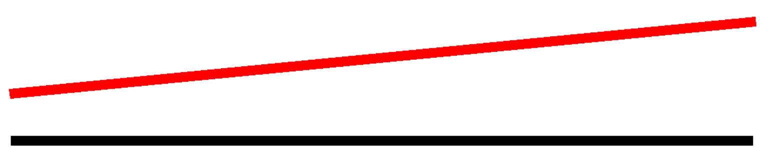
A Closer Look At Machining a Block Square, version 1

By R. G. Sparber

In this article I hope to explain in detail the error sources involved in machining a block square. However, you can always go a lot deeper into how a given machine works in order to find the exact root cause of each error.

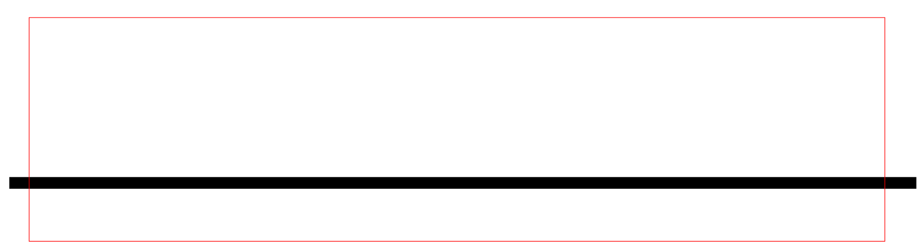
Types of Errors

There are two types of errors: time-invariant errors and time variant errors.



Time-invariant errors are deviations from ideal that do not change over time.

For example, say that I want to move a point back and forth along the lower line. This is my ideal path and there is no error. But the best I can do is move the line along the upper line. This path is both higher than the ideal path and on a slope. No matter how many times I move my point back and forth, it will always follow that upper line. This is an example of a time-invariant error.

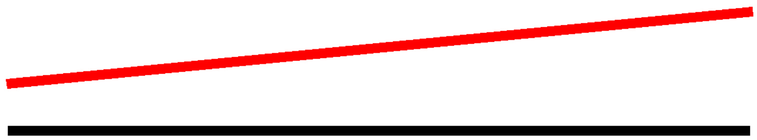


Time variant errors are deviations from ideal that do change over time.

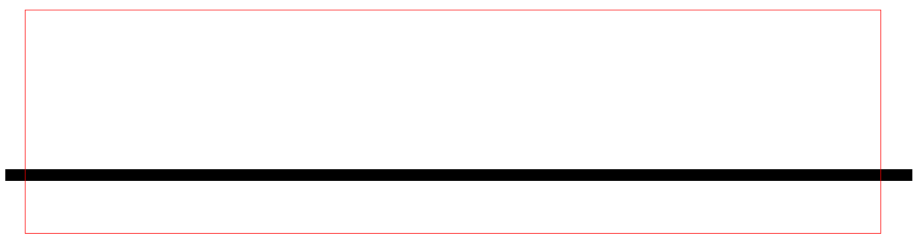
For example, say that my point moves randomly around inside the box. Sometimes it might move back and forth exactly on my ideal line but other times it might follow no predictable path. All I know is that it will stay inside the box.

[1] You are free to copy and distribute this document but not change it.

Error Correction



If we *only* have time-invariant errors, we can invent schemes for canceling this error. In the example given here, we could measure the point's position on the sloped line and subtract a correction value that will place it exactly on the ideal line.

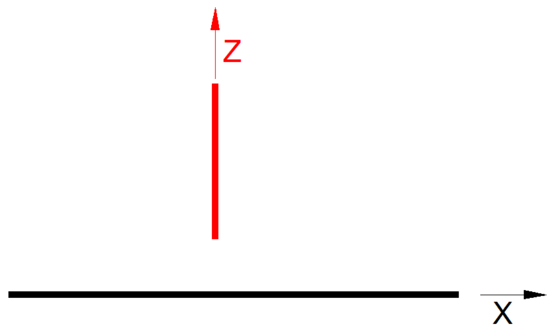


If we only have time variant errors, the best we can do is find ways to reduce it. There is no way to know what the error will be at a given moment so there is no way to cancel it.

A major source of such error is vibration. Picture a cutter randomly moving in response to the cutting force. Your best shot is to find ways to reduce this vibration so you reduce the resulting random cutter movement.

