The Power of FIVE

The Definitive Guide to 5-Axis Machining

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Foreword

If you've spent any amount of time in manufacturing, you know that efficiency matters. While saving a couple of seconds in cycle time can significantly increase efficiency in a high production manufacturing environment where thousands of parts are produced for one job, minimizing setup time is the key to increasing efficiency in job shops that manufacture small numbers of parts for multiple jobs each day.

Mike Cope, the author of this book, was co-owner of a job shop before he joined Hurco. As a machinist and applications engineer, he always evaluates the most efficient way to approach a part to minimize setup time and reduce cycle time. It's just part of his DNA. That's precisely why he is such a proponent of 5-axis. It is the most efficient way to instantly increase your profit margin on existing jobs that you manufacture on a conventional 3-axis machine. One of our customers compared the adoption of 5-axis processes to the transition from manual machining to CNC. He said bluntly, "If you're not doing this [5-sided machining on a 5-axis CNC], you're going to get left behind."

Mike's enthusiasm for 5-axis machining and Hurco's commitment to 5-axis merged 10 years ago. Hurco wanted to focus research and development (engineering resources) on technologies that would make the company's core customer (job shops) more successful. Due to Mike's real world experience as a shop owner, machinist, and applications engineer, his input to the features we develop and ability to explain the benefits to machinists are indispensable.

In addition to helping Hurco customers and distributor sales people in the field, Mike has shared his 5-axis expertise at numerous manufacturing events around the world. In fact, the impetus for this book was yet another event where he agreed to speak about 5-axis technology. Reviewing past presentations and doing some research online to make sure his information was up to date, he realized there weren't any books that provided a comprehensive view of 5-axis from the standpoint of a machinist. There are books aimed at engineers or books that discuss tool paths and CAD/CAM systems, but they were either highly technical or a bit outdated. Additionally, we noticed his post “5-axis…it just ain’t that scary” on the CNC Machinist Blog (blog.hurco.com) was the most popular.

While this book was backed by Hurco, our company supported Mike and the team in writing a book that would be relevant and helpful to all machinists. Our hope is that this book will give you useful information no matter your experience level and you’ll see there is no reason to fear 5-axis…it just ain’t that scary!

Maggie Smith
Marketing Manager
Hurco Companies, Inc.

Why 5-axis

In today's industry of modern manufacturing, shops are faced with many daily challenges. Among these challenges are efficiency, flexibility, and adaptability. Although traditional manufacturing processes certainly allow shops to address these challenges, there are more advanced technologies - like 5-axis machining – that will help streamline processes and help propel these shops to the next level of both performance and profitability.

The argument I usually hear from people in traditional 3-axis shops, against the need for a 5-axis machine is: "We don't do that kind of work." Usually when someone hears the term "5-axis" they immediately envision an impeller or complicated aerospace part. Although there is definitely a market and need for that type of high-tech "5-axis" machining, the lion's share of the work that is driving shops to buy 5-axis machines is what we refer to as 5-sided or 3+2 machining or positional 5-axis…which is machining simple geometries on multiple sides of the same part. To stay competitive, even these traditional 3-axis shops should be considering modern 5-axis technology to increase profitability.

Traditional processing usually means performing several different operations on standard 3-axis milling machines to complete one single part – which also means several individual time consuming setups for each side of the part. Not only is this an inefficient way to process parts, it can also affect both accuracy and throughput. Each time a part is placed against a vise stop, there is the potential that it can be misloaded or mispositioned, which means the finished part might not be dimensionally correct. Also, imagine if a mistake is made during the second of six operations, but isn't caught until the fourth operation. Often there is no way to recover from that kind of disaster, and all of the parts must be scrapped. Costing both time and money…neither of which is ever at a premium.

In addition to becoming more efficient in processing the actual parts, becoming more flexible and adaptable is equally as important. Since the adaptation of JIT (Just-In-Time) manufacturing – an inventory strategy that means companies will wait and order goods only as needed, thereby reducing inventory costs – shops are being forced to adapt with a much faster turnaround time. Because orders are being placed later, and delivery times are sooner, shops must find technology that allows them flexibility. Also, as if all of this wasn't enough, and just to add another level of insanity to an already challenging problem, we throw in the altered schedules. Needs change for all of us, and our customers are no different. As their needs change – sometimes daily – shops must be able to adapt quickly to those changes to survive. With traditional means of processing, the challenge to adapt quickly might be the most difficult to overcome. When you are in the middle of a multi-process setup, and your customer needs you to teardown to run the new parts that he desperately needs, it becomes very difficult to adapt and still make a profit…although, they say that any job worth doing is worth doing twice, so why should inefficient and unnecessary setups be any different!

