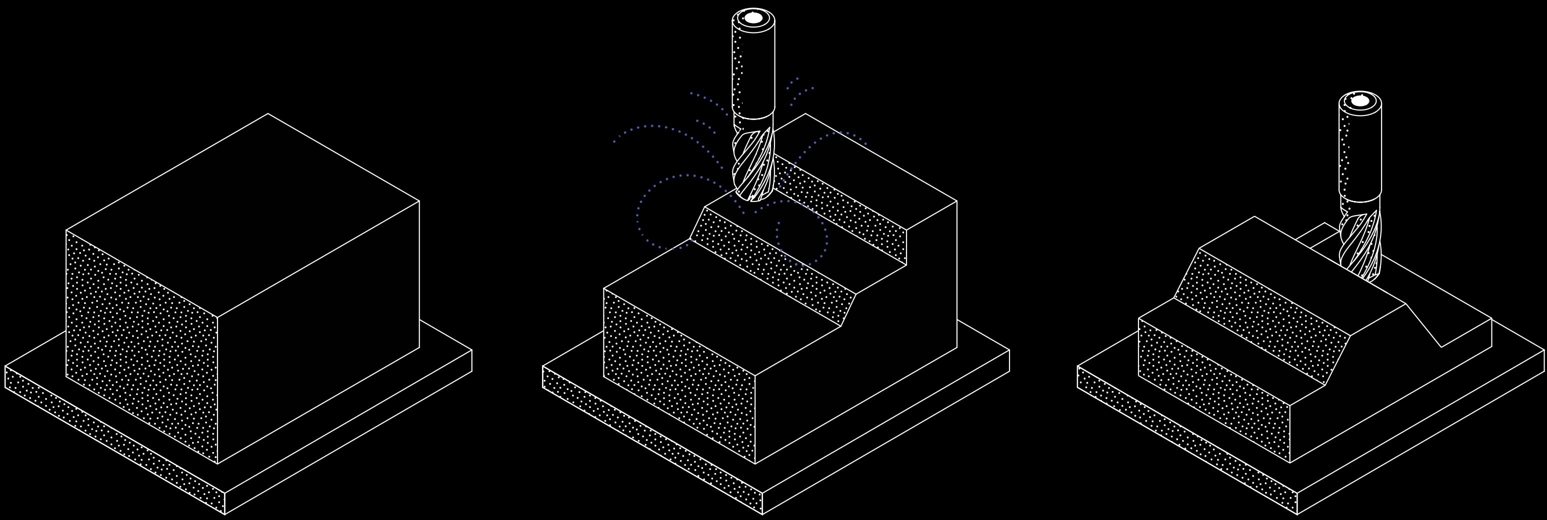

CNC machining: The complete engineering guide

Learn all you need to know about CNC machining in 25 minutes or less. Whether you're an experienced design engineer or just getting started with CNC, this guide is for you.

3D HUBS

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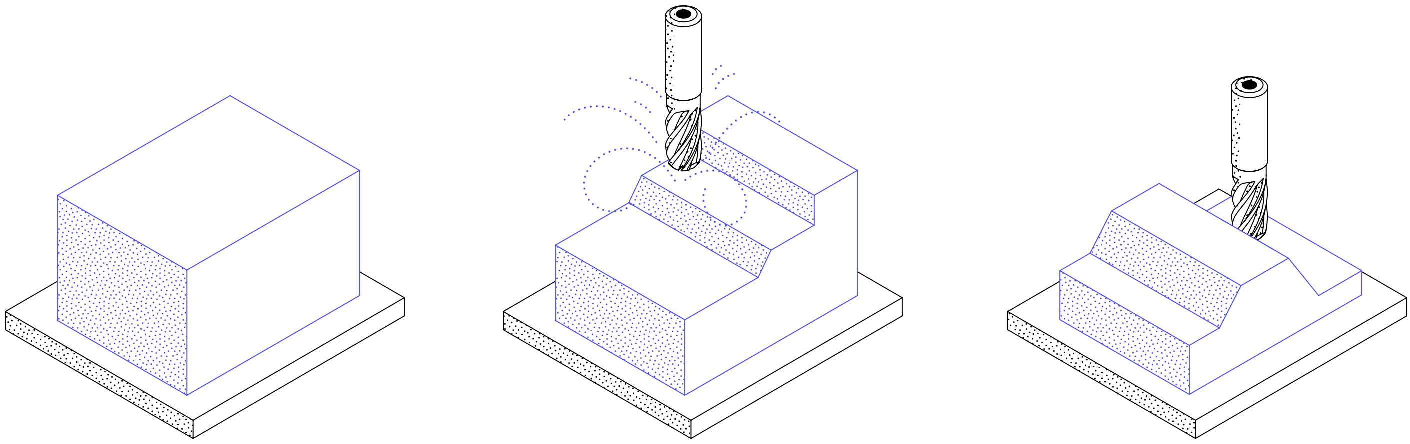
Part 1

The basics

What is CNC machining? What are the different types of CNC machines? How do they work? In this section, we answer all these questions and compare CNC machining to other manufacturing technologies to help you find the best solution for your application.

What is CNC machining?

CNC (Computer Numerical Control) machining is a subtractive manufacturing technology: parts are created by removing material from a solid block (called the blank or the workpiece) using a variety of cutting tools.



This is a fundamentally different way of manufacturing compared to additive (3D printing) or formative (injection molding) technologies. The material removal mechanisms have significant implications on the benefits, limitations and design restrictions of CNC.

CNC machining is a digital manufacturing technology: it produces high-accuracy parts with excellent physical properties directly from a CAD file.

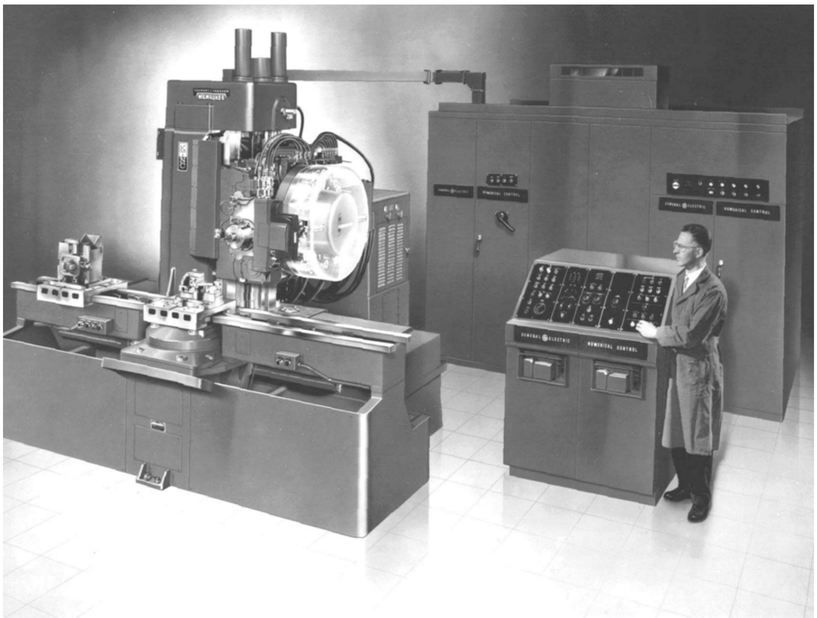
Due to the high level of automation, CNC is price-competitive for both one-off custom parts and medium-volume productions.

Almost every material can be CNC machined. The most common examples include metals (aluminum and steel alloys, brass etc.) and plastics (ABS, Delrin, Nylon etc.). Foam, composites and wood can also be machined.

The basic CNC process can be broken down into 3 steps. The engineer first designs the CAD model of the part. The machinists then turn the CAD file into a CNC program (G-code) and set up the machine.

Finally, the CNC system executes all machining operations with little supervision, removing material and creating the part.

A brief history of CNC machining



> The earliest machined object ever discovered was a bowl found in Italy and made in 700 B.C. using a lathe.

> Attempts to automate machining started in the 18th century. These machines were purely mechanical and powered by steam.

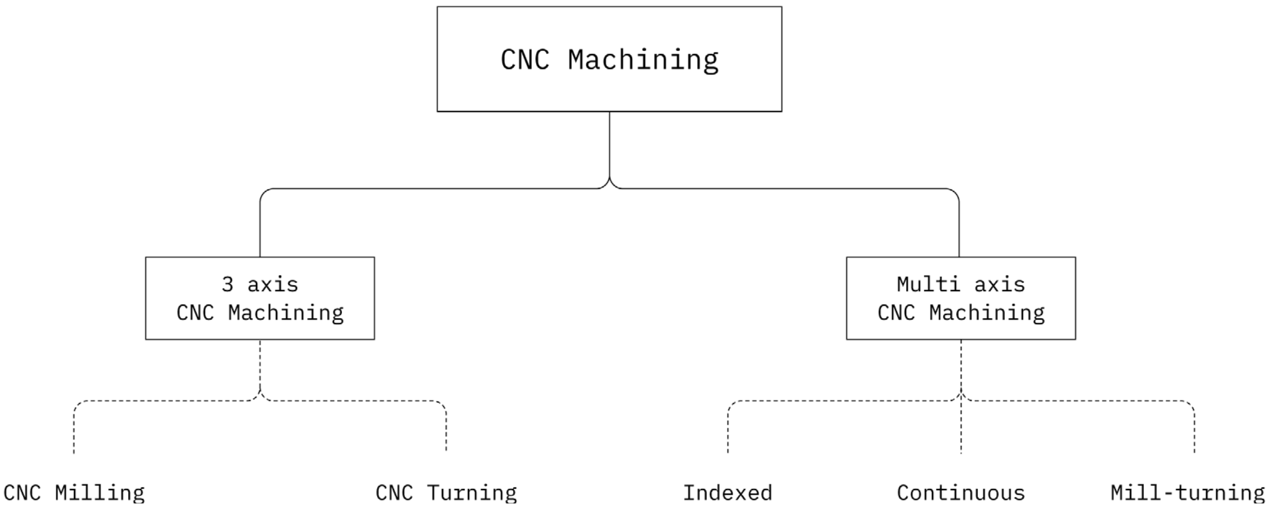
> The first programmable machine was developed in the late 40s in MIT. It used punched cards to encode each movement.

