High-Temperature Machining

Superalloys, also known as heat-resistant superalloys or high-temperature alloys, are materials that can be machined at temperatures exceeding 1000˚ F (540˚ C). No other alloy system has a better combination of high-temperature corrosion resistance, oxidation resistance, and creep resistance. Because of these characteristics, superalloys are widely used in aircraft engine components and in industrial gas turbine components for power generation. They are also utilized in petrochemical, oil, and biomedical applications, specifically for their excellent corrosion resistance.

Today, fuel efficiency and reliability drive modern aircraft engine design. Engineers have long relied upon superalloys, such as INCONEL® and Waspaloy™, for their unique high-temperature and stress-resistance properties. Such properties are especially critical to the aerospace industry.

Modern aircraft engines are far more reliable than their predecessors, and thanks to great strides in technology, it is now common to "stay on wing" for years. These engines are also powerful and dependable enough that just two can power large jetliners across entire oceans without concern. In addition to commercial applications, mission-critical defense operations increasingly rely upon the peak performance and mission readiness the engines offer.

No material is perfect, however. Historically, one drawback of superalloys has been their poor machinability. This is where Kennametal comes in.

Kennametal has decades of experience working with material providers, OEMs, and parts manufacturers, resulting in an unmatched portfolio of standard and custom solutions. We are proud to be the supplier of choice in superalloy tooling solutions for most OEMs, and their subcontractors, around the world.

We would like to share with you some of this knowledge, and are pleased to present the following guide to machining these materials. Topics covered range from understanding metallurgical properties of superalloys to the best technologies for machining.

KENNAMETAL

Superalloy Classifications

High-temperature alloys are broadly classified into three groups: nickel-base, cobalt-base, and iron-nickel-base alloys (titanium alloys are also included in this category and are discussed in detail in the Titanium Machining Guide on pages D18–D33.)

Nickel-Base Superalloys

Among the high-temperature alloys, nickel-base alloys are the most widely used. As a result, they are often found in aerospace engine and power generation turbine components, as well as in petrochemical, food processing, nuclear reactor, and pollution control equipment. Nickel-base alloys can be strengthened by two methods: through solid solution strengthening or by being hardened through intermetallic compound precipitation in fcc matrix.

Alloys such as INCONEL® 625 and Hastelloy® X are solid solution strengthened. These solid solution hardened alloys may get additional strengthening from carbide precipitation. Alloys such as INCONEL® 718, however, are precipitation strengthened. A third class of nickel-base superalloys, typified by MA-754, is strengthened by dispersion of inert particles such as yttria (Y_2O_3), and in some cases with γ' (gamma prime) precipitation (MA-6000E).

Nickel-base alloys are available in both cast and wrought forms. Highly alloyed compositions, such as Rene 95, Udimet 720, and IN100, are produced by powder metallurgy followed by forging. For the above wrought alloys and for cast alloys (Rene 80 and Mar-M-247), the strengthening agent is γ' precipitate. For INCONEL® 718, γ'' (gamma double prime) is the primary strengthening agent. Alloys that contain niobium, titanium, and aluminum, such as INCONEL 725, are strengthened by both γ' and γ'' precipitates.

Cobalt-Base Superalloys

Cobalt-base superalloys possess superior corrosion resistance at temperatures above 2000° F (1093° C) and find application in hotter sections of gas turbines and combustor parts.

Available in cast or wrought iron form, cobalt-base superalloys are characterized by a solid solution strengthened (by iron, chromium, and tungsten), by an austenitic (face centered cubic or fcc) matrix, in which a small quantity of carbides (of titanium, tantalum, hafnium, and niobium) is precipitated. Thus, they rely on carbides, rather than γ' precipitates, for strengthening, and they exhibit better weldability and thermal fatigue resistance than nickel-base alloys. Cast alloys, such as Stellite 31, are used in the hot sections (blades and vanes) of gas turbines. Wrought alloys, such as Haynes 25, are produced as sheet, and are often used in combustor parts.

Iron-Nickel-Base Superalloys

Iron-nickel-base superalloys are similar to wrought austenitic stainless steels, except for the addition of γ' strengthening agent. They have the lowest elevated temperature strength among the three groups of superalloys, and are generally used in the wrought condition in gas turbine disks and blades.