5-Axis technology is one way to address all of the challenges that we have outlined. Not only will it reduce the number of setups necessary to produce a multi-sided part, but it will also provide the flexibility to adapt to the changes brought about by our customers' changing needs. Not to mention, because all sides of the part are processed from one single setup, accuracy is improved as well. The positive effect that 5-axis technology can have on the bottom line for any shop, especially smaller shops with fewer individuals, just can't be overstated.

Getting Started with Machine Configurations

Before we dive into the ins-and-outs of this technology, let's begin with the basics. I often hear even seasoned sales professionals misspeak when they are describing the different machine configurations, so I think this is something that we need to address before moving on any further.

Obviously, 5-axis machines have two additional axes than a traditional 3-axis machine. One of these axes is a tilting axis, which has tilting limitations in either one or both axis directions. The other is a rotary axis that can spin a full 360 degrees without limitation. Combined, these two additional axes will allow the part to be tilted and rotated into any necessary orientation for machining. In the case of simultaneous machining, the motion can be performed in an ever-moving fluid type of motion. In the case of 5-sided (3+2) machining, both axes can be clamped into position to hold the part for machining.

When determining the configuration of the machine, we first need to determine what letter association (A, B, or C) will coincide with each axis. If we look at the three linear axes in alphabetical order (X, Y, and Z), we can also think about the additional axes in alphabetical order as well. The A-axis always rotates around the X-axis, the B-axis always rotates around the Y-axis, and the C-axis always rotates around the Z-axis (Fig. 1).

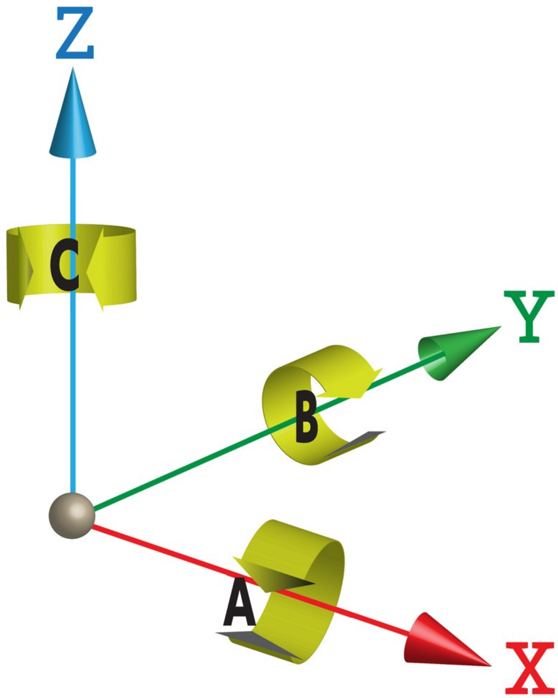

Figure 1

Now we can begin to discuss the actual combinations of these axes and how they affect the different configurations available. Trunnion machines for example, are usually in an A/C configuration (Fig. 2). This means that there is an A-axis that tilts around the X-axis, and a C-axis that rotates around the Z-axis. You will sometimes hear this type of configuration referred to as a “Table-Table” design because both the A-axis and C-axis are built into the table of the machine itself.

Figure 2

In addition to the A/C trunnion, there is a B/C configuration available, which is also referred to as a “Table-Table” style machine (Fig. 3). With the B/C trunnion machine, the B-axis tilts around the Y-axis of the machine and the C-axis rotates around the Z-axis.

