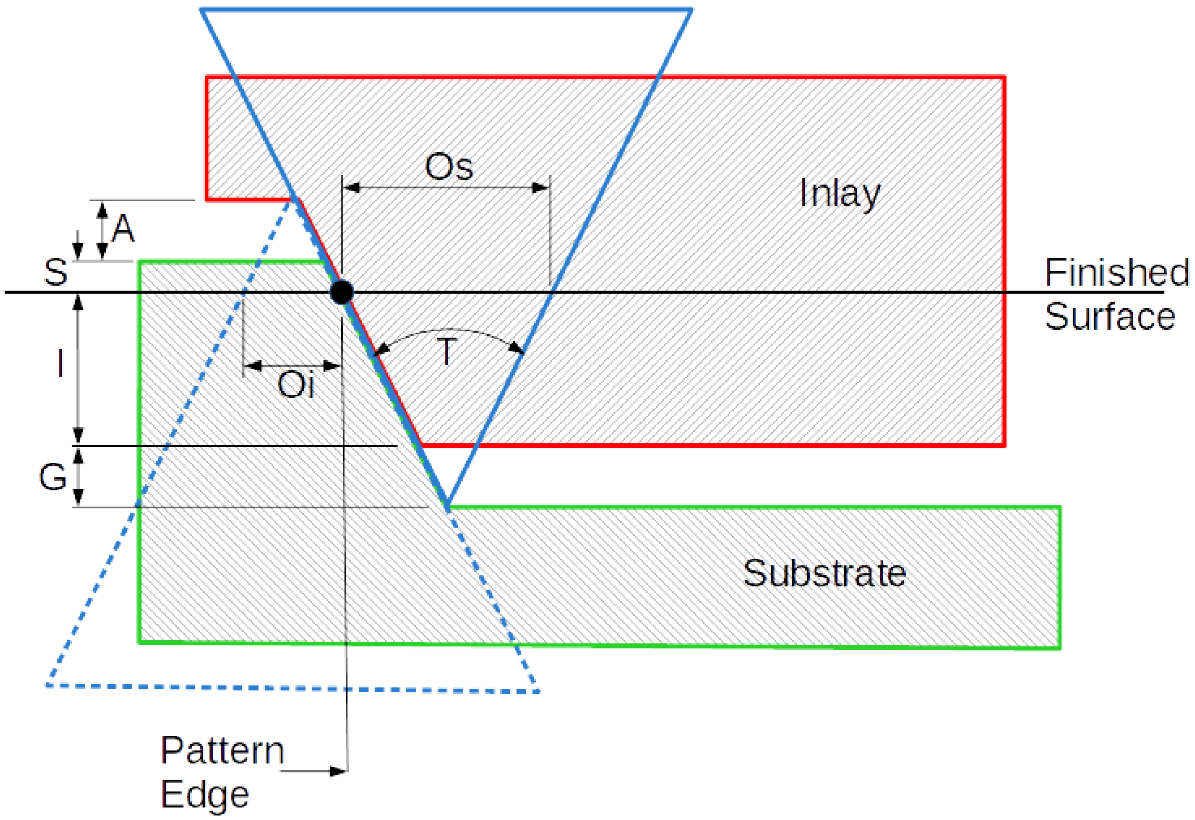


Figure 4: The V-carve Geometry

For the CamBam environment, the cutting paths to machine around the edges of the inlay pieces are computed using the V-Engrave plugin. This plugin was originally developed to make V-Engraved text, but it can be used here also. The key to understanding how it work is shown in Figure 5. Here we have a letter “A” processed with the V-Engrave MOP. The cutting paths are shown in blue. Basically the paths are formed by tracing a path along the centre lines of the parts of the letter at a depth so that the edge of the Vee cutter just reaches the outline of the letter. As a result the V-Engrave path can follow quite complex shapes with varying depths of cut to match the varying widths of the letter.