Most wrought alloys contain high levels of chromium, which provide corrosion resistance. They owe their high-temperature strength to solid solution hardening (hardening produced by solute atoms dissolved in the alloy matrix) or precipitation hardening (hardening produced by precipitate particles).

Alloys such as Haynes 556 and 19-9 DL are solid solution strengthened with molybdenum, tungsten, titanium, and niobium. Alloys such as A286 and Incoloy 909 are precipitation hardened. The most common precipitates are γ', (Ni_3 [Al, Ti]) (e.g., A286), and γ'', (Ni_3Nb) (e.g., Incoloy 909).

Another group of iron-nickel-base alloys contains high carbon content and is strengthened by carbides, nitrides, and solid solution strengthening. A group of alloys, based on Fe-Ni-Co and strengthened by γ', combines high strength with a low thermal expansion coefficient (e.g., Incoloy 903, 907, and 909) and finds application in shafts, rings, and casings for gas turbines.

Metallurgy of Superalloys

High-temperature alloys derive their strength from solid solution hardening, gamma prime precipitation hardening, or oxide dispersion strengthening.

Metallurgy is controlled by adjustments in composition as well as through processing, including the aging treatment where the solution-annealed alloy is heated until one or more phases occur. The resulting austenitic matrix — combined with a wide variety of secondary phases such as metal carbides (MC, M23C6, M7C3), γ', the ordered fcc strengthening phase (Ni_3 [Al, Ti]), or the γ'' (Ni_3Nb) — impart to the alloys their excellent high-temperature strength.

Superalloy components are typically available in cast, wrought (forged), and sintered (powder metallurgy) forms. Some important characteristics to consider about each form:

- Cast alloys have coarser grain sizes and exceptional creep strength.
- Wrought alloys have more uniform and finer grain sizes and possess higher tensile and fatigue strength.
- Powder metallurgical processing enables production of more complicated and near-net shapes.

Superalloy Classifications *(continued)*

Nickel-Base Superalloys

- Properties: High-temperature creep resistance, corrosion resistance, and thermal shock resistance.
- Potential Source(s) of Strengthening:
  - Solid solution strengthening with Co, Cr, Fe, Mo, W, Ta, and Re (e.g., INCONEL® 600 or INCONEL 625)
  - γ' (Ni_3 [Al, Ti]) precipitation hardening (e.g., INCONEL 718)
  - Oxide-dispersion strengthening (e.g., IN-100 or Waspaloy®)
- Applications: Aerospace engine components.

Cobalt-Base Superalloys

- Properties: High-temperature creep resistance and superior corrosion resistance.
- Potential Source(s) of Strengthening: Primarily solid solution strengthening (Cr, Fe, and W), but can have additional strengthening by carbides (Ti, Ta, Hf, and Nb).
- Applications: Hot sections (blades and vanes) of gas turbines and combustor parts.

Iron-Nickel-Base Superalloys

- Properties: Lowest elevated temperature strength among the superalloys, high corrosion resistance.
- Potential Source(s) of Strengthening:
  - Solid solution strengthening with Cr, Mo, and W (e.g., Discaloy)
  - γ' (Ni_3 [Al, Ti]) precipitation hardening (e.g., A286)
- Applications: Gas turbine disks and blades.

Machinability of Superalloys

As previously mentioned, superalloys generally have poor machinability. The very characteristics that provide superior high-temperature strength also make them difficult to machine. Additionally, decreased cutting tool speeds can limit productivity.

The main challenges to machining superalloys include:

- The high strength of nickel-base superalloys at cutting temperatures causes high cutting forces, generates more heat at the tool tip (compared to alloy steel machining), and limits their speed capability.
- The low thermal conductivity of these alloys transfers heat produced during machining to the tool, subsequently increasing tool tip temperatures and causing excessive tool wear, which can limit cutting speeds and reduce useful tool life.
- The presence of hard, abrasive intermetallic compounds and carbides in these alloys causes severe abrasive wear on the tool tip.
- The high capacity for work hardening in nickel-base alloys causes depth-of-cut notching on the tool, which can lead to burr formation on the workpiece.
- The chip produced during machining is tough and continuous, therefore requiring acceptable chip control geometry.