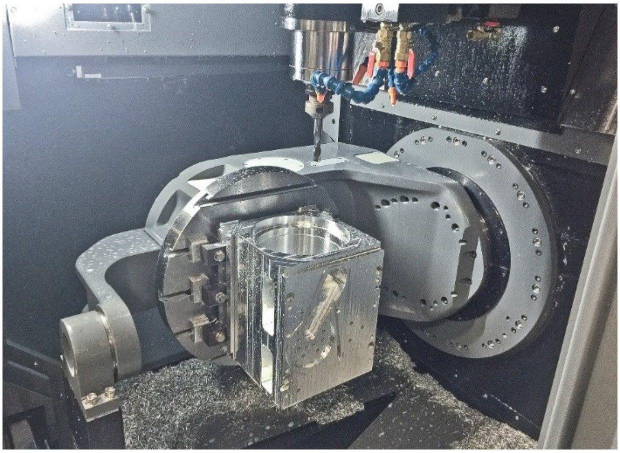

Figure 3

Another popular B/C configuration is a “Head-Table” design (Fig. 4). In this configuration, one of the axes is located on the head of the machine and the other is attached to the table. With this B/C machine the B-axis tilts around the Y-axis of the machine, and the

C-axis rotates around the Z-axis. There are also Head-Head versions of the B/C configuration where both axes are located on the head of the machine (Fig. 5). Often times this Head-Head design is present on larger machines where other configurations would not be as effective.

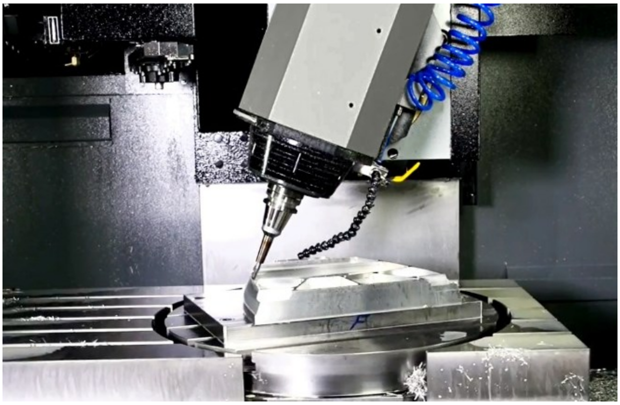

Figure 4

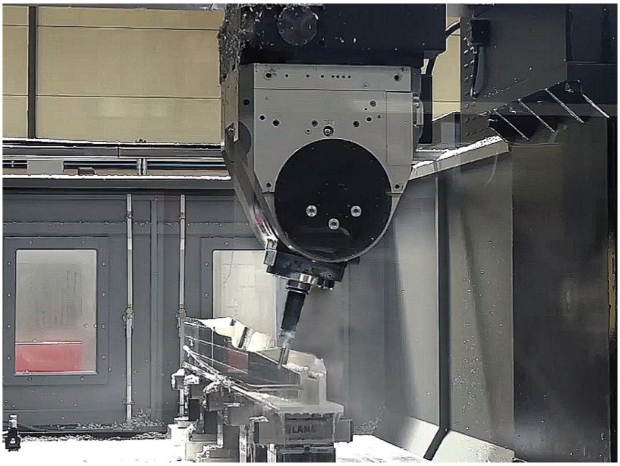

Figure 5

Of course, just like anything else that we learn, there are times when the answer to the question of which configuration is which, the answer just might be: “Well, it depends.” Although that sounds a little funny, it is true. For example: if the add-on trunnion table (Fig. 6) is installed on a vertical machining center with the tilting axis aligned along the X-axis and the rotating axis positioned so that its home position is pointing straight up towards the spindle, the configuration would be an A/C. However, if you turned the same table 90 degrees so the tilting axis was aligned along the Y-axis of the machine, it would now be a B/C configuration. The same thing can be said for a Head-Head design. The direction in which each of the axes is aligned when the machine is at the home position determines the configuration.

Figure 6

There are several reasons why each configuration is better suited for certain types of work, and we will get into the details in another chapter. For now I just wanted to clarify the axes and the possible combinations of machine configurations so you can walk up to any 5-axis machine and see the difference between them.

Machine Configurations - the pros & cons of design

Regardless of a particular OEM machine builder, there are several common machine configurations for 5-axis that are available - and each one has its own set of strengths that make it stand out among the choices.

One of the most common configurations – or at least the one most people identify with when they hear the term “5-axis machine” – is the trunnion table machine. The trunnion configuration can also be referred to as a Table-Table configuration (Fig. 7) because both rotary axes are contained in the trunnion table itself, and the head is always stationary.

Figure 7

Most operators and programmers can easily identify with this setup because it is a simple process progression from standard 3-axis machining. Since the two rotary axes are often only used to simply locate the workpiece into a desired orientation, it is easy to visualize how the machine will position and behave during machining.