> The proliferation of computers in the 50s and 60s added the “C” in CNC and radically changed the manufacturing industry.

> Today, CNC machines are advanced robotic systems with multi-axis and multi-tooling capabilities.

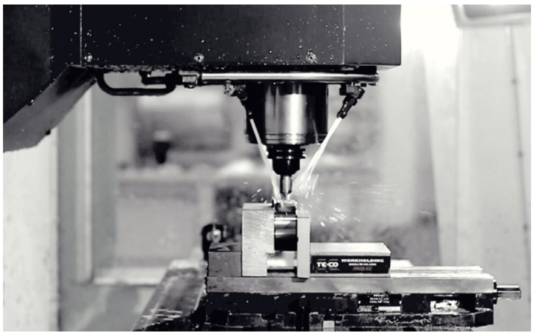
Types of CNC machines

In this guide, we will focus on CNC machines that remove material using cutting tools. These are the most common and have the widest range of applications. Other CNC machines include laser cutters, plasma cutters and EDM machines.



3-axis CNC machines

CNC milling and CNC turning machines are examples of 3-axis CNC systems. These “basic” machines allow the movement of the cutting tool in 3 linear axes relative to the workpiece (left-right, back-forth and up-down).



CNC milling

> The workpiece is held stationary directly on the machine bed or in a vice.
> Material is removed from the workpiece using cutting tools or drills that rotate at high speed.
> The tools are attached to a spindle, which can move along 3 linear axes.

3-axis CNC milling machines are very common, as they can be used to produce most common geometries. They are relatively easy to program and operate, so start-up machining costs are relatively low.

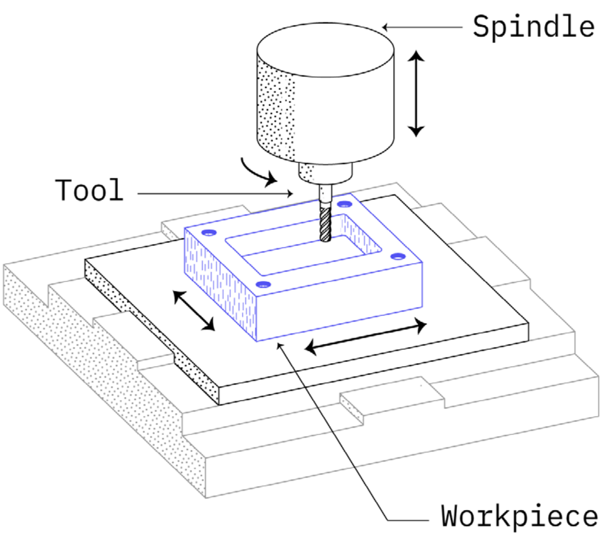
Tool access can be a design restriction in CNC milling. As there are only 3 axes to work with, certain areas might be impossible to reach. This isn’t a big issue if the workpiece needs to be rotated just once, but if multiple rotations are needed the labor and machining costs increase fast.

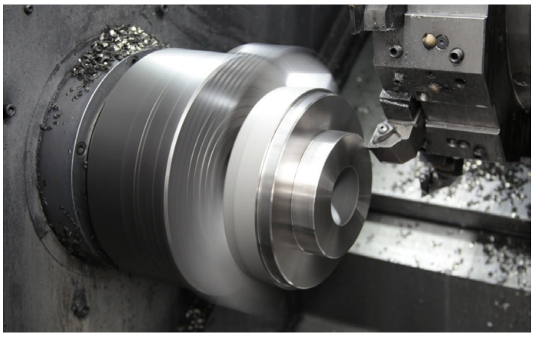
Pros

- Can produce most parts with simple geometries
- High accuracy and tight tolerances

Cons

- Tool access and workholding design restrictions apply
- Manual repositioning of the workpiece lowers the achievable accuracy





CNC turning (lathes)

> The workpiece is held on the spindle while rotating at high speed.
> A cutting tool or center drill traces the outer or inner perimeter of the part, forming the geometry.
> The tool does not rotate and moves along polar directions (radially and lengthwise).

CNC lathes are extensively used, because they can produce parts at a much higher rate and at a lower cost per unit than CNC mills. This is especially relevant for larger volumes.

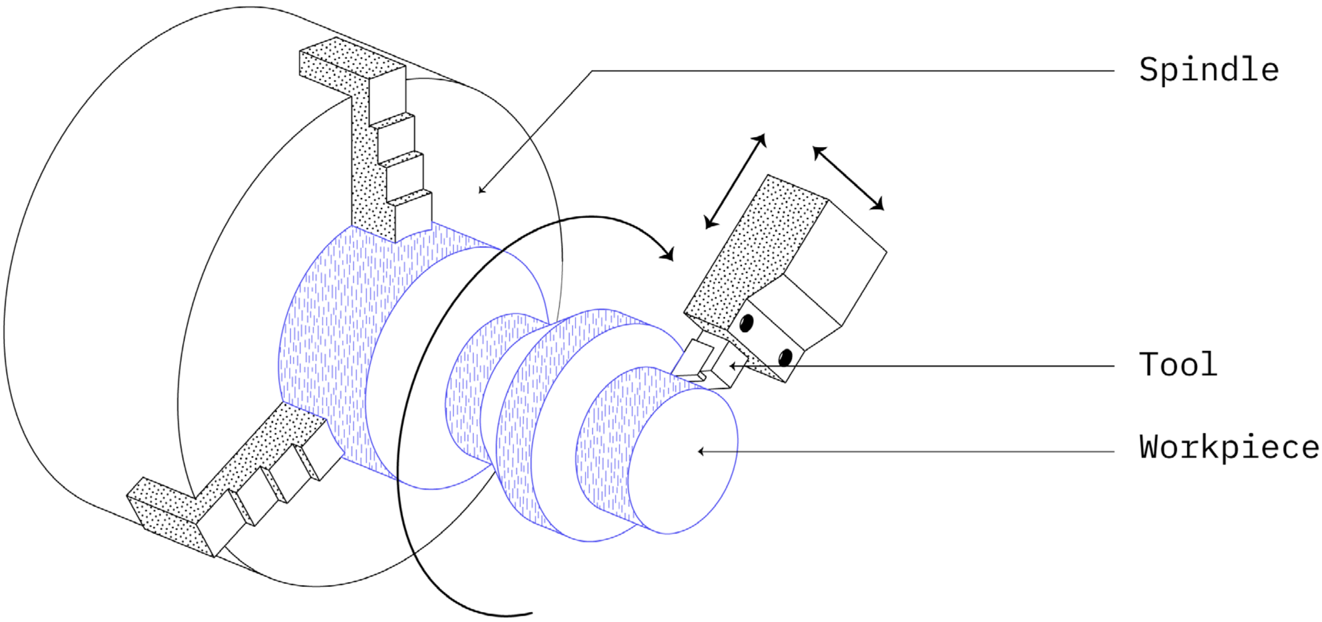
The main design restriction of CNC lathes is that they can only produce parts with a cylindrical profile (think screws or washers). To overcome this limitation, features of the part are often CNC milled in a separate machining step. Alternatively, 5-axis mill-turning CNC centers can be used to produce the same geometry in one step.

Pros

- Lowest cost per part compared to all other CNC machining operations
- Very high production capabilities

Cons

- Can only produce parts with rotational symmetry and simple geometries



5-axis CNC machines

Multi-axis CNC machining centers come in 3 variations: 5-axis indexed CNC milling, continuous 5-axis CNC milling and mill-turning centers with live tooling.

These systems are essentially milling machines or lathes enhanced with additional degrees of freedom. For example, 5-axis CNC milling centers allow the rotation of the machine bed or the toolhead (or both) in addition to the 3 linear axes of movement.

The advanced capabilities of these machines come at an increased cost. They require both specialized machinery and operators with expert knowledge. For highly complex or topology optimized metal parts, 3D printing is usually a more suitable option.

Continuous 5-axis CNC milling

> The cutting tool can move along 3 linear and 2 rotational axes relative to the workpiece.
> All 5 axes can move at the same during all machining operations.

Continuous 5-axis CNC milling systems have a similar machine architecture to indexed 5-axis CNC milling machines.

But they allow for the movement of all 5 axes at the same time during all machining operations. This way, it's possible to produce parts with complex, 'organic' geometries that can't be manufactured at the achieved level of accuracy with any other technology.