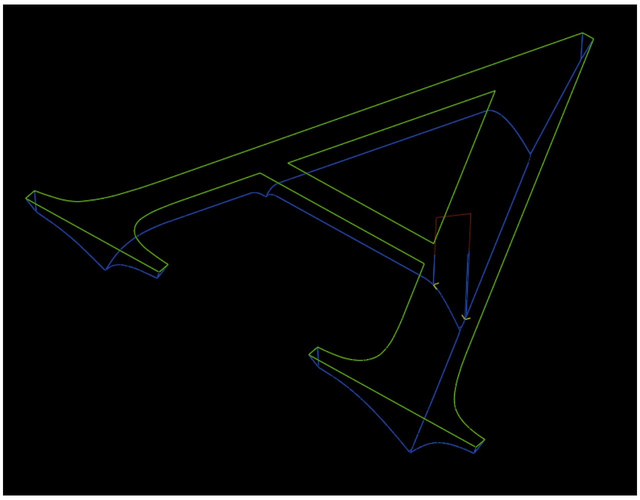


Figure 5: The V-Engrave cutting paths

To use this capability for V-carve inlay tasks we must do the following:

- **For the substrate**: create a series of enclosed shapes, using the drawn pattern as a reference, on the ***inside*** of the pattern to allow the Vee cutter to create the required sloping edges on the inside of the pattern. This can be done by creating offset shapes. The width of the offset is shown as Os in Figure 4
- **For the inlay**: create a series of enclosed shapes, using the mirrored pattern as a reference, on the ***outside*** of the pattern that allows the Vee cutter to create the required sloping edges on the outside of the pattern. This is done also using the offset capability in CamBam. The width of this offset is shown as Oi in Figure 4 .

Both Os and Oi are defined at the finished surface (after sanding) so that the final inlay shapes match the required edge of the pattern. The calculations for these offset values are given Figure 6. Remember that the MOP for the inlay is done on a mirror image of the original drawing.

Definitions & Values	Tool Angle	T
	Air Gap	A
	Sanding Allowance	S
	Inlay thickness	I
	Glue Gap	G
Substrate Material	Substrate Offset	-tan (T / 2) * (I + G) * 2
	Stock Surface	-S
	Substrate Roughing Clearance	tan (T / 2) * I
	Substrate Target Depth	-(S + I + G)
Inlay Material	Inlay Offset	+tan (T / 2) * (S + A) * 2
	Stock Surface	-I
	Inlay Roughing Clearance	tan (T / 2) * (A + S)
	Inlay Target Depth	-(I + S + A)

Figure 6: The Mathematics for V-carve

The calculations have been embedded in a CamBam plugin (Inlay Calculator) as shown in Figure 7. This plugin was initially developed by "EddyCurrent" for CamBam, and updated to V2.1 by this author. To use the plugin it is just necessary to enter the five required parameters, then transfer the results to the related MOPs.