Often, the trunnion machine will offer better undercut capabilities than other machine configurations because the table can tilt farther (at least in one direction) than the swivel head designs (110 degrees in the example machine pictured in Fig. 7), which provides more access to the underside of a workpiece. The trunnion configuration can also give the operator a larger overall usable work volume because the table simply tilts and locks into position, which gives the XYZ axes their full range of travel. In a swivel head machine design, some of the overall work envelope must be utilized to accommodate the length of the tool as the head tilts back and forth. This scenario can be magnified when machining with longer tools, which can impact the overall work envelope tremendously.

The trunnion style of machine can also be a better choice for heavy metal removal. Due to the fact the head doesn't articulate, therefore allowing the use of geared or belt driven spindles, this machine type will usually offer more torque at lower RPMs. This stationary head design will also eliminate the possibility of pushing the head out of position while machining, which can sometimes happen on swivel head machines during extremely heavy cuts.

The next machine configuration we should discuss is the swivel, or articulating head machine. This type of machine can be either a Head-Head configuration, where all rotations are completed by the head, and the table is stationary; or the Head-Table configuration that consists of a tilting head and a rotating table (see the Hurco VMX42SRTi machine pictured (Fig. 8), which is a Head-Table design).

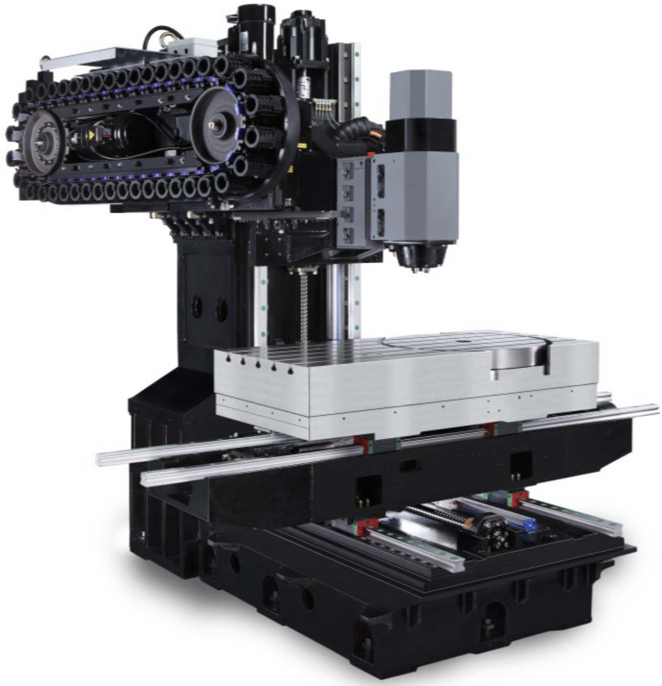

Figure 8

This Head-Head or Head-Table design allows you to machine much heavier parts than the trunnion design. Since the table doesn’t tilt, the entire weight of the part is transferred directly down through the base of the machine and onto the floor, making this a very rigid setup for larger parts. Also, the design of the table itself – in contrast to the trunnion style machine – allows for larger parts regardless of weight because the trunnion is limited by the size of the part that can be placed between the table risers.

Furthermore, as we mentioned in a previous section, the rotating head allows for the use of shorter or more standard length tooling when machining because all rotations of the tool happen above the part. On a traditional A/C trunnion style machine, the spindle has to reach out over the tilting table and the closer the table tilts toward 90 degrees, the more the spindle has to reach. This will often cause the operator to use longer than desired tooling to accommodate for this scenario (Fig. 9). This also means that when purchasing an A/C trunnion style machine, you really need to think about the size of the work you will be running on the machine, and size it accordingly (i.e., the smaller the work, the smaller the machine). However, this limitation isn't present on the B/C style trunnion machine because the table tilts left and right (B-axis), which means the tool can simply position on either side of the rotated table and never needs to reach out over it from behind (Fig. 10).