These advanced capabilities come at a high cost, of course, as both expensive machinery and highly-trained machinists are needed.

Pros

- Manufactures complex parts at a level of accuracy that's impossible with any other process
- Produces very smooth 'organic' surfaces with minimal machining marks

Cons

- Highest cost per part of all CNC machines
- Tool access restrictions still apply

Indexed 5-axis CNC milling

> During machining, the cutting tool can only move along 3 linear axes.
> Between operations, the bed and the toolhead can rotate, giving access to the workpiece from a different angle.

Indexed 5-axis CNC milling systems are also known as 3+2 CNC milling machines, since they are using the 2 additional degrees of freedom only between machining operations to rotate the workpiece.

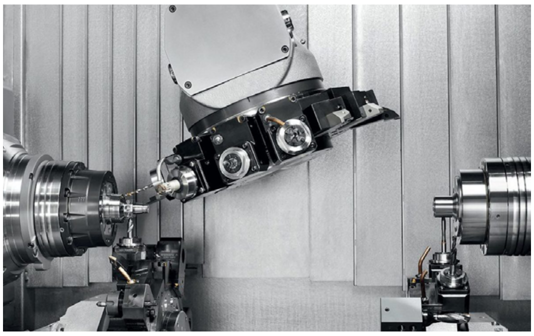
The key benefit of these systems is they eliminate the need to manually reposition the workpiece. Meaning parts with more complex geometries can be manufactured faster and at higher accuracy than in a 3-axis CNC mill. But they lack the true freeform capabilities of continuous 5-axis CNC machines.

Pros

- Eliminates the need for manual repositioning
- Produces parts with features that don't align with one of the main axes at a higher accuracy

Cons

- Higher cost than 3-axis CNC machining
- Can't produce very accurately contoured surfaces



Mill-turning CNC centers

> The workpiece is attached to a spindle that can either rotate at high speed (like a lathe) or position it at a precise angle (like a 5-axis CNC mill).
> Lathe and milling cutting tools are used to remove material from the workpiece, forming the part.

Mill-turning CNC centers are essentially CNC lathe machines equipped with CNC milling tools. A variation of the mill-turning centers are swiss-style lathes, which have typically higher precision.

Mill-turning systems take advantage of both the high productivity of CNC turning and the geometric flexibility of CNC milling. They are ideal for manufacturing parts with 'loose' rotational symmetry (think camshafts and centrifugal impellers) at a much lower cost than other 5-axis CNC machining systems.

Pros

- Lowest cost of all 5-axis CNC machining systems
- High production capabilities and design freedom

Cons

- Tool access restrictions still apply
- Most suitable for parts with a cylindrical outline

To summarize

> 3-axis CNC milling machines manufacture parts with relatively simple geometries with excellent accuracy and at a low cost.

> CNC lathes have the lowest cost per unit, but are only suitable for part geometries with rotational symmetry.

> Indexed 5-axis CNC milling machines manufacture parts with features that don't align with one of the main axes quickly and with very high accuracy.

> Continuous 5-axis CNC milling machines manufacture parts with highly complex, 'organic' geometries and smooth contours, but at a high cost.

> Mill-turning CNC centers combine the benefits of CNC turning and CNC milling into a single system to manufacture complex parts at a lower cost than other 5-axis CNC systems.

Use the table below for a rough estimate of the cost per hour of the different CNC machines. The cost is presented relative to that of a 3-axis CNC milling machine, which is typically $75 per hour.

CNC machine type	Machining cost
CNC milling (3-axis)	$75 (baseline for comparison)
CNC turning (lathe)	$65 (- 15%)
Indexed 5-axis CNC milling	$120 (+ 60%)
Continuous 5-axis CNC milling	$150 (+ 100%)
Mill-turning CNC centers	$95 (+ 25%)

Benefits and limitations of CNC machining

Here's a list of the key strengths and limitations of CNC machining. You can use it to help you decide whether CNC maching is the right technology for your application.

Benefits of CNC machining

Small-to-medium production

CNC machining is a very **price-competitive option** for manufacturing small-to-medium volumes (from 10-1000 parts). In fact, when ordering 10 identical parts, the unit price is cut by about 70% compared to a one-off part.

This is because 'economies of scale' start to kick in: the relatively high start-up costs of CNC are spread over multiple parts. In contrast, additive technologies (3D printing) do not scale as well for higher volumes - the unit price is relatively stable.

Formative technologies (injection molding or investment casting) only make economic sense for production volumes in the 1000s as they have very high start-up costs.

Excellent material properties

CNC machined parts have excellent physical properties, identical to the bulk material. This makes CNC machining the ideal technology for applications where **high-performance** is essential.

Additionally, virtually every common material with enough hardness can be CNC machined. This gives engineers the flexibility to select a material with optimal properties for their application.

One-off custom parts and prototypes

In contrast to formative technologies (injection molding), CNC machining **doesn't need any special tooling**. So the on-demand production of custom one-off parts and prototypes is economically viable.

This is especially relevant for **one-off custom metal parts and prototypes**, where CNC is the most cost-competitive solution.

Quick turnaround times

The advances of modern CNC systems, CAM software and digital supply chains have greatly accelerated the production times.

Now CNC machined parts are typically **ready for delivery within 5 days**. This is comparable to the turnaround of industrial 3D printing processes, such as SLS.

Highly accurate parts with tight tolerances

CNC machining can create parts with greater dimensional accuracy than most other common manufacturing technologies. During the final finishing machining steps, material can be removed from the workpiece very accurately, achieving extremely tight tolerances.

The standard tolerance of any dimension in CNC machining is **± 0.125 mm**. Features with tighter tolerances down to ± 0.050 mm can be manufactured and even tolerances of ± 0.025 mm are feasible. That's about a quarter the width of a human hair!

Limitations of CNC machining

Relatively high start-up costs

In CNC machining, start-up costs are mainly connected to **process planning**. This step requires manual input from an expert, so start-up costs are usually relatively high when compared to, for example, 3D printing, where process planning is highly automated.

However, these costs are still much **lower than formative manufacturing** processes (injection molding or investment casting), which require the preparation of custom tooling.

It's important to keep in mind that the start-up costs are fixed. There's an opportunity to significantly reduce the unit price per part by taking advantage of 'economies of scale', as we saw above.

Geometric complexity has a high cost

Being a subtractive technology, machining complex geometries comes at an increased cost. It's also restricted by the mechanics of the cutting process.

Parts with complex geometries either require the use of a **multi-axis CNC machining system or manual labor** from the machinist (repositioning, realigning etc.). To help you keep the price of CNC machined parts to a minimum, we've compiled a list of design tips.

Tool access and workholding restrictions

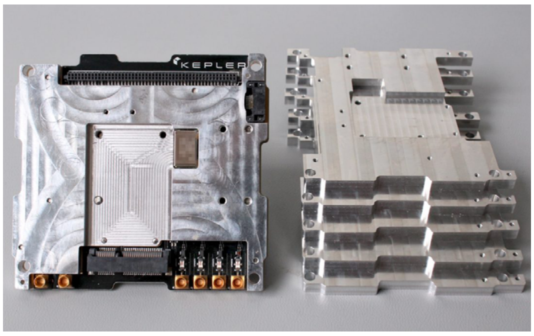
Since a part is produced by removing material from a solid block, a cutting tool with a suitable geometry has to exist. It should also be able to access all necessary surfaces.

For this reason, parts with internal geometries or very steep undercuts, for example, can't be machined. Holding the **workpiece securely in place is essential** for CNC machining and introduces a certain design limitation. Improper workholding or a workpiece with low stiffness can lead to vibrations during machining.

This results in parts with lower dimensional accuracy. Complex geometries might require custom jigs or fixtures.

Applications of CNC machining

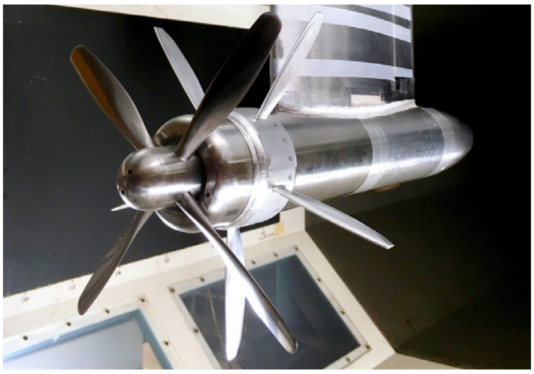
Here are some examples of how and why CNC machining is used for a range of different applications.



Space

CNC machining is one of the very few manufacturing processes that's suitable for creating parts for space applications. Not only because CNC parts have excellent accuracy and material properties, but also because of the wide range of surface treatments that can be applied to the parts after machining.

For example, KEPLER used CNC machining and space grade materials to go from a sketch on a napkin to a satellite in space in 12 months.



Aerospace

Aerospace was one of the first industries to use CNC machining. This is because CNC machining can manufacture lightweight parts with excellent physical properties and very tight tolerances. CNC machining is used both for aircraft parts and during the development stages.

For example, Tomas Sinnige is a PhD researcher at the Delft University of Technology. With his team of researchers, Tomas used CNC machining to manufacture scaled-down versions of their prototype engine, with the goal of increasing the efficiency of modern propeller engines.