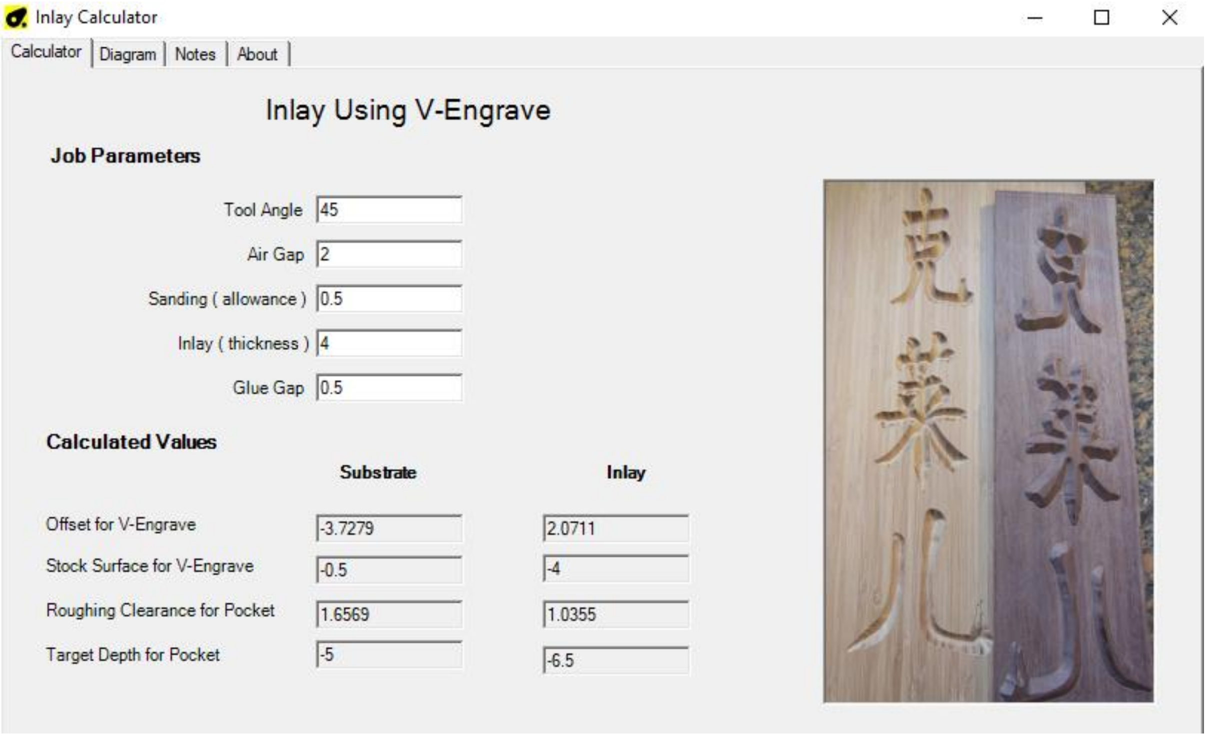


Figure 7: The Inlay Calculator Plugin (v.2.1)

Applying these Offset operations must be done with care as the results may not always be predictable, or perhaps even fully correct on first attempt. For both the substrate and the inlay we must ensure that the offsets correctly represent the actual geometry of the drawing, including any enclosed and/or intersecting polygons. For example if the original pattern contains enclosed shapes (i.e. shapes with holes) then special care is required. For these shapes "inside" has a special meaning; it means "inside the shape" but also "outside" the hole.

Depending on the original inlay pattern different approaches may be required. Generally, however, these Shapes must be first converted to Regions (where the enclosed shape is taken as a hole in the enclosing shape). This can require a number of steps and some special tasks depending on the geometry involved. For both the substrate and inlay then:

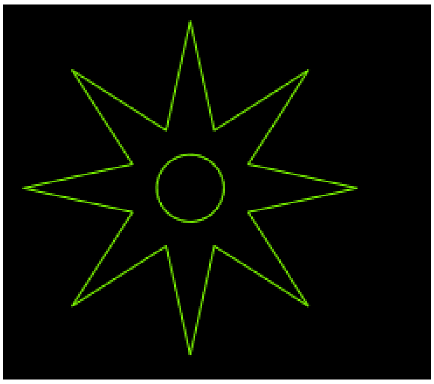
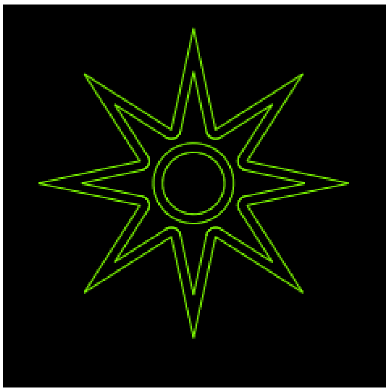
- Select all the Shapes defining the outline of the original drawing
- Convert all Shapes to Regions (those Shapes that enclose Shapes should convert to Regions with holes).
- Create an Offset Shape inside (i.e. –ve) for the substrate, and outside for the inlay (i.e. +ve) using the computed values. Note that for the holes in a Substrate region the Offset will be to the inside of the shape, and the opposite for the Inlay.
- It may be useful to create a Union of the new shapes.
- Select all Polylines & Regions in the original drawing and the offset drawing and if any of these intersect then Break at the intersections. You may now need to manually edit the drawing to remove those edges that are not required.
- Convert all of these Shapes to Regions.

- Review results to ensure that the all the Offsets are now regions, correct as necessary.

A number of examples are shown in Figure 8:

- For case (a): This is a simple case. With the shape defined as a Region, then the –ve Offset will produce the required result (as Polylines) that need to be converted to Regions again to form the two (inner and outer) regions.
- For case (b): In this case the initial geometry is built from four circles, then with some editing to produce 3 Polylines. These are converted to a single Region, with 3 holes, then the Offset applied, then converted to a Region again.
- For case (c): the original geometry has 3 circles that come quite close to each other. After converting to a Region the offsets will create a rather complex result that must be manually edited to remove the edges that overlap or are outside the required offsets, then the remaining edges joined, to form Polylines, then converted to a Region with 2 holes.