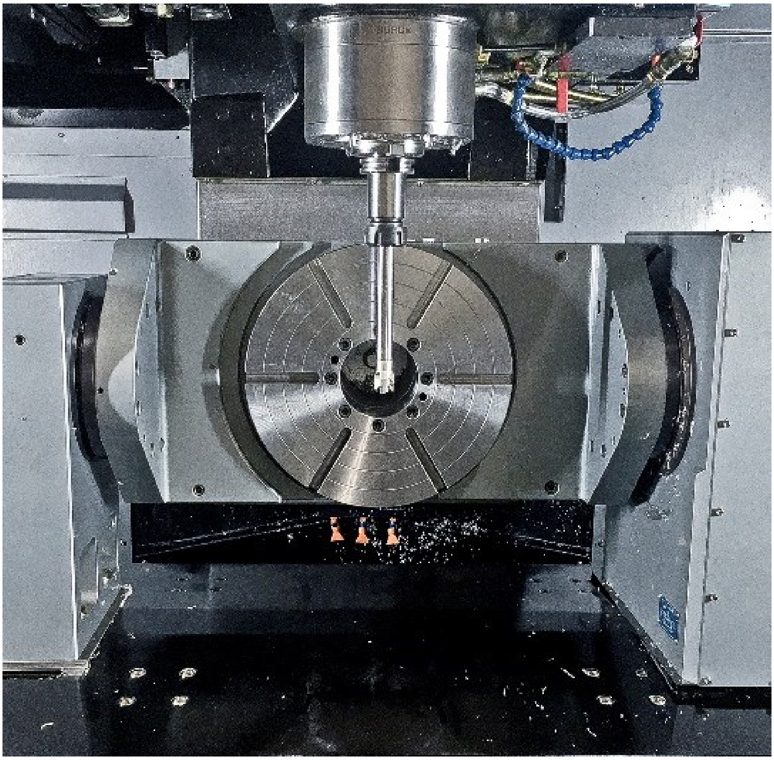

Figure 9

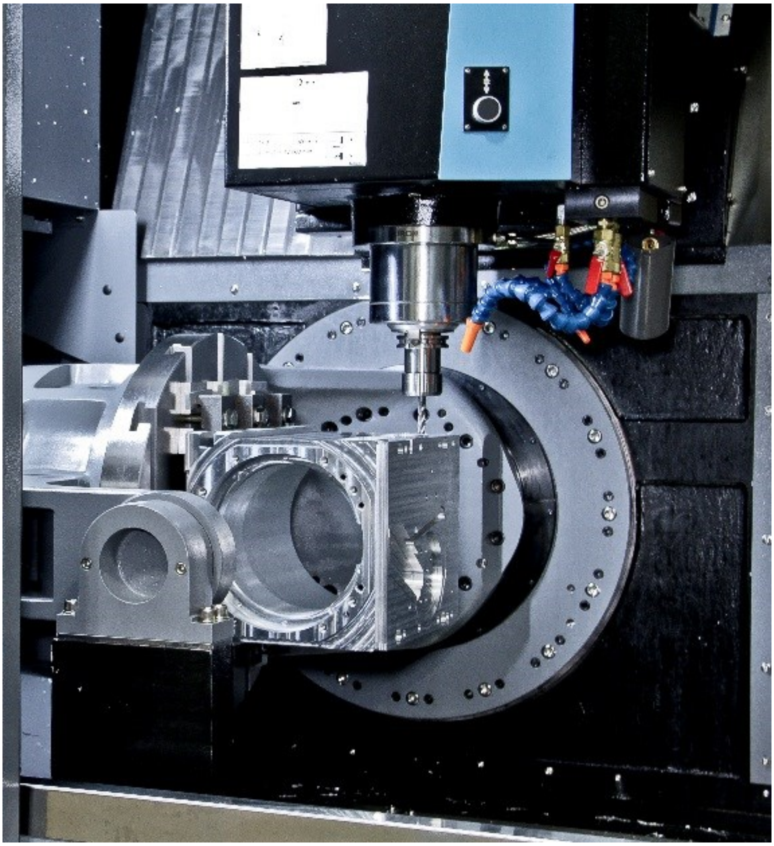

Figure 10

As you can see by the VMX42SRTi (Fig. 11), the Head-Table design can be more versatile than a trunnion or Head-Head type of configuration. In addition to 5-axis work, the entire table can be utilized for multiple vise setups, for plate work, or for machining the 6th side of the part (in preparation for a 5-axis setup) when machining in 3-axis mode. With the head tilted to 90 degrees, a tombstone can be utilized on the C-axis table to simulate a horizontal machine setup for better chip control or to allow for more parts to be machined in one setup.