Automotive

CNC machining is most used in the automotive industry when manufacturing high-performance custom parts is required.

For example, the Dutch company PAL-V designs Personal Air and Land Vehicles. These are essentially the world's first flying cars. During the development stages, they chose CNC machining to prototype and manufacture key components.

Product design and development

The ability to quickly manufacture custom metal parts with great dimensional accuracy, makes CNC machining an attractive option for producing functional prototypes. This is essential during later stages of design and development.

The design team of DAQRI, for instance, used CNC machining to prototype their professional Augmented Reality (AR) hardware. They selected this process as it was the most cost-competitive solution capable of producing custom metal parts with the required level of detail and at the small-scale needed for their designs.

Electrical and electronic

CNC machining has many applications in the electrical and electronic manufacturing industry: from the prototyping of PCBs to the manufacturing of enclosures.

TPAC, for example, used CNC machining to manufacture an enclosure for their high-power electronic sensing systems. Heat dissipation and electrical insulation were the main design requirements in this case. So, CNC machined, anodized aluminum was ideal for their one-off custom enclosure.

Tooling and industrial manufacturing

A very common industrial application of CNC machining is the fabrication of tooling for other processes. For example, the molds in injection molding are commonly CNC machined from aluminum or tool steel. Precious Plastic, for instance, developed a system for the developing a world that turns waste plastic into iPhone cases! For this purpose, they used a low-cost manual injection molder and custom CNC machined molds.

Sports and motorsports equipment

High-performance sports and motorsports manufacturers always try to increase the performance of their products by reducing their weight.

CAKE is a Swedish company that designed and developed the first off-road electric motorbike. Since it's the first of its kind, every single component of the motorbike was custom-made with CNC machining to achieve the intended level of quality and durability.

CNC machining vs. 3D printing

Both CNC machining and 3D printing are exceptional tools. However, each technology has unique benefits, and is more suitable for different situations. When choosing between CNC machining and 3D printing, there are a few simple guidelines you can apply to the decision making process.

As a general rule of thumb, parts with relatively simple geometries, that can be manufactured with limited effort through a subtractive process, should generally be CNC machined. Especially when it comes to producing metal parts.

Choosing 3D printing over CNC machining makes sense when you need:

> A low-cost plastic prototype

> Parts with very complex geometry

> A turnaround time of 2-5 days

> Speciality materials

To summarize:

CNC offers greater dimensional accuracy and produces parts with better mechanical properties than 3D printing. But this usually comes at a higher cost for low volumes and with more design restrictions.

Read the full comparison →

Scaling up production

If high volumes are needed (1000s or more) neither CNC machining nor 3D printing are likely to be suitable options.

In these cases, forming technologies, such as investment casting or injection molding, are more economically viable due to the mechanisms of economies of scale. For quick reference, use the table below.

In this simplification, it's assumed that all technologies are able to produce the geometry of the part in question. When this is not the case, 3D printing is generally the preferred method of manufacturing.

No. of Parts	Plastic	Metal
1 - 10	3D printing	3D printing (consider CNC machining)
10 - 100	3D printing and CNC machining	CNC machining
100 - 1000	CNC machining (consider injection molding)	CNC machining (consider investment casting)
1000+	Injection molding	Investment or die casting

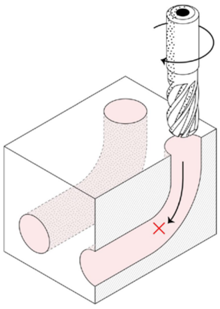
Part 2

Design for CNC machining

In less than 15 minutes, you'll learn all you need to know to design parts optimized for CNC machining. Get familiar with Design for Machinability (DfM) rules, cost reduction tips, material selection guidelines, and surface finishing recommendations.

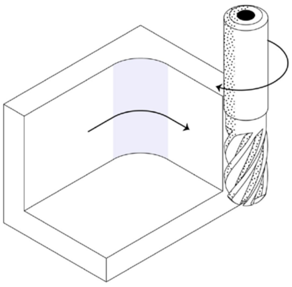
CNC machining design restrictions

The design restrictions in CNC machining are a natural result of the mechanics of the cutting process and in particular:



Tool access

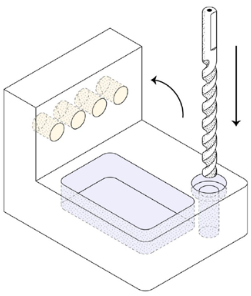
Surfaces that can't be reached by the cutting tool, can't be CNC machined. This prohibits the fabrication of parts with internal 'hidden' geometries, for example, and puts a limit on the maximum depth of an undercut.



Tool geometry

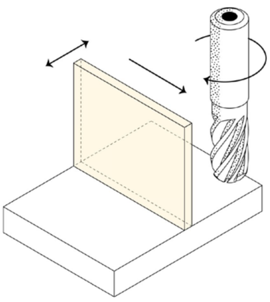
Most CNC machining cutting tools have a cylindrical shape with a flat or spherical end, restricting the part geometries that can be produced.

For instance, the internal vertical corners of a CNC part will always have a radius, no matter how small a cutting tool is used.



Workholding

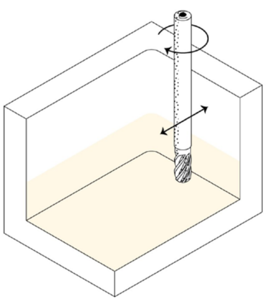
The geometry of a part determines the way it will be held on the CNC machine and the number of setups required. This has an impact on the cost, but also the accuracy of a part. For example, manual repositioning introduces a small, but significant, positional error. This a key benefit of 5-axis versus 3-axis CNC machining.



Workpiece stiffness

Due to the cutting forces and the temperatures developed during machining, it's possible for the workpiece to deform or vibrate.

This limits, for example, the minimum wall thickness that a CNC machined part can have and the maximum aspect ratio of tall features.



Tool stiffness

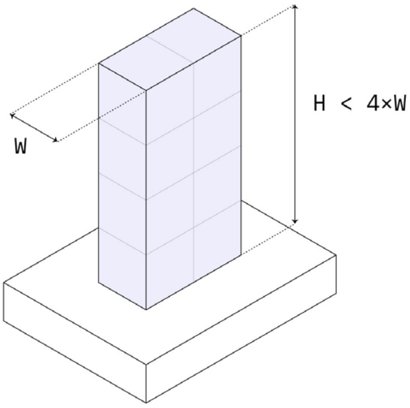
Most CNC machining cutting tools have a cylindrical shape with a flat or spherical end, restricting the part geometries that can be produced.

For instance, the internal vertical corners of a CNC part will always have a radius, no matter how small a cutting tool is used.

Design rules for CNC machining

In the table below, we summarize how these restrictions translate into actionable design rules.

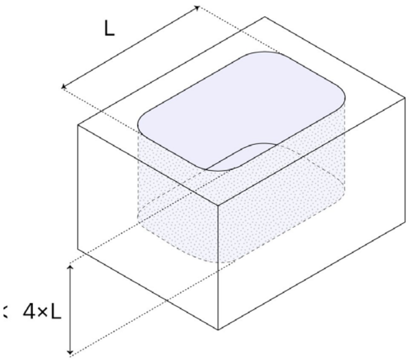
Read the detailed guidelines →



Tall features

Recommended max. ratio: height / width < 4

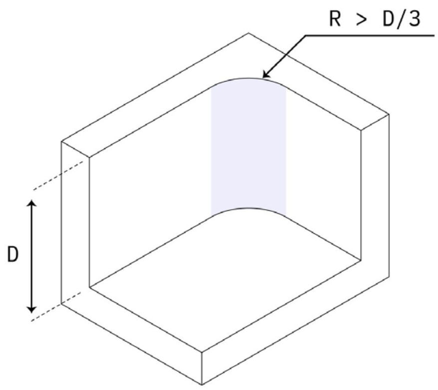
Tall features are difficult to machine accurately, as they are prone to vibrations. Consider the overall geometry of the part: rotating the part by 90° degrees during machining changes the aspect ratio.



Cavities and pockets

Recommended depth: 4 x cavity width
Feasible depth: 10 x tool diameter or 25 cm (10")

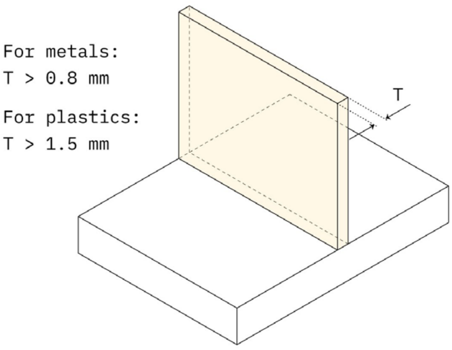
Deeper cavities need to be machined with cutting tools with larger diameter affecting the fillets of the internal edges.



Internal edges

Recommended: larger than 1/3 x cavity depth

For internal vertical edges, the larger the fillet the better. Edges on the floor of a cavity should be either sharp or have a 0.1 mm or 1 mm radius.