There is probably no single process to follow as it seems that the steps required will depend on the original geometry, particularly if it contains holes and especially if it contains narrow sections of inlay. The same issues must be resolved for both the substrate and the inlay, the difference being that for the substrate the V-Engrave shapes are on the "inside" while for the inlay they are on the "outside" of the original drawing.

Initial Geometry	**Required Geometry for V-Engrave**
 (a)	

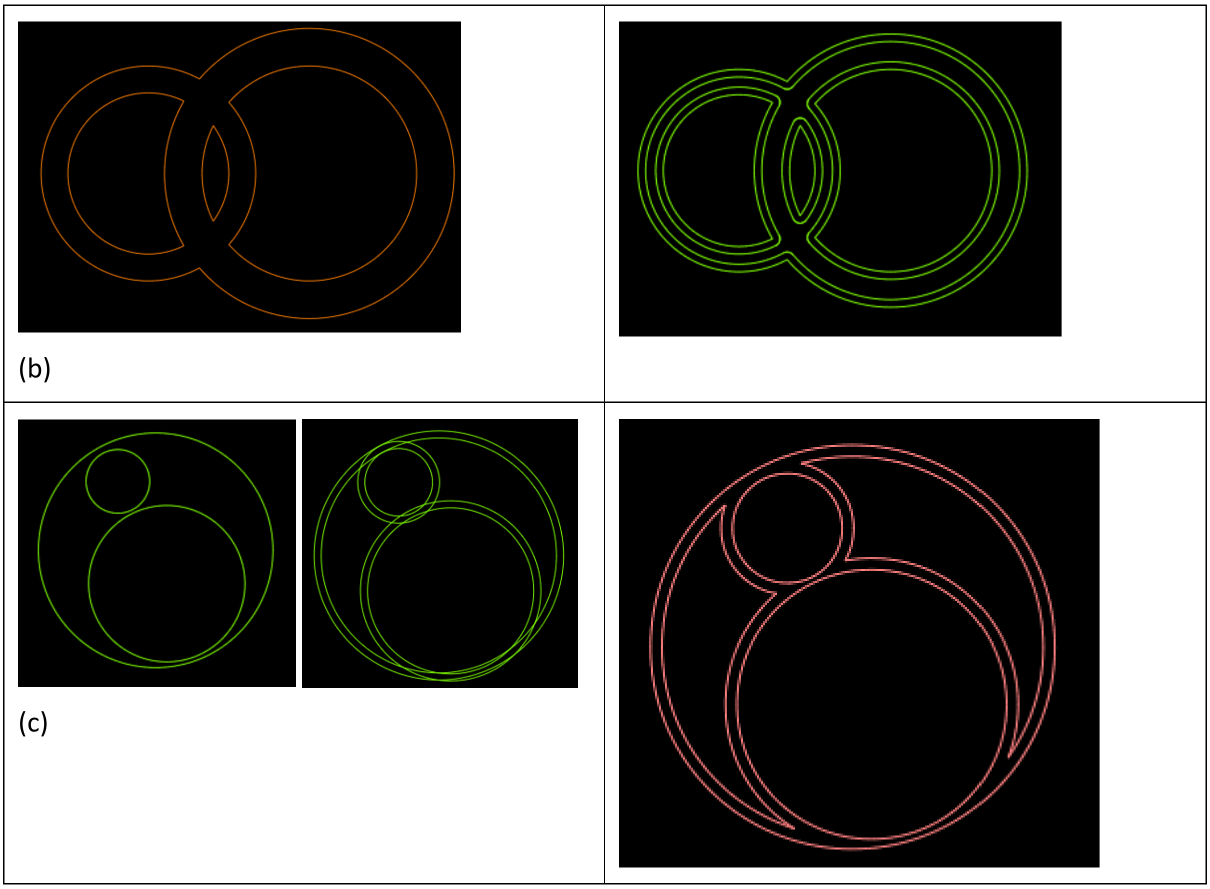


Figure 8: Some examples for Offset construction

With these regions correctly defined we can now apply the V-Engrave MOP to carve the sloping edges of the pocket to be machined in the substrate (or inlay, where the offset is +ve). The V-Engrave MOP will describe a path for a Vee shaped cutter so that the edges of the cut will follow the edges of the Regions, adjusting the depth of cut to suit. The Vee cutter must be large enough to cut to the required depth without the depth exceeding its height. An important thing to also note is that where the widths of the V-Engrave regions are narrow, the depth of the Vee cut must be necessarily shallow. As a result the thickness of the inlay at those locations will be less than the nominal thickness.