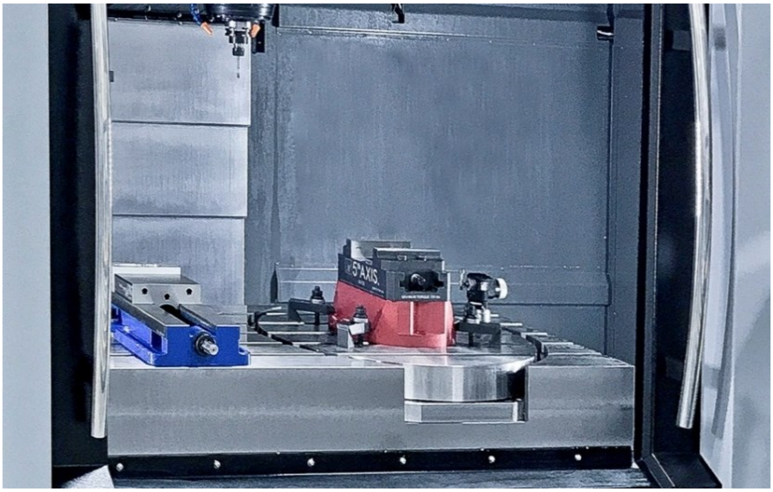

Figure 11

In addition to the dedicated 5-axis machine configurations discussed earlier, there are also a large number of “add-on” 5-axis tables available that can be attached to existing 3-axis machines for increased productivity. Although somewhat limited in the size of work that can be run, these add-ons can be a fantastic way to improve efficiency. Most controls, like the Hurco WinMax control, can be adapted very easily to accept these add-on 5-axis tables. However, when you’re adding a table to an existing machine, you definitely need to consider the age of the control technology on the machine, and whether it is worth the substantial investment that usually accompanies these tables.

Direction or Rotation: the right-hand rule

There is often confusion about which direction is a positive move, and which direction is a negative move in machining – particularly when it comes to rotary axes. We also hear terms such as: the right-hand rule, ISO standard vs. Non-ISO standard. In this section I will try to explain these terms, and hopefully give you a better understanding of their meaning.

Before we get started, I would like to offer a tip that makes this process much simpler. If you always envision the tool moving, and NOT the axes of the machine moving, you will never go wrong. Not only for linear XYZ movements, but also rotary movements. This concept will also help you transition between a standard 3-axis machine where the table moves and the tool is always stationary and a traveling column machine where the column moves and the tool moves with it. If you train yourself to think about the individual axis of the machine moving instead of the tool, then the positive and negative movements of the X and Y axes will be opposite on these two machine configurations. For example: a positive X-axis movement of the tool on the traditional 3-axis means the table moves to the left. However, a positive movement of the tool on the traveling column machine means the tool (column) will move to the right. But if you think about the tool moving, they will both be identical, and transitioning between machine configurations won't be confusing.

The term right-hand rule applies to a method of determining the positive direction of travel – for a particular axis – using your right hand to illustrate the coordinate system. This method will also determine the positive axis direction for an ISO standard rotation or movement. ISO is an acronym for the International Organization for Standardization – an organization that provides a standardization (ISO 841:2001) to maintain consistency between different builders. The term Non-ISO obviously refers to rotations that are exactly the opposite of ISO standard.

To apply the right hand rule (Fig. 12), hold your right hand in a manner in which your hand is lying flat, and your palm is pointing upward. Now extend your index finger and thumb, and point your social finger (middle finger) straight upward. With your remaining two fingers curled as if making a fist, your three extended fingers are now pointing in a positive direction for the X, Y, and Z axes.

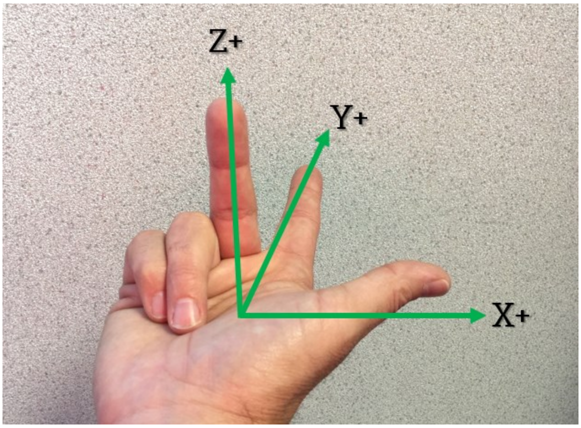

Figure 12

For rotary movements we can also use the right hand rule…and our right hand (Fig. 13). To determine the direction of an A-axis rotation (around the X-axis), with your hand opened, and your palm facing upwards, point your thumb along the positive direction of the X-axis. Now curl your fingers from an open to a closed state…the direction your fingers are curling depicts a positive rotation direction of the tool in the A-axis.