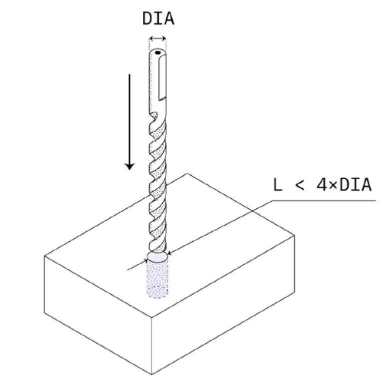


Minimum wall thickness

Recommended: 0.8 mm (for metals)
Feasible: 0.5 mm
Recommended: 1.5 mm (for plastics)
Feasible: 1.0 mm

Decreasing the wall thickness reduces the stiffness of the workpiece, increasing vibrations and lowering the achievable tolerances.

Plastics are especially prone to warping and thermal softening, so a larger minimum wall thickness is necessary.

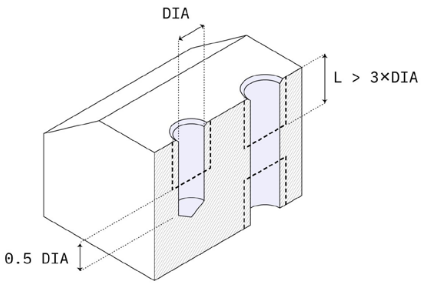


Holes

Recommended diameter: standard drill bit sizes
Recommended depth: 4 x nominal diameter
Max. depth: 10 x nominal diameter

Holes with standard diameter are preferred, as they can be machined with a standard drill bit. Blind holes machined with a drill will have a conical floor. Holes with non-standard diameter will be machined with an end mill tool and should be treated as cavities (see previous rule).

Blind holes machined with an end mill tool will be flat.

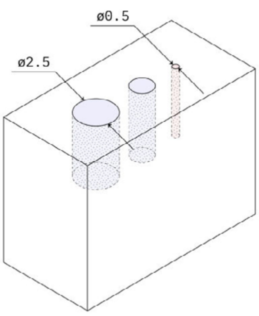


Threads

Recommended length: 3 x nominal diameter
Recommended size: M6 or larger
Feasible size: M2

Choose the largest threads possible, as they are easier to machine. Threads longer than 3 times the nominal diameter are unnecessary.

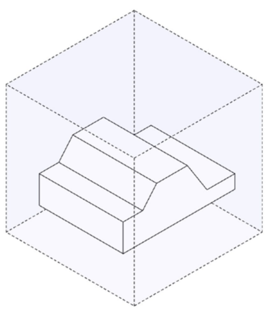
Always design threads as cosmetic in your CAD package and include a technical drawing with your order.



Small features

Recommended: 2.5 mm (0.100")
Feasible: 0.100 mm (.010")

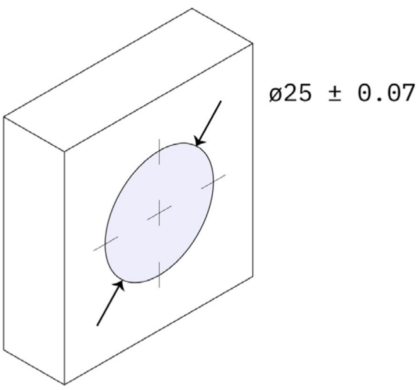
Cavities and holes down to 2.5 mm (0.1") can be CNC machined with standard cutting tools. Anything below this limit is considered micro-machining and must be avoided unless necessary.



Maximum part size

CNC milling: 400 × 250 × 150 mm (typically)
CNC turning: Ø 500 mm x 1000 mm (typically)

Very large CNC machines can produce parts with dimensions up to 2000 x 800 × 1000 mm (78" x 32" x 40"). 5-axis CNC machining systems typically have a smaller build volume.



Tolerances

Standard: ± 0.125 mm (.005")
Feasible: ± 0.025 mm (.001")

Tolerances (unilateral, bilateral, interference or geometric) should be defined on all critical features, but **do not** over-tolerance.

If no tolerance is specified in the technical drawing, then the standard ± 0.125 mm will be held.

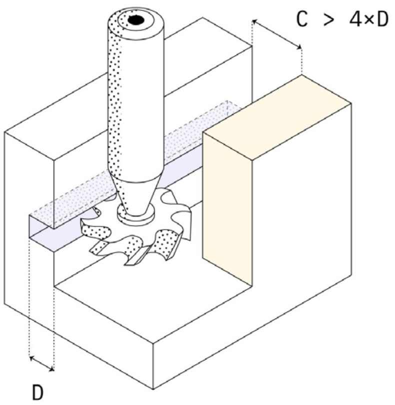
Designing undercuts

Undercuts are features that can't be machined with standard tools, no matter how the part is rotated, because the cutting tools can't access all the surfaces.

If square aluminum extrusions were manufactured with CNC machining, their grooves would be considered undercuts. Undercuts can be machined using special T-shaped, V-shaped or lollipop-shaped cutting tools, if designed correctly.

Here are some practical guidelines to help you get started with designing undercuts.

Learn more about undercuts →

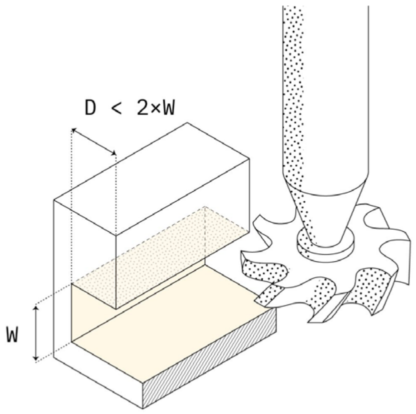


Undercut dimensions

Recommended width: 3 mm (1/8") to 40 mm (1 ½")
Max. Depth: 2x width

Design undercuts with a width of whole millimeter increments or a standard inch fraction. For undercuts with non-standard dimensions, a custom cutting tool must be created.

The standard tools have a cutting depth of approximately 2 times their width. This limits the achievable depth.



Undercut clearance

Recommended min. clearance: 4x depth

For undercuts on internal faces, add enough clearance between the opposing walls to ensure tool access.

Part 3

Materials for CNC machining

CNC machining can be used with a very wide range of engineering metals and plastics.

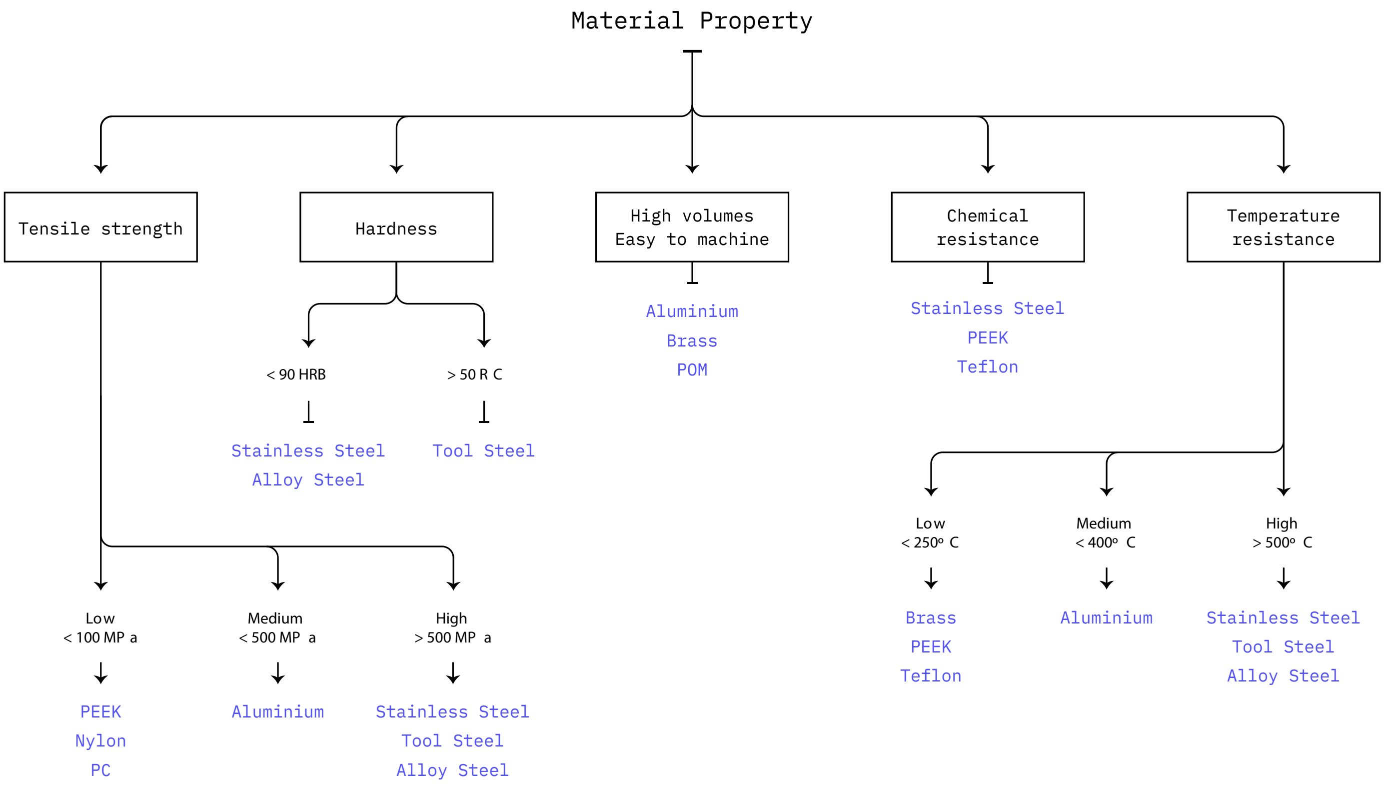
In this section, you'll learn more about the key characteristics of the most popular materials. We'll also examine the most common finishes that are applied to CNC machined parts.

