Xometry

Ultimate Guide

The Complete Guide to CNC Machining

Everything You Need to Know About CNC Machining

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Chapter 1

CNC Machining Basics

What is CNC Machining? Learn the basics and background of subtractive manufacturing



Digital Manufacturing Basics

Computer numerical control (CNC) machining was invented more than 50 years ago, and since then, its high capacity for precision and automation has helped create countless products. Across industries — from defense, automotive, and aerospace, to medical, precision, and manufacturing — this sophisticated technology has become part of the world's industrial DNA.

How did CNC machining come to be?

During World War II, the United States was quickly churning out ships, aircraft, and vehicles for the military. And even once the war ended, production kept up as the country experienced a post-war boom in home construction, infrastructure expansion, and transportation. Naturally, engineers and designers needed tools to help them efficiently meet the growing demand for industrial products.

Enter CNC machining. John T. Parsons, who worked in the production of helicopter rotor blades, was one of the first people to champion CNC machining. He and his colleagues at Wright-Patterson Air Force Base in Dayton, Ohio used interpolation curves, which could be applied to machining with computational methods, to achieve the complex tapers required for rotor blades. As Parsons' company got called upon to make more and more complex aircraft parts, they turned to computational methods to achieve their desired shapes.

This was partly the genesis of CNC machining.

Building off of Parsons' innovations, MIT's Servomechanisms Laboratory later developed a working machine able to use computational methods to fabricate precise machine parts. Their servo-mechanisms were able to use the Cartesian coordinates — the numerical control — to steer the machine and its moving parts, to fabricate with automated precision. Such automation only grew more sophisticated through the rest of the twentieth century and continues to develop today.

How does CNC machining differ from traditional machining?

In traditional machining, a skilled machinist operates a machine, removing or forming metal. This is done according to specifications provided by designers and engineers, usually through an engineering drawing or blueprint. They use turn wheels, dials, switches, chucks, vices, and a variety of cutting tools made of hardened steel, carbide, and industrial diamond then use measurement instruments to ensure all of the dimensions are correct.

CNC machining performs the same function as traditional machining — metal cutting, drilling, milling, boring, grinding, and other metal forming and removal functions — but it uses computer numerical control rather than manual control by a machinist. It is automated, driven by code and developed by programmers. It is about as precise the first time of cutting as the 500th. Widely used in digital manufacturing (and sometimes in low-volume production runs), it can be revised and altered for modifications and different materials.

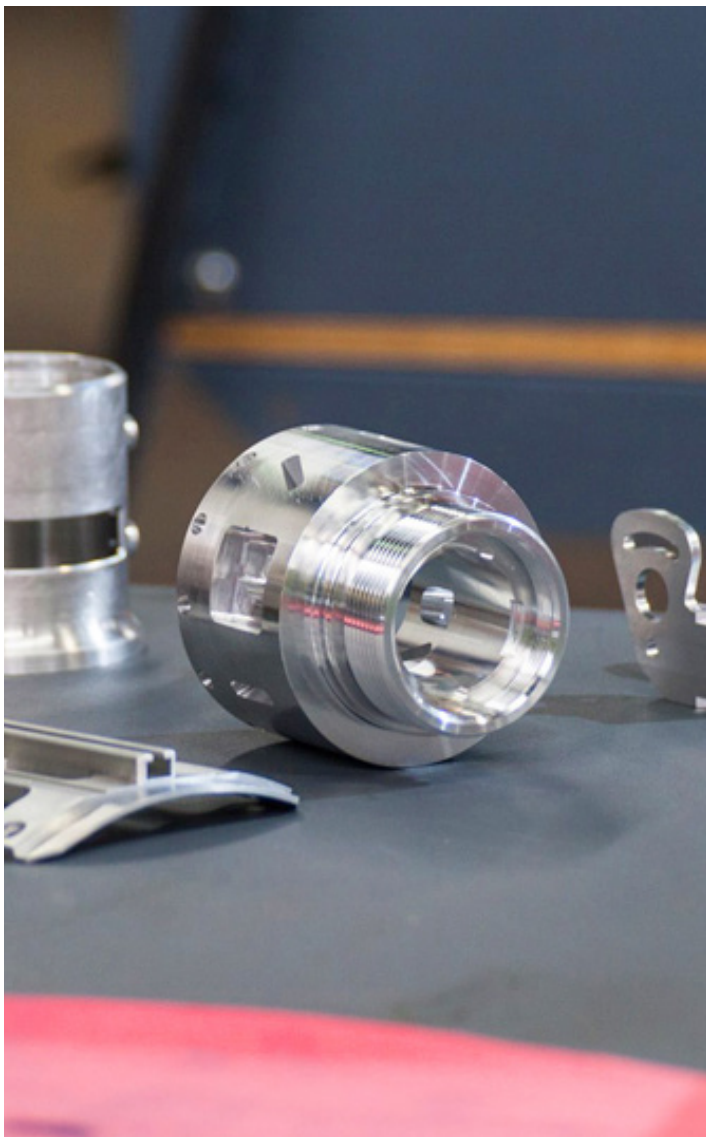
This type of machining is much more precise and has largely superseded traditional machining (though not entirely) in manufacturing, fabrication, and industrial production. It uses mathematical coordinates and the power of computing to achieve the same end, with the greatest accuracy. Specifically, computer numerical control uses Cartesian coordinates. These are spatial coordinates — in several dimensions — using coordinates and axes. The automation of cutting tool machines controls its cutting, boring, drilling or other operation using the numerical control of a computer that reads the coordinates. These coordinates were designated by engineers in the product's digital drawing and design.