These V-Engraved paths will create the edges of the pockets to be machined in both the substrate and inlay. As a result of using the V-Engrave MOP, the shapes to be machines will follow the edges of the inlay, even well into any sharp corners.

With the V-Engrave Regions defined the next steps are:

- For the substrate: create a pocket MOP to machine out the remaining material in the *inside* of the V-Engrave paths. This can be done by using the original geometry and specifying a substrate roughing clearance in the MOP so that the cutter will stay away from the edge by this amount so that it only cuts up to the centre (or close to it) of the V-Engrave path way. This roughing offset is computed as shown in Figure 7.
- For the inlay: create a pocket MOP to machine out the remaining material *outside* the V-Engrave paths and inside the outer border of the item being made. A pocket MOP is created for these shapes by specifying a roughing clearance for the inlay roughing clearance as also computed in Figure 7.

The process for putting all these steps together requires come care, and the following stages and steps are suggested as a way of managing the data preparation.

1) **Create Base Geometry:** This stage creates the geometry in 4 layers, the first two layers are to represent the substrate and the second two represent the inlay.
   a) Create the base (original) geometry in Layer 0. This should include all the outline shapes to be inlayed, as well as the outer boundary of the substrate, and simplified to ensure that all shapes are clean. Pay particular attention to Polylines, particularly if they have been obtained from a DXF file import where badly formed Polylines are common.
   b) Create four (4) new layers, naming them:
      i) Layer 1 – substrate engrave
      ii) Layer 2 – substrate pocket
      iii) Layer 3 – inlay engrave
      iv) Layer 4 –inlay pocket
   c) Copy all the shapes from Layer 0 and paste them into the other four layers as follows:
      i) Copy all shapes from layer 0 and paste them into Layer 1
      ii) Copy all shapes from layer 0 and paste them into Layer 2 (so that layer 2 is initially the same as layer 1).
      iii) Set Layer 0 as active, then select all shapes in Layer 0 and then Edit|Transform|Mirror them about the Y axis at X=0. It might then be useful to move all of these new shapes away from the Y-axis so they can be clearly seen. Select all the newly created shapes in Layer 0 and move them to Layer 3.
      iv) Copy all shapes in Layer 3 and paste them into Layer 4.
   d) Check that each layer contains the correct shapes:
      i) Layer 1 should be the same as layer 0
      ii) Layer 2 should be the same as layer 0
      iii) Layer 3 should be the mirror of layer 0
      iv) Layer 4 should be the same as layer 3.
   e) Compute using the Inlay Calculator plugin the required offsets and clearances for both substrate and inlay depending on:
      i) Vee cutter angle (T)
      ii) The required inlay thickness (I)
      iii) The required air gap (A)
      iv) The sanding allowance (S)
      v) The glue gap (G)

      You will need to decide on the required values for each of these parameters; they will depend on the thicknesses of the substrate and inlay materials, the Vee cutter properties, and some experience!

2) **Create Offset Geometries**: these are used to specify the required edges for the V-Engrave MOPS for both the substrate and the inlay.
   a) For Layer 1: Substrate Engrave: This geometry will provide a set of paths for the V-Engrave operation to cut paths with sloping sides along the edges, and on the **inside**, of the inlay shape boundary.
      i) Hide all other layers
      ii) Set layer 1 as active layer
      iii) Create the “inside” Offset Regions for the V-Engrave MOP (as described above).
   b) For Layer 2: Nothing to do.

c) For Layer 3: Inlay Engrave: This geometry will provide a set of paths for the V-Engrave operation to cut paths with sloping sides along the edges, and on the **outside**, of the inlay shape boundary.
   i) Hide all other layers
   ii) Set layer 3 as active layer
   iii) Create the "outside" Offset Regions for the V-Engrave MOP (as described above).
d) For Layer 4: Nothing to do.