Materials for CNC machining

Selecting the right material is a crucial step in the design process. The optimal material option is highly dependent on your specific use case and requirements.

Since almost every material with sufficient hardness can be machined, CNC offers a very large range of material options to choose from. For engineering applications, metals and plastics are most relevant and will be the focus of this section. Surface finishes can also alter the properties of CNC machined parts which we'll examine them below.

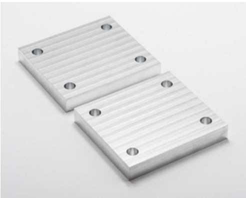
To get started, take a look at this decision tree. It contains high level material recommendations that cover the most common design requirements.



Metals

CNC machining is primarily used with metals and metal alloys. Metal can be used for both the manufacturing of custom one-off parts and prototypes and for low-to-medium batch production. Aluminum 6061 is by far the most used material in CNC machining.

Learn more about the most common CNC metals →



Aluminum

> Excellent strength-to-weight ratio
> High thermal and electrical conductivity
> Natural protection against corrosion

Stainless steel

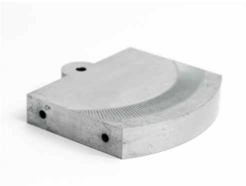
> High strength and ductility
> Excellent wear and corrosion resistance
> Can be welded, machined and polished

Alloy steel

> General use alloys
> Improved hardness, toughness, fatigue and wear resistance over mild steels
> Low chemical resistance

Mild steel

> General use alloys
> Low-cost
> Good mechanical properties, machinability and weldability



Tool steel

> High hardness
> Stiffness, abrasion and thermal resistance
> Used for dies, stamps, molds and other industrial tooling

Brass

> Excellent machinability
> Frictional characteristics
> Aesthetically pleasing golden appearance

Plastics

Plastics are lightweight materials with a wide range of physical properties. They're often used for their chemical resistance and electrical insulation properties. Plastics are commonly CNC machined for prototyping purposes prior to injection molding.

Learn more about the most common CNC plastics →

ABS

Common, lightweight thermoplastic materials with good mechanical properties and excellent impact strength.

Polycarbonate (PC)

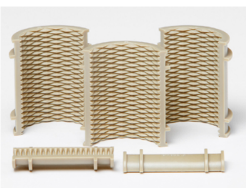
Excellent impact strength, thermal resistance and toughness. Can be colored or transparent. Suitable for outdoor applications.

Nylon

General purpose engineering thermoplastic with all-around good mechanical properties and excellent chemical resistance.

POM (Delrin)

Easiest-to-machine engineering thermoplastic with high stiffness, excellent frictional characteristics and good thermal stability.



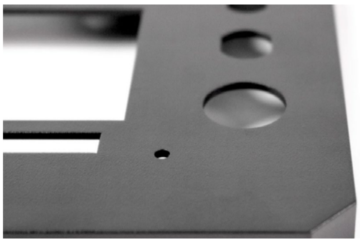
PEEK

High-performance engineering thermoplastic used in the most demanding applications.

Surface finishes

Surface finishes are applied after machining and can change the appearance, surface roughness, hardness and chemical resistance of the produced parts. Below is a quick summary of the most common finishes for CNC.

Find out more about surface finishes →



Powder coating

Powder coating adds a thin layer of strong, wear and corrosion resistant, protective polymer paint on the surface of a part. It can be applied to parts of any material and is available in many colors.

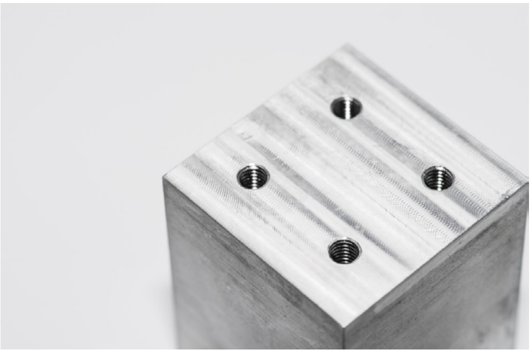
Extra cost: $$

Pros

- Strong, wear and corrosion coating for functional applications
- Higher impact resistance than anodizing
- Compatible with all metal materials

Cons

- Can't be applied to internal surfaces
- Less dimensional control compared to anodizing
- Not suitable for small components



As-machined

As-machined parts have the tightest tolerances, as no extra operations are performed on them. But marks following the path of the cutting tool are still visible.

The standard surface roughness of as-machined parts is 3.2 μm (125 μin) and can be reduced to down to 0.4 μm (16 μin) with further operations.

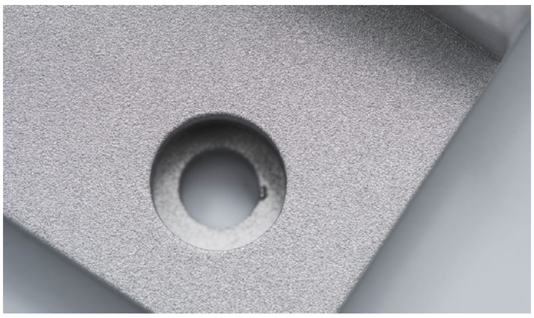
Extra cost: None

Pros

- Tightest dimensional tolerances
- No added cost (standard finish)

Cons

- Visible tool marks



Bead blasting

Bead blasting adds a uniform matt or satin surface finish on a machined part, removing all tool marks.

Bead blasting is mainly used for aesthetic purposes, as the resulting surface roughness is not guaranteed. Critical surfaces or features (like holes) can be masked to avoid any dimensional change.

Extra cost: $

Pros

- Visually pleasing matte or satin finish
- Low-cost surface finish
- Available in different levels of coarseness

Cons

- Visible tool marks

Anodizing (clear or colored)

Anodizing adds a thin, hard, non-conductive ceramic coating on the surface of aluminum parts, increasing their corrosion and wear resistance.

Critical areas can be masked to retain their tight tolerances. Anodized parts can be dyed producing a smooth aesthetically pleasing surface.

Extra cost: $$

Pros

- Durable, visually pleasing coating
- Can be applied to internal cavities
- Can be colored to any Pantone tone

Cons

- More brittle than powder coating
- Only compatible with aluminum and titanium

Hardcoat anodizing

Hardcoat anodizing produces a thicker, high-density ceramic coating that provides excellent corrosion and wear resistance.

Hardcoat anodizing is suitable for functional applications. The typical coating thickness is 50 μm and, usually, no color is applied. Critical areas can be masked to retain their tight tolerances.

Extra cost: $$$

Pros

- High wear resistance coating for top-end engineering applications
- Can be applied to internal cavities
- Good dimensional control

Cons

- More brittle than powder coating
- Only compatible with aluminum and titanium

Silk screening

Silk screening is an inexpensive way to print text or logos on the surface of CNC machined parts for aesthetic purposes.

It can be used in addition to other finishes (for example, anodizing). The print can be applied only to the external surfaces of a part.

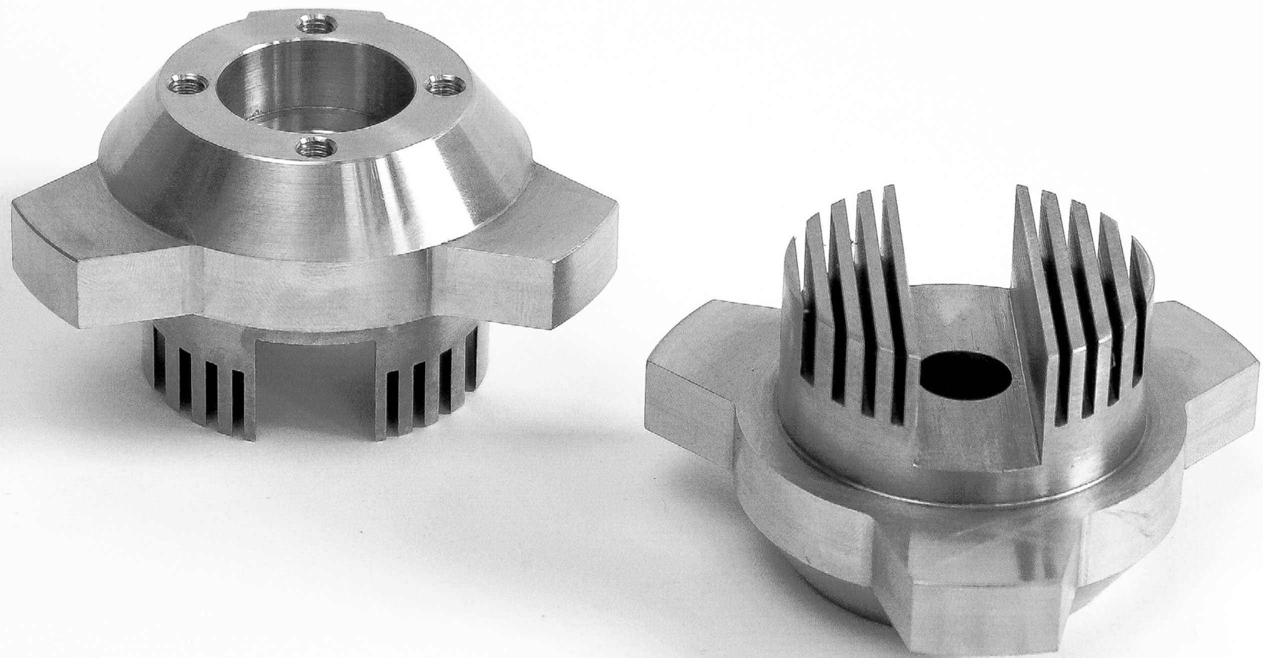
Extra cost: $

Pros

- Low-cost printing of custom text or logos
- Available in many colors

Cons

- Can be only applied to external flat surfaces of a part



Part 4

Cost reduction tips

Learn more about what affects the costs in CNC machining. Use these 3 actionable design tips to cut the price in half and you keep your project on budget.