What is the CNC machining process?

CNC machining uses subtractive processes, which means feedstock is machined to final form by subtracting and removing material. Holes are drilled, lots and pathways are bored, and metal stock is shaped into new material with varying tapers, diameters, and shapes.

For subtractive manufacturing, shapes are achieved by the subtraction of material. This contrasts with other types such as additive manufacturing — where materials are added, layered and deformed to a specified shape. It also contrasts with injection molding where material is injected in a different state of matter, using a mold, and formed to a specified shape.

CNC machining is versatile — and can be used with various materials, including metals, plastics, wood, glass, foam, and other composite materials. This versatility has helped make CNC machining a popular choice across industries, enabling designers and engineers to fabricate products with efficiency and precision.



Chapter 2

Pros & Cons of CNC Machining

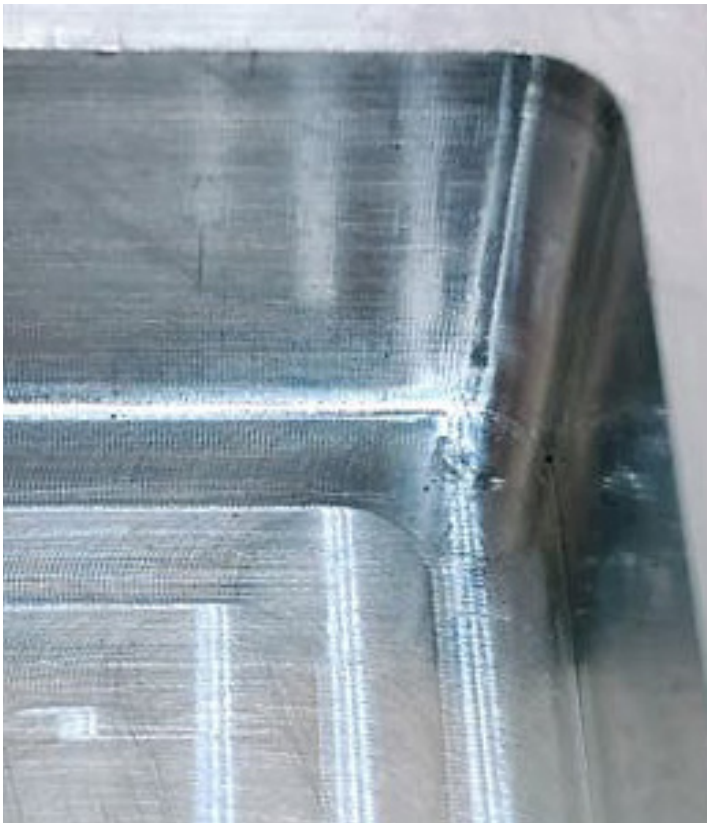
Learn the advantages and disadvantages of CNC Machining for Prototyping and Productiondisadvantages of CNC Machining for Prototyping and Production