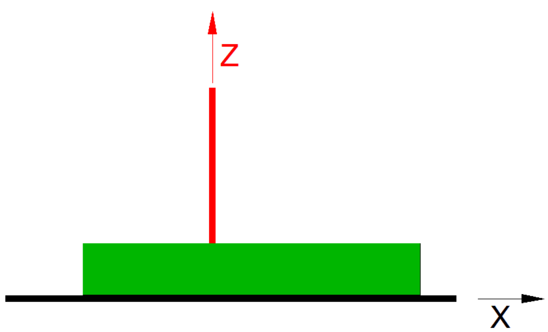
The Essence of a Two Dimensional Milling Machine

There is no need to deal with the complexity of three dimensions. Instead, let's consider an ideal two dimensional milling machine.

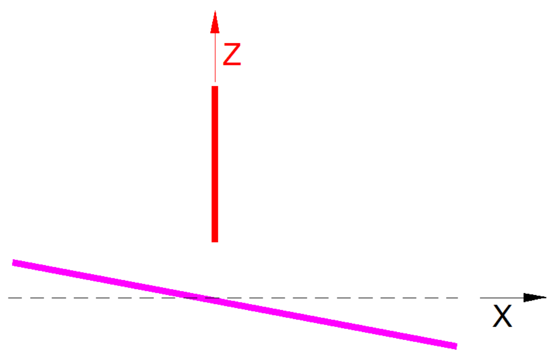


We have our mill table. It is parallel to the X axis and moves along it.

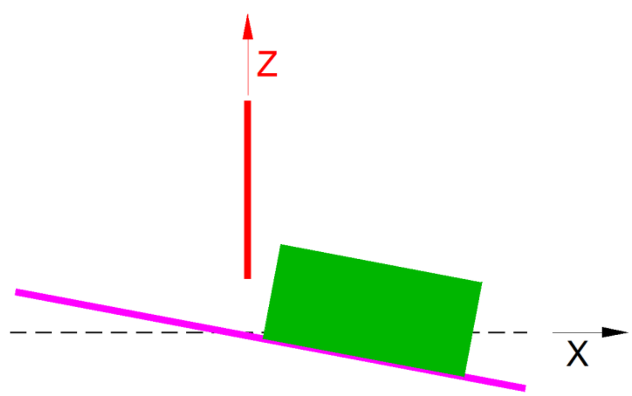
Exactly perpendicular to the mill table is my end mill aligned with the Z axis. The end mill can side mill any surface it touches leaving a perfectly vertical face. If the end mill cuts on the end, it will leave a surface parallel to the X axis.



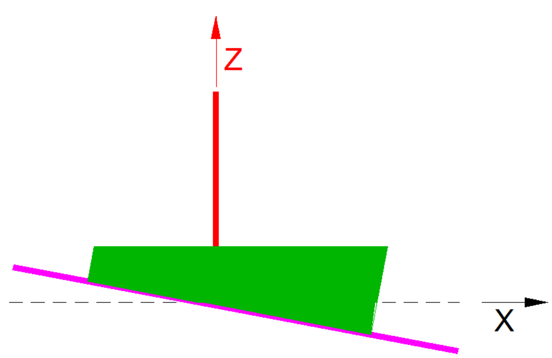
The green rectangle is a product of my ideal two dimensional milling machine. The top line was cut by the end of the end mill so is perfectly parallel to the X axis. The ends were side milled so are perfectly parallel to the Z axis.



Let's now move one step away from this ideal case. My mill table will still be perfectly flat but it is no longer parallel to the X axis. However, my end mill is still parallel to the Z axis and the end of the end mill is still parallel to the X axis. My table still moves parallel to the X axis.

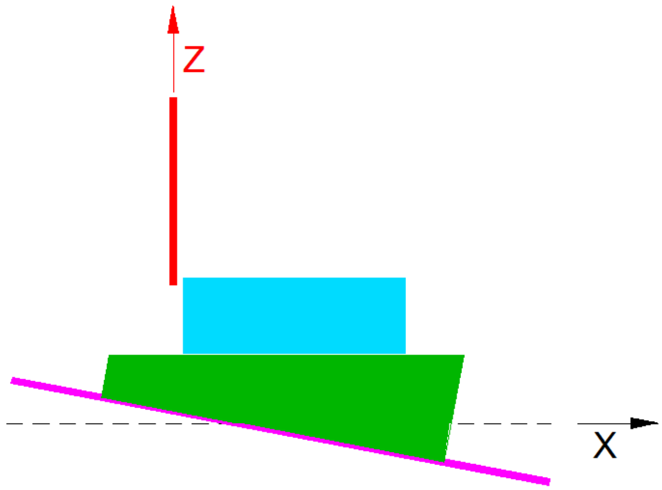


I put a work piece down on my mill table in preparation for milling.