Tips to keep your CNC project on budget

The cost of CNC machined parts depends on the following:

> **Machining time and model complexity:** The more complex the geometry of a part is, the longer it takes to machine and the more expensive it will be.

> **Start-up costs:** These are related to the preparation of a CAD file and the process. They are significant for smaller volumes, but are fixed. There is an opportunity to reduce the unit price by taking advantage of economies of scale.

> **Material cost and finishes:** The cost of the bulk material and how easily that material can be machined greatly affects the overall cost.

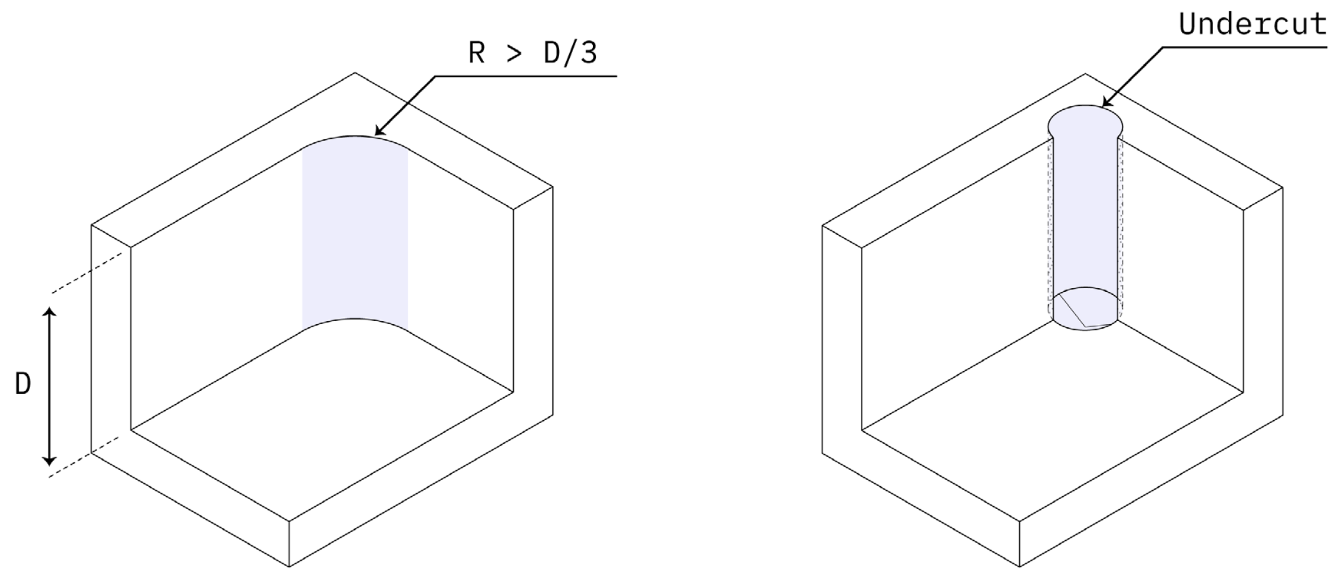
As a rule of thumb:

`To minimize the cost of CNC machined parts, stick to designs with simple geometries and standardized features.`

In the next sections, we re-examine some of the design rules we visited previously with cost-reduction in mind. With these 3 design tips, you can drastically reduce the cost of your CNC machined parts.

Learn 11 more tips to further reduce the cost of your CNC parts →

Tip #1: Increase the size of all fillets or add undercuts to sharp edges



To reduce machining times, add a fillet that is as large as possible to all internal (and external) vertical edges. This way a larger tool can be used, removing more material with each cut, and a circular toolpath can be followed, cutting each corner at a higher speed.

When a 90° internal edge is needed, reducing the radius will not do the job. In these cases, use an undercut instead (see above).

To minimize cost:

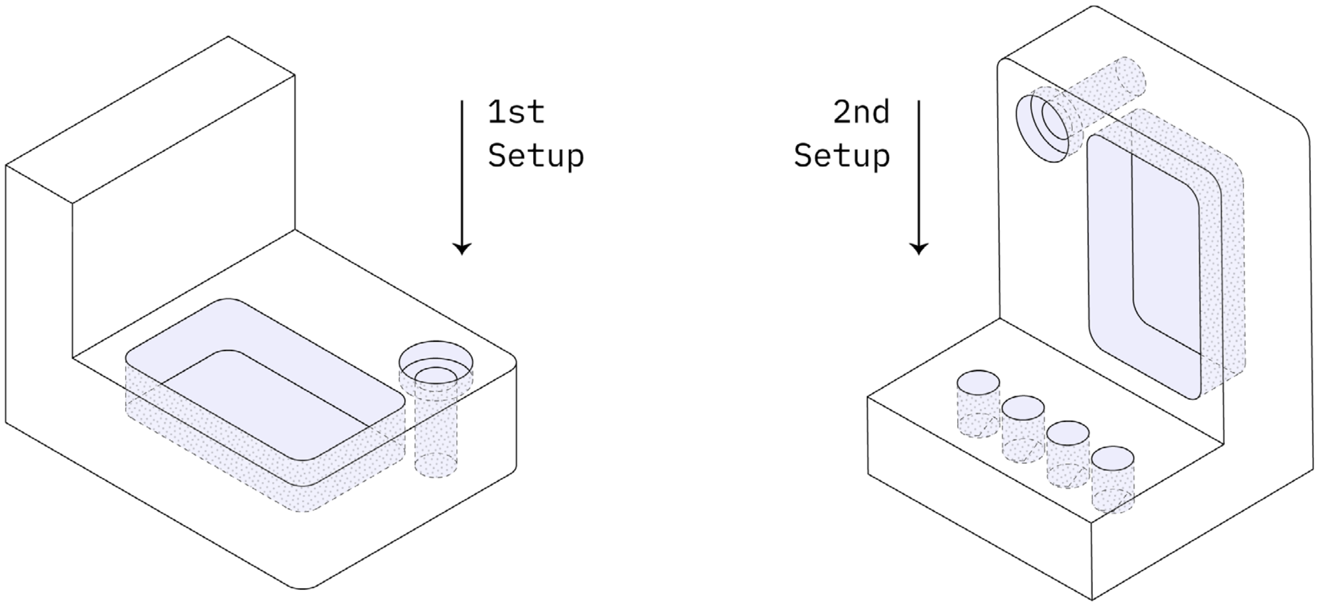
> Add a radius that is slightly larger than 1/3 of the depth of the cavity

> Add a small fillet also to external edges

> Use undercuts when a 90° internal corner is required

> Use the same radius for all edges to save time on tool changes

Tip #2: Minimize the number of machine orientations



The part above requires at least two machine setups in a 3-axis CNC mill. After the features on one side are machined, the workpiece is rotated manually.

This requires manual labor increasing costs. Alternatively, a multi-axis CNC machines can be used. This also increases the machining costs though by about 60% to 100%.

To minimize cost:

> Design parts that can be machined in one or two setups in a 3-axis CNC mill

> If this is not possible, consider splitting the part into multiple geometries that can be machined in one setup and assembled later.

Tip #3: Consider the cost of the material

Cost	Metals	Cost	Plastics
$	Aluminum 6061	$	POM (Delrin)
$$	Alloy steel 4140	$$$	ABS
$$	Aluminum 7075	$$$	Nylon (PA 6)
$$$	Brass C360	$$$	Polycarbonate (PC)
$$$$	Stainless steel 304	$$$$	PEEK

It's obvious that selecting a material with physical properties that surpass the requirements of your application can quickly and unnecessarily increase the cost of your CNC machined parts.