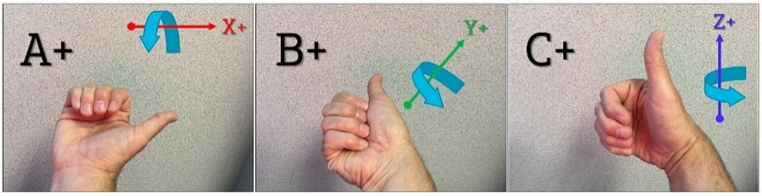

Figure 13

The same process can be used for any rotary axis. For the B-axis, lay your thumb along the positive direction of the Y-axis, and your curling fingers simulate a B-axis positive rotation of the tool. For the C-axis, point your thumb straight up in the Z-axis positive direction, and your curling fingers simulate the positive movement of the tool around the C-axis.

Regardless of builder, and regardless of machine configuration, this handy (pun intended) right hand rule will help you when programming the tool, jogging the machine axes, or deciding which way to move an offset to bring in the dimensions of a workpiece.

The Benefits of 5-axis

The most obvious benefit of the adaptation of 5-axis technology is that a part can be manufactured in one setup, or at least in far less setup operations than a traditional 3-axis process. However, there are other benefits as well.

With 5-axis machines, you can machine very complex parts from a single solid billet of material. Therefore, in shops where small batches of parts are required (such as prototype or research and development manufacturing), machining from a billet eliminates the need to create castings for this type of work. A large billet can be loaded into the machine, and the entire finished part can be created without the additional cost of production for these small runs.

5-axis technology can also help with things as simple as fixturing parts; especially for short run jobs with fewer quantities. Instead of designing and manufacturing an elaborate fixture that might not get used again, simply clamp the part in a standard machine vise and use the two additional axes to position the part. This can help speed the setup process tremendously, and can reduce the amount of unnecessary or otherwise useless fixtures lying around the shop. It can also help reduce manufacturing costs by eliminating the need to purchase additional fixturing components like clamps and toggles as well as the eliminating the need to purchase additional tooling and material to machine the fixture. All of these things can be expensive, and increase the cost of production, therefore making these shops less competitive in the marketplace.

Although the following technique is most often reserved for advanced part processing and 5-axis simultaneous programming, another benefit of 5-axis technology is the ability to use shorter, more standardized length tooling when machining deep cavities or taller part features (Fig. 14). Since you can always keep the tool tilted away from the contact point on the part, the spindle nose is able to get closer to the work, which lets you use shorter tooling. In a standard 3-axis machine, to machine the bottom of a deep cavity, for example, the tool must stick out of the holder more than the depth of the cavity to reach the bottom. However, if you can tilt the part or tool to allow more clearance, you can then cut the same feature with a much shorter tool. This will increase rigidity, allowing for a faster feedrate, deeper depth of cut on each pass, and an overall improvement in surface finish quality – while also helping to decrease cycle times. The more the length to diameter ratio is increased when machining, the more problems you must overcome. Therefore, the ability granted by the adaptation of 5-axis technology for this type of work is very beneficial.

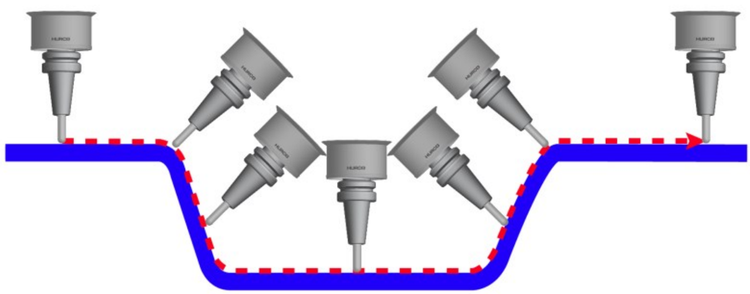

Figure 14

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