As I move my table, the top of the work piece is cut off. Note that the top of the work piece has been cut parallel to the X axis while its height varies.

Look what I can do with this freshly cut line. It is parallel to the X axis even though my mill table is not. Why not use it as my ***new*** mill table surface?

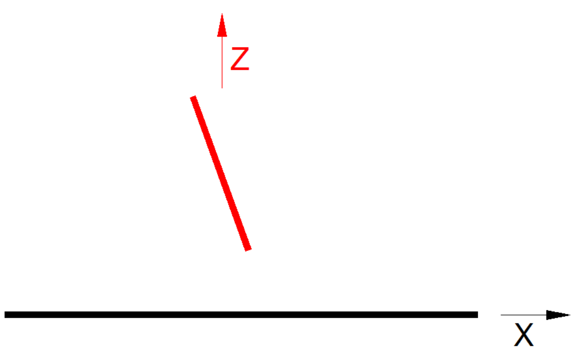


I plunk down a new work piece to cut. It is sitting on top of the green base that just had its top cut parallel to the X axis. Look familiar? It is the same as when we cut our first work piece on an ideal table.

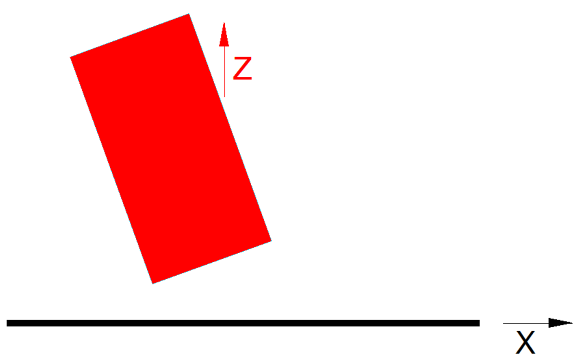
As long as we do not remove and re-install the green base, it will remain an ideal support parallel to the X axis.

What I just described is the central concept of soft jaws. We cut them in place and they align with one or more axes.

Now let's do this all again but with the cutter misaligned. This condition is commonly called being "out of tram".



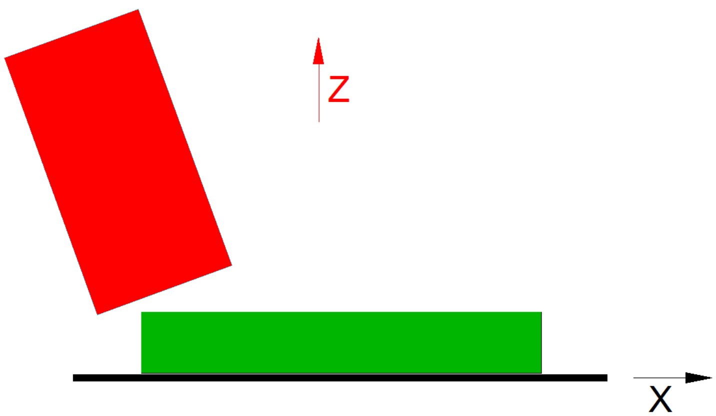
So you don't miss the error, I have shifted the mill head and therefore the end mill over by 20°.



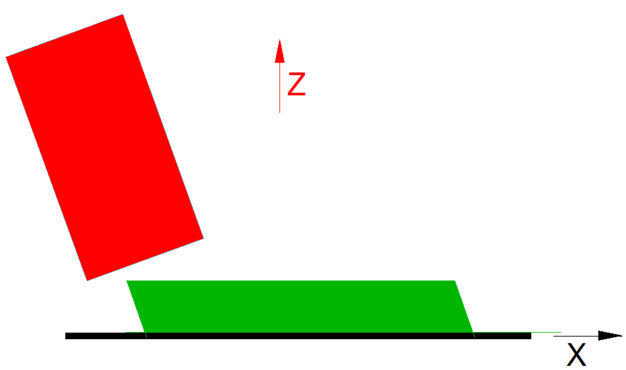
I don't want you to miss what happens at the end of the end mill so have made it wider.