Pros: Timely, reliable, accurate and robust

CNC milling and turning are highly accurate and repeatable processes. Tight tolerances between +/-0.001" – 0.005" can be achieved, depending on specifications. Machines can be programmed to reliably run for 24 hours, 7 days a week if necessary, so CNC milling is a good way of getting parts produced on demand.

Using standard tooling, CNC machining is particularly valuable for creating custom, one-off parts, i.e. for replacing legacy components or delivering a specialized upgrade to a customer. It is also conceivable to scale single-part production to runs exceeding 10,000 units. Depending on the unit number, size, and complexity, the turnaround for components can be as short as one day. With shipping and delivery, deadlines can be met within a week.

Another primary advantage of CNC technology is the achievable mechanical properties. By cutting away from a bulk material, rather than thermally transforming it as in injection-molding or additive manufacturing, all desirable mechanical properties of the metal or plastic of choice are retained. More than 50 industrial grade metals, alloys, and plastics can be machined using CNC milling and turning. This selection includes aluminum, brass, bronze, titanium, stainless steel, PEEK, ABS, and zinc. The only material requirement for CNC machining is that the part has an adequate hardness to be fixtured and cut.



Pros: Costs that Work for You

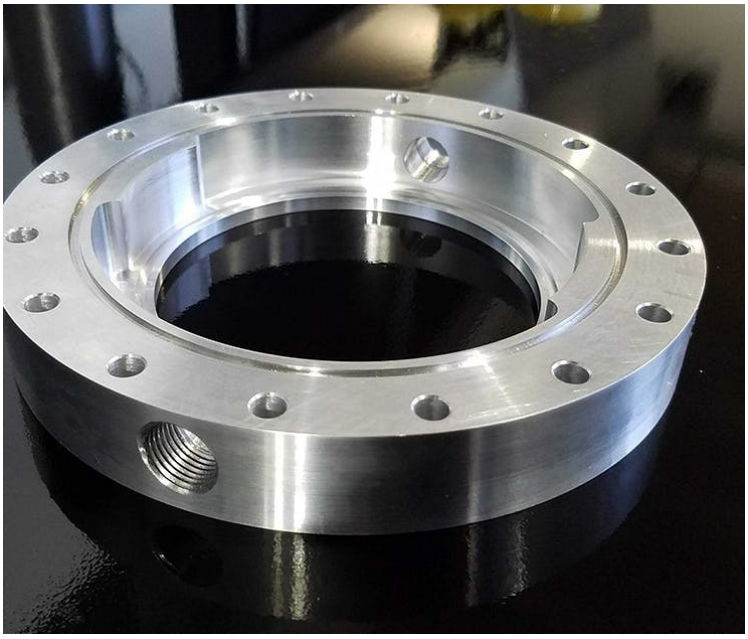
To achieve the most cost-effective CNC machined parts, larger production runs are recommended to spread the cost of machine setup. Unit price decreases incrementally when CNC machining up to volumes in the thousands where it plateaus. Structured batch production and shipments of CNC parts can help mitigate wastage or inventory costs.

Of all the various machine configurations, 3-axis CNC milling, the simplest setup, is generally the cheapest method of making uncomplicated parts with high tolerances. CNC turning on a lathe is also a highly cost competitive process when cylindrical workpieces like threaded rods and shaft couplings are required. Typically, a lathe would cost 15% less than the 3-axis machine for a similar part.