To minimize cost:

> Select the material with the lowest cost with the properties that fulfill your design requirements

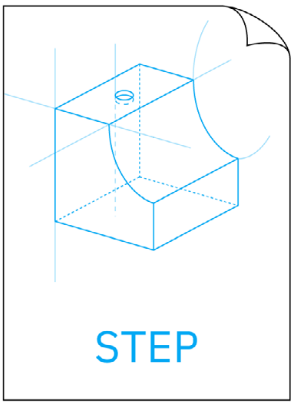
> Use online instant quoting to get quick feedback on the price of each material

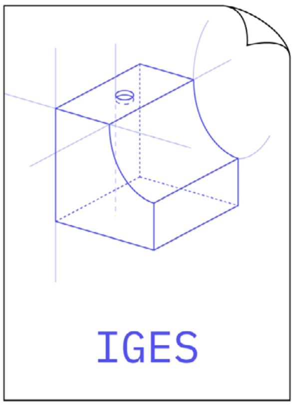
Part 5

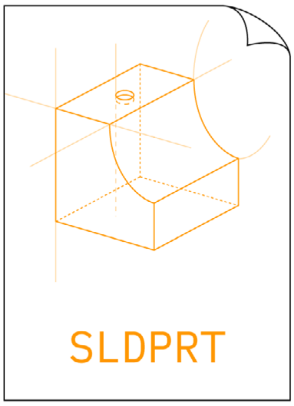
Start CNC machining

With your parts designed and optimized for CNC machining, it's time to start thinking about manufacturing. In this section, we walk you through the 3 simple steps needed to manufacture custom parts with CNC machining.

Step 1: Export your design to a CNC-compatible CAD file format







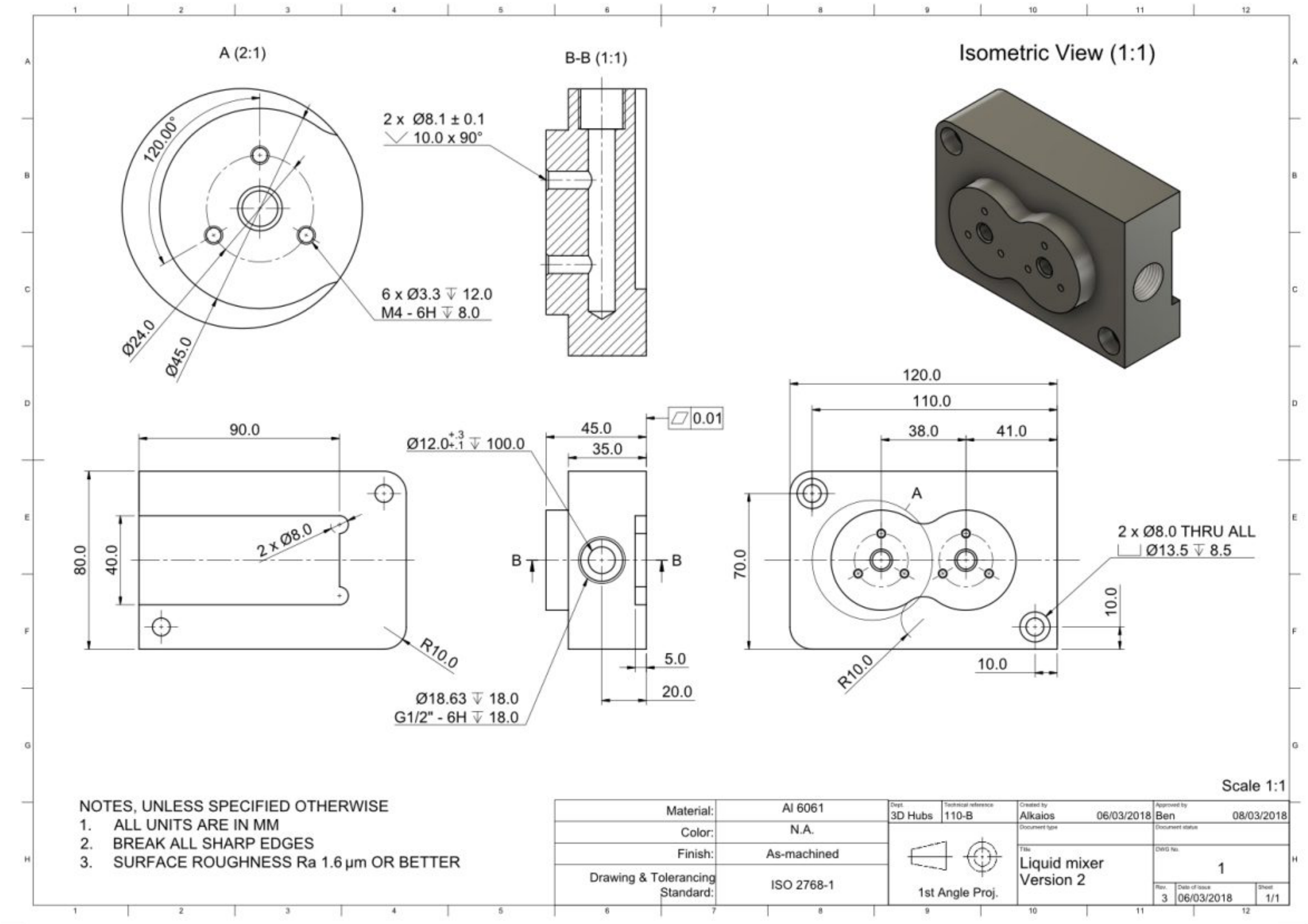
The file formats predominantly used in CNC machining are STEP and IGES. These formats are open source, standardized and can be used across platforms.

For best results:

`Export your designs directly from your native CAD software into the STEP file format.`

On 3D Hubs, you can also upload files and get an instant quote for file formats used in your the native CAD software, including SLDPRT, 3DM, IPT, SAT and X_T.

Step 2: Prepare a technical drawing



A technical drawing isn't always required for machining parts with CNC. Yet it's recommended to include one in your order as it has information that is not presented in a STEP file.

A technical drawing is required in the following situations:

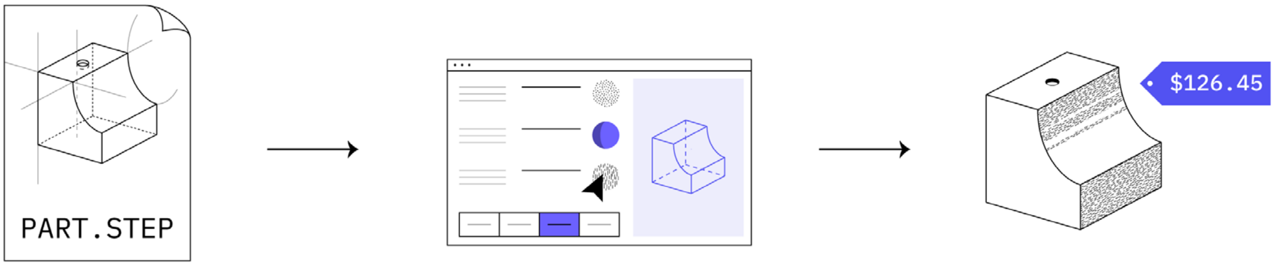
> When your design contain threads

> When any tolerances are specified

> When certain surfaces need a different finish

Learn how to correctly prepare a technical drawing for CNC →

Step 3: Get an instant quote and start manufacturing



1

Upload your 3D CAD files
In a supported format

2

Specify your requirements
Material, surface finish, lead time...

3

Get an instant quote
And start manufacturing

With 3D Hubs, outsourcing parts for CNC machining is easy, fast and highly price-competitive.

By combining a network of manufacturing services with our smart sourcing engine, you can instantly access readily available production capacity for the best possible quotes and lead times.

When you upload your parts to 3D Hubs, our automated Design for Machinability analysis will detect any potential design issues before production begins and will give you an instant quote, based on our machine learning algorithm.

This way you can be sure that you always receive the best price in the market at the fastest turnaround times for your CNC machining parts!

Upload your parts

Curious about the cost of CNC machining? Receive an instant quote for your CNC machined parts now.

Get an instant quote →

Part 6

Useful resources

In this guide we discussed everything you need to get started with CNC machining. But there's plenty more to learn.

On the next page, we list the best and most useful resources on CNC machining and other digital manufacturing technologies if you want to delve deeper.

Knowledge base

There's a lot more to learn about CNC machining in our Knowledge Base - a collection of technical articles on all manufacturing technologies, written by manufacturing experts and curated by 3D Hubs.

Here's a selection of our most popular articles on CNC machining:

> Reducing the cost of CNC machined parts →

> 3D Printing vs. CNC machining →

> 25 CNC machining materials compared →

> How to design parts for CNC machining →

Learn to machine

Are you looking to get your hands dirty with CNC machining? There are several ways you can learn how to operate a CNC mill or CNC lathe.

> **Visit your local Fab Lab:** Many Fablabs and Makerspaces have CNC milling capabilities and they will run courses on how to opperate them. Visit the official list of Fab Labs to find one near your area.

> **Find resources online:** There are a lot of useful resources online to help you hone your CNC machining skills. The Titans of CNC Academy and NYCCNC are probably 2 of the best sites to get you started.

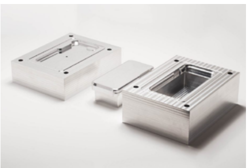
> **Apply for an apprenticeship:** Apprenticeships are probably the best way to kickstart your career as a CNC machinist. They are offered by established machine shops and many universities.

Other guides

Want to learn more about the world of digital manufacturing as a whole? There are more technologies to explore:

Injection molding:
The complete engineering guide

After reading this article, you'll know the fundamental mechanics of the injection molding process and how these relate to its key benefits and limitations.



What is 3D printing?

Find everything you need to know about 3D printing. Whether you are getting started or you're an experienced user, you'll find this guide packed with useful tips.