This is one place where my two dimensional view is lacking. As the end mill moves across the surface of my work piece, it will cut a line.

But in three dimensions, you would see a dished out surface perpendicular to this line. The top ridges and the bottom of each dish do line up with the X axis. The surface finish suffers from this out of tram condition.



Back to our two dimensional view of the world. My end mill is not parallel to the Z axis but it still moves parallel to the X axis. As I cut the top of my green rectangle, I will still get a line parallel to the X axis. It doesn't matter that the end mill is off, I still get a line that is true.



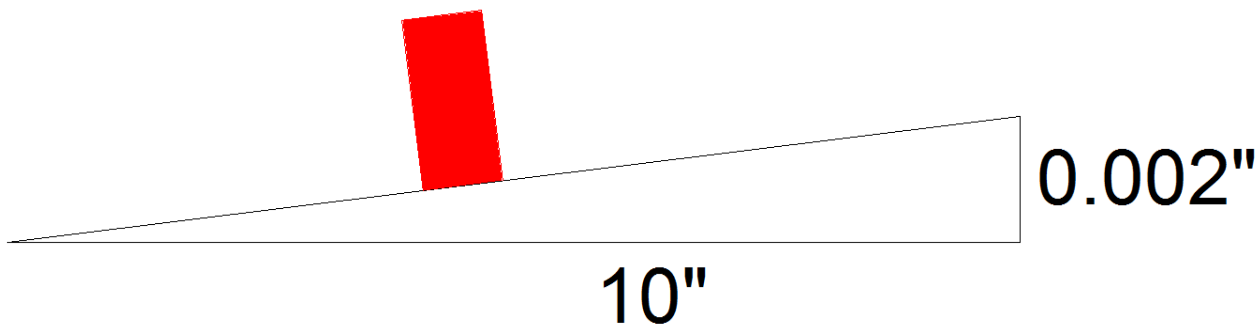
The place we run into trouble is when side milling. You can see the sides of my work piece are parallel to the end mill and not to the Z axis.

We started with a table that was perfectly aligned with the X axis and an end mill perfectly aligned with the Z axis. Then I tilted the table but still had it moving along the X axis. By first cutting a soft jaw, we were able to reestablish a surface parallel to the X axis and cancel this time-invariant error.

Then I tilted the end mill and showed how it still cut a line parallel to the X axis. However, when side milling we received the full error.

Before we leave the subject of a misaligned end mill, I want to put some numbers to it. More details can be found at http://rick.sparber.org/tram.pdf .

Say you tram your mill head and find a variation in the Dial Test indicator of 0.002" over a 10" circle along the X axis. This means the spindle is tilted at a slope off of true by 0.002" in 10".



The face cut by side milling will have this same error. If the face was 1" tall, the error would be 0.0002. Even if you were able to side mill using a 10" long end mill, the error due to being out of tram would only be 0.002". This assumes that the end mill would not be bending due to the force of side milling.

My point here is that as long as you can keep the head "reasonably" well trammed, this error is "small". On my little RF30 mill, my *time-variant* error is around 0.0002" so this tram error is hidden by the error I cannot control.

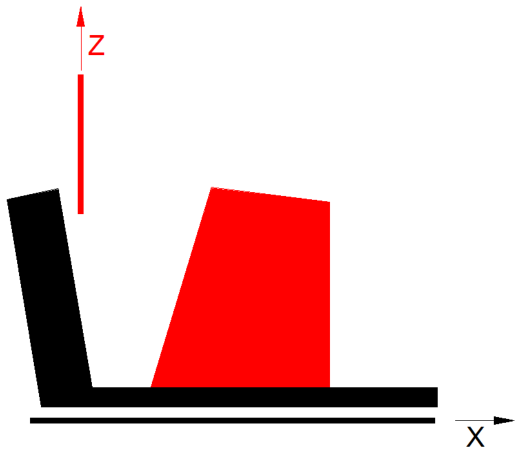
For the rest of this discussion, I will assume that my mill head is perfectly trammed and that the end mill is parallel to the Z axis.

I have drawn a two dimensional mill vise. The fixed jaw and vise ways are black. The movable jaw is red.