With 5-axis CNC machining, the options are split into two configurations: indexed 5-axis

CNC milling and continuous 5-axis CNC milling. In indexed 5-axis CNC milling, the workpiece is automatically rotated to give tools more access to mill features. The extra two directions of movement are done between milling steps without removing the part from its fixture. The difference with continuous 5-axis CNC milling is that the machine can simultaneously move in all directions as the workpiece is cut. Both processes eliminate the added cost and potential margin for human error that comes with manually repositioning a workpiece. Due to these benefits, 5-axis machining is the best solution for complex components.

In comparison to “basic” 3-axis CNC mills, 5-axis machining comes at an increased expense, with indexed 5-axis CNC milling being the cheaper of the two. Continuous 5-axis CNC milling typically costs over 20% higher than an indexed 5-axis machine, and about double that of a standard 3-axis mill.



A rocket engine injector radial passage CNC machined from aluminum 6061 for engineers at UC Irvine. See more.



Chapter 3
Tips for CNC Machining

Digital Manufacturing Essentials: 7 Tips to Help You Design for CNC Machining



Key Checklist for Quality Design

CNC machining is the manufacturing method of choice when you need simple parts with tight tolerances, excellent mechanical properties, and scalable low volume production. To achieve the highest impact from each of these strengths, there are several key factors that you should consider during the design process.

Your decisions will vary depending on the technology used, i.e. 3-axis, 4-axis or 5-axis milling, and mill orientation, i.e. horizontal or vertical. Every variant, however, will circle back to four key questions:

1. What size and shape drill bit can I use?
2. Can this tool access the feature that I want to mill?
3. How much vibration will this make (at the cost of precision)?
4. How will the heat of the bit affect the material I am working with?

With these four questions in mind, here are seven basic rules to follow for effective CNC machined part design. Tip: A chart of standard bit sizes and diameters for reference throughout this article can be found here.

7 Rules of CNC Machining

Rule 1: All roads lead to radii
As the majority of drill bits are cylindrical by design, this means any internal cuts you make will also create a curved corner/edge, also known as a fillet. When designing a part containing internal fillets, "the bigger the better" is a good rule to follow. The resulting corner will be half the diameter of the tool used.

Use a non-standard radius, e.g. 1.25 mm rather than 1 mm, to give a tool clearance to cut the corner. Where possible, design using a different wall and floor radii too so the same tool can be used throughout.

The exact measurement for internal corners will be relative to the depth of the cavity being machined. When inserting internal corners and edges, account for a radius more than one third the depth of the cavity.

Rule 2: Undercut for right angles
To create right angles in a CNC machined part, it is better to add undercuts to the design rather than attempting to reduce the radius

of your corners for a similar effect. To avoid the added cost of custom tooling, design an undercut with a standard dimension, i.e. 3 mm to 40 mm wide in whole mm increments. Due to the shape of tools used, keep undercuts shallow where possible. The maximum achievable depth of undercutting tools will be double the width of the head.

Rule 3: Fillets give you cavities
Cavity/pocket depth is typically relative to the diameter of the tool used to make internal fillets. As a guide, pocket depth should be up to 3 - 4 times the tool diameter. Any deeper than 6 times the tool diameter will require a larger tool. This will result in sacrifices to the radius of your corners.

Cavity width should also be considered when machining a pocket. Keeping depth to a maximum of 4 times the width is a good guide measurement.

Rule 4: Tall features, bad vibrations
As with the depth of cavities and pockets, the maximum height for tall features is up to 4 times the feature's width. The taller a feature, the more prone to vibration it is, reducing the machined precision of your part.

Rule 5: Avoid thin walls
Generally speaking, it is better to have thicker walls in the design of your part. As with tall walls, vibrations increase when producing thin features. When machining plastics, heat also has to be taken into consideration. Thinner walls will be more susceptible to softening and warping due to the friction of the toolhead.

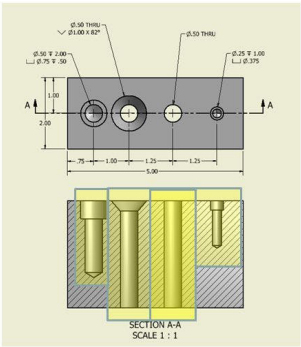
As a guide, between 1.0 and 1.5 mm is an appropriate minimum thickness for plastic walls. Minimum walls within the range of 0.5 mm and 0.8 mm are possible in metal parts.