3) Create MOPs: This stage create the four required MOPS using the Layers 1, 2, 3 and 4 respectively and name them to match. The Pocketing MOPs will use an end mill and the V-Engrave MOPS a Vee cutter.

a) Substrate V-Engrave:
   i) Create a new Part and name it "1-substrate engrave"
   ii) Select all the shapes in Layer 1, excluding the outer boundary.
   iii) Create a new MOP using V-Engrave and set these computed substrate parameters:
      (1) Stock surface
      (2) Vee cutter angle
b) Substrate pocket:
   i) Create a new Part and name it "2-substrate pocket"
   ii) Select all the shapes in Layer 2, excluding the outer border.
   iii) Create a new pocket MOP and set these computed substrate parameters:
      (1) Stock surface (set to 0.0)
      (2) Roughing clearance
      (3) Target depth
      (4) End mill diameter
c) Inlay V-Engrave:
   i) Create a new Part and name it "3-inlay engrave"
   ii) Select all the shapes in Layer 3, excluding the outer border.
   iii) Create a new MOP using V-Engrave and set these computed inlay parameters:
      (1) Stock surface
      (2) Vee cutter angle
d) Inlay pocket:
   i) Create a new Part and name it "4-inlay pocket".
   ii) Select all the shapes in layer 4, including the outer border.
   iii) Create a new pocket MOP and set these computed inlay parameters:
      (1) Stock surface (set to 0.0)
      (2) Roughing clearance
      (3) Target depth
      (4) End mill diameter

In addition the Feed rate the spindle speed must be set to suit the material being machined, The best diameter for the end mill may be effected by the shapes being inlayed as this cutter needs to be able to get well into any sharp corners in the inlay shapes, so a small diameter end mill may be required.

4) **Machining**: The machining for the two substrate MOPS (1 & 2) should be done with the same setup (to maintain alignment), though the order it not critical. Similarly for the inlay MOPs.

5) **Finishing**: The inlay must be flipped over and glued into the substrate, taking care to align the two parts. It will need to be clamped until the glue cures. The excess inlay stock can be cut/machined away and the surface sanded.

Some Samples

For these samples I have used the same pattern for the top of a cheeseboard using both methods. The photos show snapshots of the steps involved in more or less the correct sequence. For a comparison of the outcomes in terms of the sharpness of the resulting inlay vertices the results can be seen in Figure 13 for pocket inlay and Figure 23 for V-carve inlay.

Pocket Inlay Example

The materials used for this sample were:

- Substrate: 19 mm Tasmanian Oak (Eucalyptus regnans/obliqua)
- Inlay: 5.5 mm Tasmanian Myrtle (Nothofagus cunninghamii)
- The inlay depth is 5 mm.
- A 3.175 mm diameter end mill was used for pocketing and profiling.

Figure 9: Machining the pockets in the substrate

Figure 10: Machining the profiles to cut out the inlay parts

Figure 11: Inlay parts glued into substrate

Figure 12: Finished surface after sanding

Figure 13: Close up of inlay vertices

V-carve Inlay Example

The materials used for this sample were:

- Substrate: 19 mm Jarrah (Eucalyptus marginata)
- Inlay: 12 mm Tasmanian Oak (Eucalyptus regnans/obliqua)
- The inlay depth is 4 mm.
- The Vee bit was 45º, and the pockets were cleared with a 3.175 mm end mill.

Figure 14: Cutting the V-Engrave MOP for the substrate

Figure 15: Clearing the substrate with the pocket MOP

Figure 16: The finished substrate

Figure 17: Cutting the V-Engrave MOP for the Inlay

Figure 18: Clearing the Inlay with a pocket MOP

Figure 19: The finished Inlay

Figure 20: The Inlay glued into the substrate

Figure 21: Clearing the top part of the inlay material.

Figure 22: The finished item

Figure 23: Close up of Inlay vertices

Summary

Both methods can produce quite good results within the framework outlined in Table 1. From experience, however, and in an attempt to provide some overview in three important areas:

- Effort and complexity:
    - The pocket inlay method is simpler, but requires some test machining to get an accurate set of cutting parameters for a good final fit.
    - The V-carve inlay requires very careful attention to detail and can be complex to manage, particularly if the inlay shapes are complex and relatively fine.
- Quality of outcome
    - The pocket inlay requires compromise on sharp vertices, though the effects can be minimised by using a smallest practical cutter diameter.
    - The V-carve technique can produce sharper vertices.
    - Inlays with narrow width sections are probably more easily handled with a pocket inlay, though this this will depend on wood characteristics.
- Robustness in use
    - Pocket inlays can be resurfaced many times (assuming the inlay materials is thick enough) with no loss of detail.
    - V-carve inlays with narrow sections of inlay may lose their shape (fine details) after any aggressive sanding.