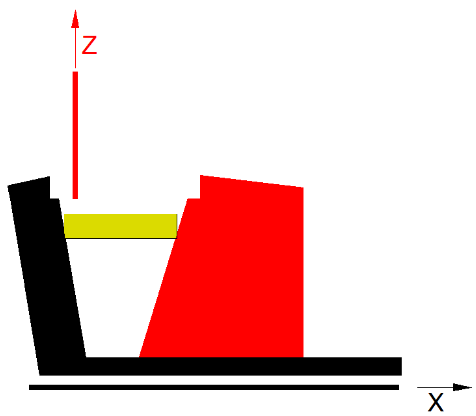
This is the ideal case so the vertical face of the fixed and movable jaws are perpendicular to the vise ways.

Contrast the above ideal vise with this sorry excuse. The fixed jaw and movable jaw are clearly not perpendicular to the vise ways.

However, these are time-invariant errors meaning that the vise is solid and does not distort over time. I should be able to cancel these errors. The standard approach that I use is the cutting of soft jaws.



I mount the vise on my ideal mill



and will cut my soft jaws. To do this I first clamp a piece of packing in the jaws so that the vertical parts of the steps about to be cut are approximately the same distance apart as when I clamp my work piece[2]. Then I lock my end mill's height above the vise ways. Since this is just a two dimensional view, cutting involves moving the end mill left and right to cut the two steps.

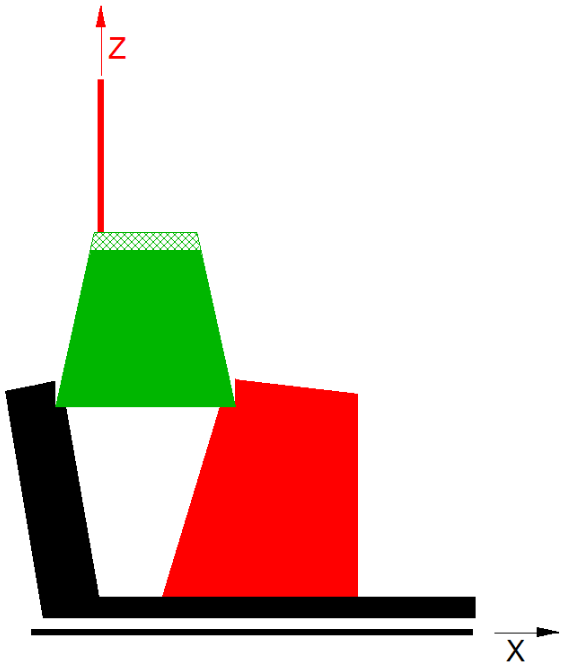
It is essential that all surfaces be absolutely clean. It is equally essential that all surfaces that are supposed to be in full contact have no gaps due to misalignment. This is especially true for the vertical surfaces that are small.

The two steps define a line that is perfectly parallel to the X axis. Each step need only be about 0.1" wide in order to support the work piece.

The vertical faces might be only 0.2" tall yet have plenty of holding power as long as the work piece has flat sides. For more holding power, place a strip of paper between the vertical faces and the work piece. This will fill in all of those microscopic gaps and greatly increase the holding power.

Note that it does not matter if the vise ways are parallel to the X axis. All that matters are those tiny steps cut by the end mill.

[2] See http://rick.sparber.org/Articles/sj/sj6.pdf for more details. Also see http://rick.sparber.org/Articles/ViseDef/ViDef.htm for how to verify your vise is sound.

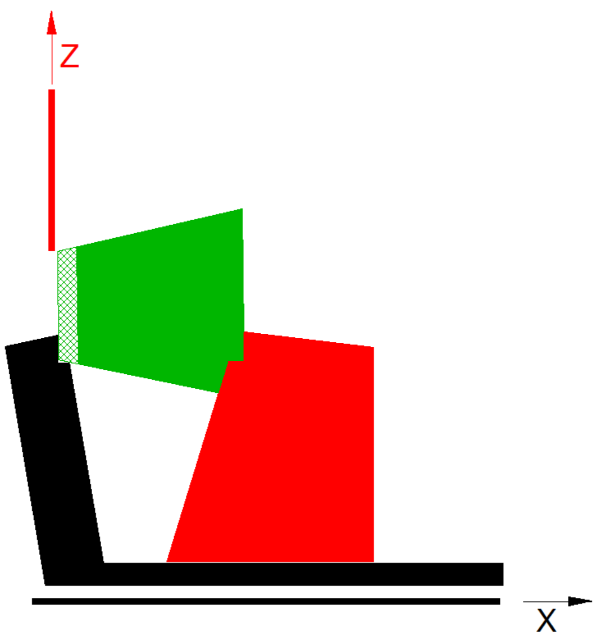


I have chosen a work piece with a flat bottom and flat but tapered sides.