Walls should be thicker if they are supporting or taller to avoid vibration and chatter.

Rule 6: Stick to the standards when making holes
There are two types of holes to choose from in CNC milling: blind holes and through holes. No matter which of these types is chosen, the recommended depth and diameter are the same. Hole diameter should correlate to standard drill bit sizes from 25.5 mm (over 1 mm diameter) and above. The maximum hole depth relies on the nominal diameter of a hole. It is common to create a hole depth equal to 10 times the nominal diameter of a hole.

Hole Definitions

- Through/Thru
  - Hole cuts through entire thickness
- Clearance
  - Hole large enough to allow screw head (and driver) to pass through
- Blind
  - Hole does **not** cut through entire thickness



Rule 7: Stick to the standards for threads
Sticking to standard sizes is also important when creating threads. The larger the thread, the easier it is to machine. Length should be kept to a maximum of 3 times the nominal diameter of a hole. Avoid extra costs by sticking to off-the-shelf thread sizes in your parts.

Design for CNC Machining Checklist

Reference Check

Feature	Rule
Internal corners/edges	Radius ≥ one third cavity depth
Undercuts	Design using standard dimensions: 3 mm to 40 mm
Pockets	Guide maximum depth is 4 x the width
Tall features	Guide maximum height is 4 x the width
Walls	Minimum wall width for plastic: 1.0 - 1.5 mm, Metal: 0.5 mm - 0.8 mm
Holes	Depth should be kept within 10 x the nominal diameter of the hole
Threads	Length should be kept within 3 x the nominal diameter of the hole

Chapter 4
Industrial Applications of CNC Machining

5 Innovative Applications

Introduction
From its roots in the aerospace industry, CNC machining has branched out to the production of much more than just helicopter rotor blades (as cool as that is). Some of the most common applications of the technology now include mold-making, tooling, and fixturing. Going beyond the Earth's atmosphere, CNC machining is used to prototype parts for space. It is also used in product development and end-use production of parts for medical, automotive, industrial and electronics industries.

Focusing on these five areas, in particular, we've compiled a list of innovative applications made possible by CNC machining.

Breaking into aerospace and beyond
The mechanical properties and achievable accuracy of CNC machining mean that it lends itself well to the stringent regulations of the aerospace sector. An AS9100D certification signifies that a CNC machining facility is capable of maintaining the quality standards established by the Society of Automotive Engineers for this industry.
CNC machining applications in aerospace vary from small parts, such as tooling and component housings, through to medium and large components integral to an aircraft's landing gear, wings, and bodies. This applies to both civil and military vehicles.

At NASA, CNC machining is mission-proven manufacturing technology. The method has been applied at the agency to everything



from ground testing and internal engineering projects to its interstellar missions and voyages to the International Space Station (ISS).

Specialist workshops at leading aerospace manufacturers also use CNC machining. The speed brake of the F-15 Eagle fighter jet, for example, is made by Boeing's proprietary CNC machining methodology.

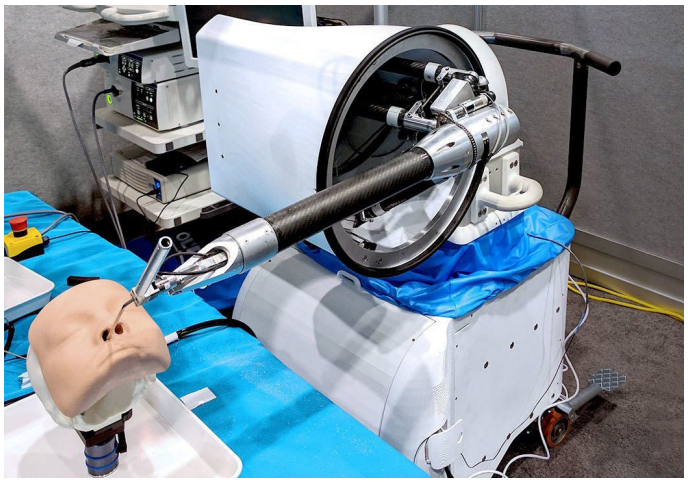
By selecting CNC machining, aerospace OEMs can consolidate part assemblies, thereby increasing mechanical stability and reducing complexity — which is valuable when it comes to replacement. Over the lifetime of an aircraft, the multiple coating options for CNC machining, like anodizing, also offer a high degree of protection against corrosion from the elements, making it a valuable option for end-use production



Improving surgical operations

In medicine, CNC machining is especially practical in the rapid prototyping of devices. By matching material selections between a prototype and end-use part, a proof-of-concept medical device can be made to provide the same mechanical performance as its mass-produced equivalent, leading to better testing at those critical early stages.

At Galen Robotics, a Californian med-tech developer, CNC machining is combined with other manufacturing processes to develop new solutions for noninvasive surgery. Focusing on the field of otolaryngology, the team seeks to improve surgeons' means of operating on delicate areas like the ear, nose, and throat. An assistive device conceptualized by the Galen Robotics team has undergone a number of iterations, thanks to the quick turnaround of CNC machining. As a result, the device is now undergoing clinical testing.



The material selection in CNC machining is also essential to producing end-use devices in healthcare. Common medical-grade materials, such as Titanium 6Al-4V, PEEK, and Stainless Steel 17-4 are all CNC machineable. Both titanium and PEEK have proven to have high biocompatibility when implanted into the body. The precision of CNC machines makes it possible to create a complex surface texture on the implants, which in turn helps encourage the in-growth of live cells and reduces the risk of rejection from human immune systems.

Read more about the Medical Robot Built by Galen Robotics here.

The competitive edge in car racing and renovation

Ever dreamed of renovating a classic car? CNC machining could help with that, too. Ideal for producing legacy parts no longer in production, this method is perfect when sturdy construction is required. Vintage Volkswagen camper vans sold by GoWesty in Los Osos, California, aim to be "in better shape than when they came off the factory line" after renovation. Roller bearings used on the sliding doors of the vans and sections of the electronic fuel injection (EFI) system are just a handful of the parts made for GoWesty by Xometry's CNC machining partners.

In race car development, CNC machining is also useful when seeking a competitive edge.



The 2018-2019 Penn Electric Racing Team and their car produced with the help of Xometry CNC machining.

Several parts for UPenn Racing Team's electric race car have been made using this technique. High-performance parts for their record-breaking vehicle include method blocks to hold the battery in place and enable an acceleration of 0 to 60 mph in less than 3 seconds. The bellcranks, vital to the performance of the suspension system, are also produced using CNC machining.

One of the main advantages CNC machining offers to the automotive sector is its flexibility. Parts from pre-production to volume batches can be made with the technology, retaining high-performance characteristics. As in aerospace, there are also many coating options available for CNC machined car parts, these include electrophoretic coating, conversion coatings, and paint finishes.

CNC turning industrial piping and mold-making into savings

The industrial sector encompasses a broad segment of manufacturing across heavy machinery, machine tools, industrial robotics, petrochemicals, power generation, and oil and gas. The applications therein are incredibly varied, including the production of pipes, toolheads and couplings. By opting for CNC machining in these cases, manufacturers in some cases are able to reduce machine downtime and to deliver more competitive production costs.

If a gear breaks in a machine, this causes a halt in the production line. In order to attain the gear from a supplier, the manufacturer would typically have to wait more than one month for delivery. In addition, the part may have to be ordered in bulk, resulting in a financial loss and potentially added cost of keeping the inventory.

CNC machining makes it possible and economical to produce a single gear or small runs of the product. By using the right manufacturing service provider with multiple global locations, the turn-around time for this part is typically reduced to within one or two weeks.