The bottom makes good contact with the horizontal faces of my soft jaws so is parallel to the X axis.

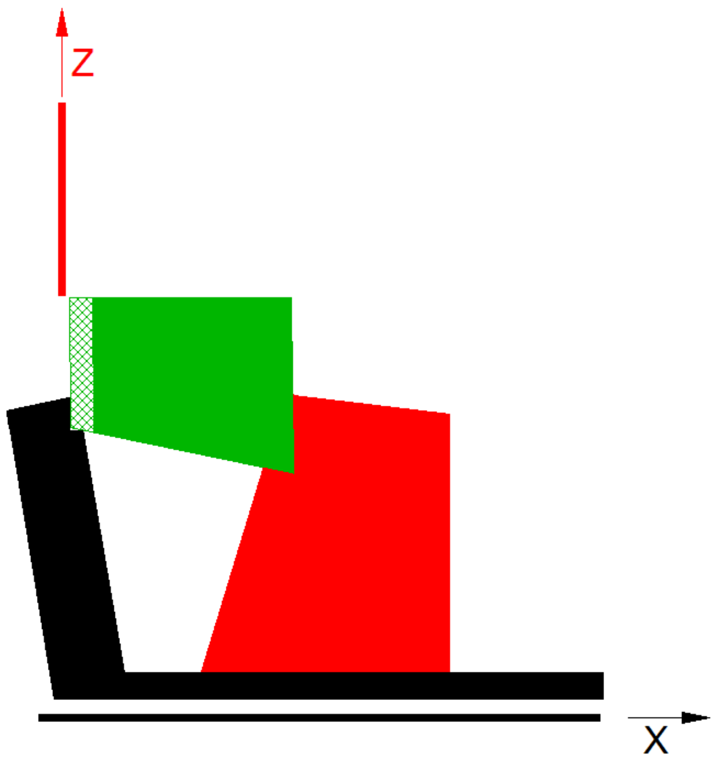
The work piece has been placed so the tapered sides angle away from the vertical faces of the soft jaws. In this way the clamping force will not try to squeeze the block up and out of the vise.

I applied a cross hatched pattern near the top of the work piece so you can track it for the remainder of the process. Thanks to Matthew TINKER for suggesting this way to track the cuts.



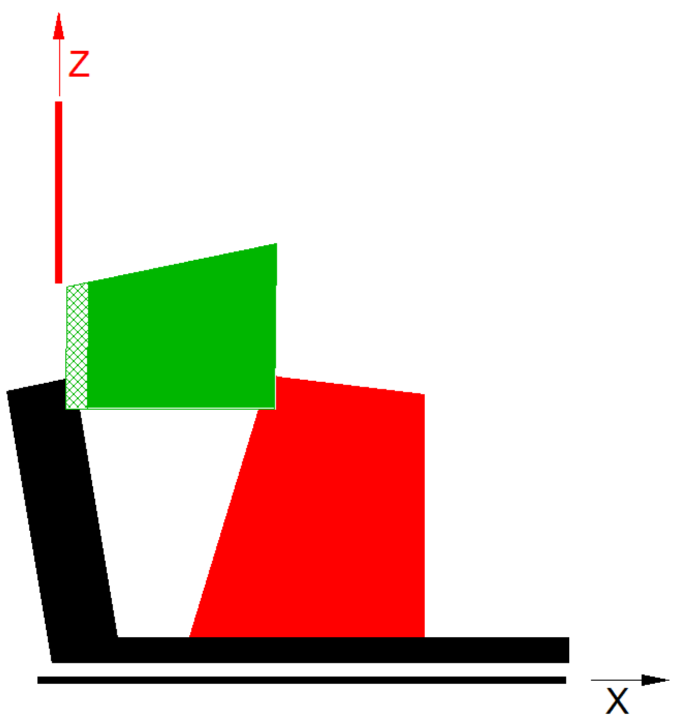
My desire to make the defects in the work piece obvious have caused me a problem in this next drawing. Notice that the movable jaw's step is unable to accept the corresponding corner of the block. Given a work piece that is far closer to square from the start, this would not be a problem.