At home with electronics

Practically all consumer electronics devices today are made using CNC machining. Custom electronics housings and the PCBs inside these devices, as well as smartphones and tablets, are all beneficiaries of the machines. For PCBs, in particular, CNC milling is advantageous because it doesn't require the use of chemicals integral to other fabrication processes. For Mac users, interaction with CNC milling is part of the daily routine. Casing for the AppleMacBook laptop is milled from a single piece of aluminum, delivering the rigidity and performance of the solid bulk material. Named the "unibody enclosure," this essential piece of Apple hardware has been part of the production line since 2008.

Chapter 5

CNC Machining Materials

Explore the various material options for CNC Machining

Aluminum

Key properties: Aluminum is highly regarded for its strength-to-weight ratio and corrosion resistance. It also exhibits good thermal and electrical conductivity.

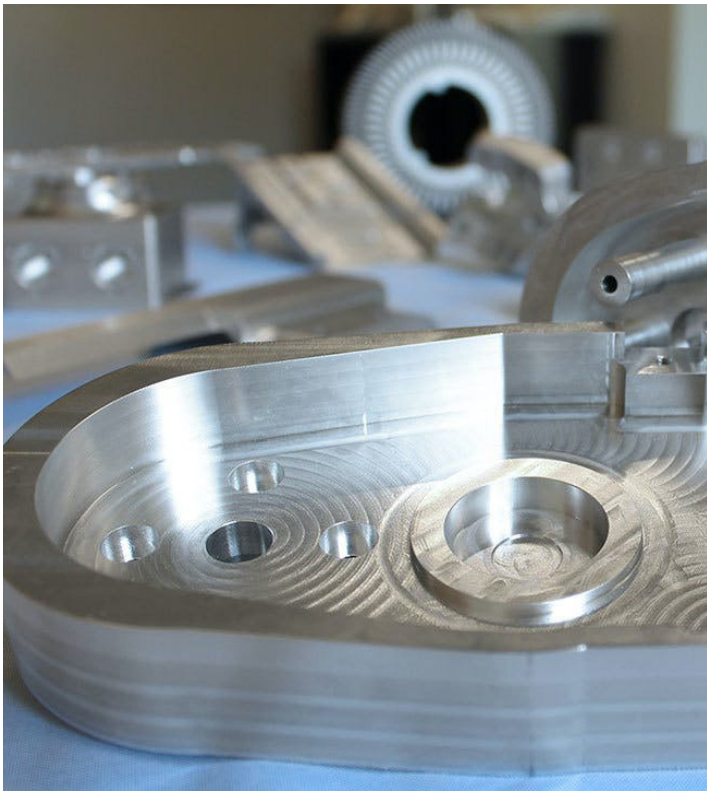
- Aluminum 6061-T6: 6061 is one of the most commonly used varieties of aluminum, finding universal application. T6 designation gives the material an ultimate tensile strength 276 MPa. Common applications: general

- Aluminum 7075: 7075 has an ultimate tensile strength of 572 MPa, which is comparable to steel. Useful for high-stress applications, its use is somewhat limited by high cost. Common applications: aerospace, automotive, marine

- Aluminum 2024-T3: A 2000 series alloy, 2024-T3 has a high strength-to-weight ratio with a tensile strength of 400–430 MPa and yield strength of at least 270–280 MPa. Through T3 designation it has been solution heat treated and cold worked. Common applications: industrial, aerospace, medical, electronics

- Aluminum 5052: At 117 MPa, the fatigue strength of this variety is higher than most aluminium alloys. It also has exceptional resistance against seawater and salt spray. Common applications: marine, aerospace, electronics

- Aluminum MIC-6: Similar to the 7000 series of aluminum alloys, MIC-6 is a cast plate material commonly used in tooling and base plates. Common applications: aerospace, electronics, gears



Brass, Bronze, and Copper

Key properties: Pure copper is a soft and malleable metal with very high thermal and electrical conductivity. Both brass and bronze are alloys of copper. Brass is a combination of copper and zinc, and bronze is mainly copper with tin. In general, brass is valued for its machinability and high strength retention. Bronze has low-friction properties with high resistance to corrosion. Brass, bronze and copper are all often selected for their aesthetic appearance.

- Brass C360: A highly machinable material, C360 is the lowest cost of all brass alloys. Sectors: industrial, commercial

- Brass 260: The most ductile brass alloy, 260 is used in greater quantity than others of this variety. Sectors: industrial, commercial

- C932 M07 Bearing Bronze: Used for light-duty applications, this alloy is easy

to machine and corrosion resistant. Sectors: general

- ETP Copper C110: This alloy has the highest electrical conductivity (100% IACS) of any metal except silver (105% IACS). Sectors: electric, building, medical

- Copper 101: The base material for many brasses and bronzes, Copper 101 has high ductility (5% to 50% elongation) and impact strength. Sectors: electronics, automotive, commercial

Steel

Key properties: Arguably offering the widest variety of CNC machining materials, steel is available as stainless, alloy, tool and mild varieties. Generally speaking, steels have good mechanical properties and are easy to machine.

- Steel 1018: This low-carbon, general-purpose steel is ductile and suitable for forming and welding. Sectors: general, gears, screws, nuts

- ASTM A36: An example of mild steel, A36 is a low-cost alloy with good mechanical properties, including an ultimate tensile strength of 400–550 MPa and 20% elongation at break. Sectors: gears, construction

- Alloy Steel 4130: This versatile steel alloy is optimized in composition for strength (670 MPa ultimate), toughness (435 MPa tensile strength at yield) and machinability. Sectors: aerospace, oil & gas, automotive

- Stainless Steel 304: The most common variety of stainless steel and exemplary of the base qualities of steel, this alloy has a higher corrosion resistance than most other steels, with lower conductivity. It is not suitable for applications that require welding. Sectors: food, screws, automotive

- Stainless Steel 17-4: This precipitation hardened stainless steel is known for its high strength and mechanical properties which can be further developed through heat treatment. With good mechanical properties even in operating temperatures of 600 Fahrenheit and high corrosion resistance, this material works very well in demanding environments. Sectors: Nuclear, marine, food, and medical.

Titanium

Key properties: Although heavier than aluminum (but still lighter than steel), titanium is also known for its exceptional weight-to-strength ratio. Due to its hardness, many varieties of titanium are deemed difficult to machine.

- Titanium Grade 2: An unalloyed variety of titanium, Grade 2 is a common form of this metal, with high strength (344 MPa ultimate) and exceptional corrosion resistance. It is often used to make heat exchangers. Sectors: aerospace, automotive, chemical

- Titanium 6Al-4V: Another commonly used titanium variety, this alloy is best used when low density (4.429–4.512 g/cm3) and excellent corrosion resistance are required. Sectors: medical, aerospace, marine, gas

Zinc

Key properties: Zinc is not commonly used in CNC machining because most varieties are too brittle for the process. In some particular forms, the material becomes easy to work and is readily treatable.

- Zinc Sheet Alloy 500: A continuous-cast alloy, this machinable zinc has good electrical conductivity and is highly resistant to corrosion. Sectors: construction

Plastics

Key properties: Lightweight and strong, some industrial plastics can be considered as low-cost replacements for metal parts. Incredibly versatile, plastics have wide-reaching applications across all industries.

- ABS: This common, high-strength thermoplastic with electrical insulation properties is good for low-cost, lightweight tooling and for prototypes. Sectors: general, medical, automotive, electronics

- Acetal: Branded as Delrin, this material is arguably the easiest plastic to machine. It has excellent stiffness (flexural strength 82.7 MPa), low friction and good resistance to moisture. Sectors: general, gears, electronics, medical, construction

- Nylon 6/6: A common polyamide, Nylon 6/6 — or simply 66 — has high mechanical strength (66 MPa), rigidity and good stability under heat and chemical exposure. Sectors: automotive, electronics, gears, pipes

- PEEK: This high-grade thermoplastic is used in a variety of mechanically demanding situations. Sectors: medical, aerospace, automotive, electronics

- Polycarbonate: Commonly referred to as PC, this clear plastic has excellent optical properties. It is durable, lightweight and strong, with high impact resistance (600–850 J/m). Sectors: general, electronics, aerospace, automotive, pipes