The key thing to see here is that the cross hatched face and its opposite face are parallel and are perfectly aligned with the vertical parts of the soft jaw. The bottom surface is not in contact with the horizontal parts of the soft jaws.



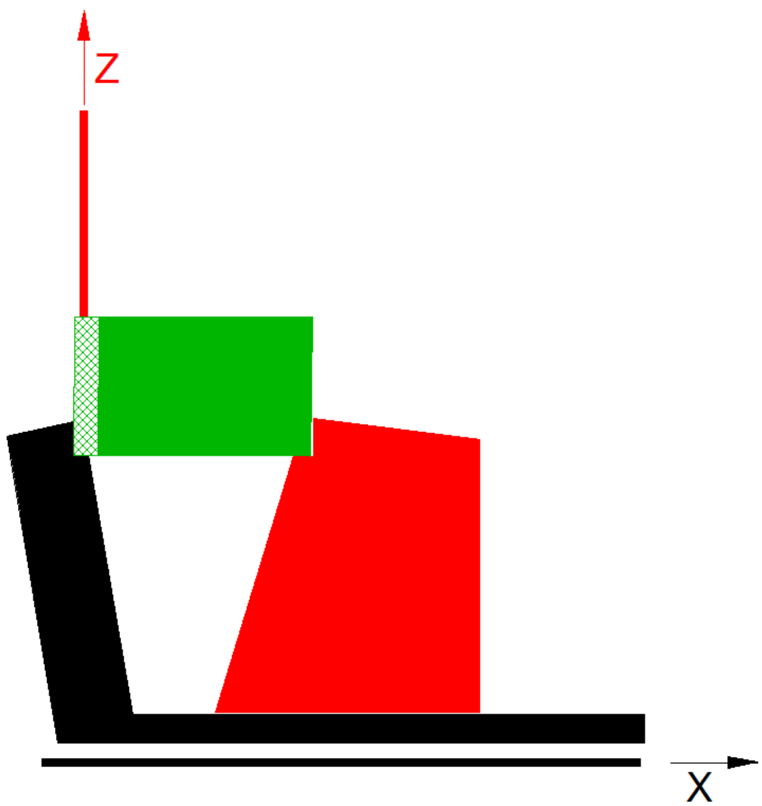
When I make my cut, I will get the top edge parallel to the X axis and perpendicular to the cross hatched edge.

Given the present shape of the work piece, I would not want to put the cross hatched edge down on my soft jaw steps. Doing so would put a tapered edge in the vise such that the vise pressure would tend to squeeze it out. So instead, I will flip the block over.



When I cut this top edge, it will be parallel to the X axis and perpendicular to the Z axis.

It will also be parallel to the bottom edge of the work piece and perpendicular to the cross hatched edge.



With the top edge cut, I now have a work piece cut on 3 sides. Each side is perpendicular to its neighbor. The 4th side is our reference and was already straight so did not need cutting.

In the past, I have always blindly cut the faces in sequential order. Now that I look at it in more detail, I see that the order should depend on the taper of the work piece. In all cases I want the taper to be such that the force of the vise does not push the block up.

With all four sides cut square, the next challenge is to cut the ends perpendicular to these four sides. There are a few ways to do this:

1. With the block as set above, side mill the first end. Then put the work piece on end in the soft jaws and lightly cut the opposite end. Then go back to the first end and finish cut it if you want to remove any error due to tramming.
2. Put the work piece in a precision V block. This will align two of our four sides perpendicular to the XY plane. Then clamp in the vise and lightly cut the end. With one end true, turn it over and cut the second end in the soft jaws.
3. Use the method detailed in http://rick.sparber.org/sbed.pdf starting on page 6.
4. Or you could set the end facing up and use a square on the vise ways to set it true.

I'm sure there are many more ways to do this.

Acknowledgements

I must thank Paul Alciatore for challenging my old thinking on this subject. I want to also thank Matthew TINKER for showing me how effective it is to make a unique pattern on one edge of the block during the machining steps.

These generous people again demonstrate that "all of us are smarter than any one of us".

I welcome your comments and questions.

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