In addition to the challenges mentioned above, the metallurgical route by which the components are produced also affects their machinability. These materials are easier to machine in the solution annealed (soft) condition than in the heat-treated (hard) condition. Furthermore, under similar conditions of heat treatment, the iron-nickel-base superalloys are easier to machine than the nickel-base or cobalt-base superalloys.

Finish machining is critical for aerospace components because the quality of the machined surface may influence the useful life of the components. Great care is taken to ensure that there is no metallurgical damage to the component surface after the final finishing pass.

Tool Life Modeling • KC5010/KC5510 Machining Ti6Al4V

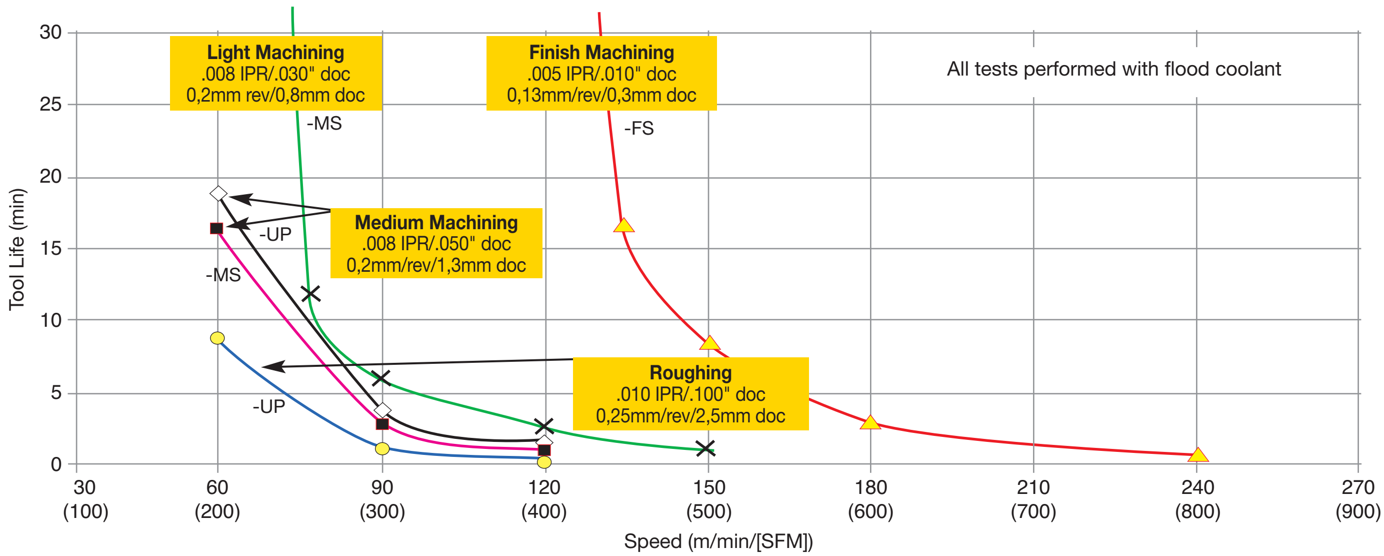
◇ CNMG432UP / CNMG120408UP — .008 IPR/.050" doc, 0,2mm/rev/1,3mm doc

■ CNMG432MS / CNMG120408MS — .008 IPR/.050" doc, 0,2mm/rev/1,3mm doc

△ CNGG432FS / CNGG120408FS — .005 IPR/.010" doc, 0,13mm/rev/0,3mm doc

✕ CNMG432MS / CNMG120408MS — .008 IPR/.030" doc, 0,2mm/rev/0,8mm doc

○ CNMG432UP / CNMG120408UP — .010 IPR/.100" doc, 0,25mm/rev/2,5mm doc



KC5010 — UP performs well in medium machining applications at 60–90m/min (200–300 SFM)
KC5510 — FS performs well in finishing applications at 137–168m/min (450–550 SFM)

Machining Guidelines for Superalloys

When machining with CARBIDE tooling:

- PVD coated carbide tools with positive rakes are suitable for finishing and medium machining.
  - Reduces cutting forces and temperatures
  - Minimizes part deflection
- Always maintain high feed-rate and depth of cut.
  - Minimizes hardening
- Use a generous quantity of coolant with carbide tools.
  - Reduces temperature build-up and rapid tool wear
- Utilize high-pressure coolant whenever possible.
- For rough cutting, T-landed ceramic inserts are recommended.
- With carbide inserts, use moderate cutting speeds.
  - Minimizes tool tip temperatures and encourages longer tool life
- Never allow tool to dwell.
  - Minimizes possibility of work hardening and subsequent problems in downstream process

When machining with CERAMIC tooling:

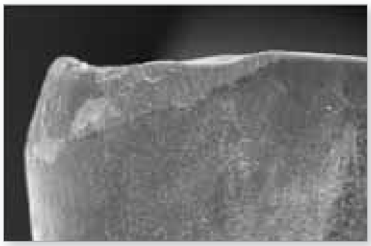
- Higher cutting speeds of 600–4000 SFM are possible with ceramic tools (SiAlON and SiC whisker-reinforced Al_2O_3).
- There is no need for coolant.
- Depth-of-cut notching is more pronounced (versus carbides).
- When notching is severe (primarily in roughing cuts on forgings with scale), use higher lead angle.
  - Reduces tool pressure and work hardening and improves surface finish

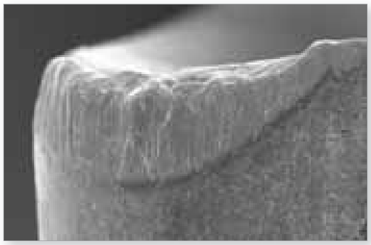
When machining with PCBN tooling:

- Use low-content PCBN grades for finishing and semi-finishing at low depth of cut, but optimize the cutting conditions for each individual part, and pay close attention to surface condition.
- Use sharp edge uncoated grades for better surface finishes and close tolerance.
- Use coated grades to increase tool life and productivity.

Machining Challenges for Superalloys

- High-Temperature Alloys have a low thermal conductivity, meaning heat generated during machining is neither transferred to the chip nor the workpiece, but is heavily concentrated in the cutting edge area.
- These temperatures can be as high as 1100°C to 1300°C, and can cause crater wear and severe plastic deformation of the cutting tool edge.
- Crater wear can, in turn, weaken the cutting edge, leading to catastrophic failure. Crater wear resistance is an important tooling property requirement for machining High-Temperature Alloys.
- Plastic deformation, on the other hand, can blunt the edge, thereby increasing the cutting forces. Retention of edge strength at elevated temperatures is also a very important tooling requirement while machining High-Temperature Alloys.
- The chemical reactivity of these alloys facilitates formation of Built Up Edge (BUE) and coating delamination, which severely degrades the cutting tool — leading to poor tool life. An ideal cutting tool should exhibit chemical inertness under such extreme conditions.
- The hard, abrasive intermetallic compounds in the microstructure cause severe abrasive wear to the tool tip.
- The chip produced in this machining is tough and continuous, and requires superior chip breaker geometry.
- Heat generated during machining can alter the alloy microstructure, potentially inducing residual stress that can degrade the fatigue life of the component.





High-Temperature Alloy Characteristics and Troubleshooting

Nickel-Base, Heat-Resistant Alloys (140–475 HB) (≤48 HRC)

Astroloy, Hastelloy®, B/C/C-276/X, INCONEL® 601/617/625/700/706/718, IN100, Incoloy® 901, MAR-M200, Nimonic®, Rene 41, Udimet®, Waspaloy®, Monel®

Material Characteristics

- High forces at the cutting edge.
- High heat concentration in cutting area.
- High cutting speed may cause insert failure by plastic deformation.
- Relatively poor tool life.
- Small depths of cut are difficult.
- Rapid workhardening.
- Usually abrasive rather than hard.

Troubleshooting

Problem	Solution
Depth-of-cut notch	1. Increase toolholder lead angle. 2. Use tougher grades like KC5525™ and KY4300™ in -MS, -MP, and -RP geometries or ceramic grade KY1540. 3. Use a 0,63mm/.025" or greater depth of cut. 4. Depth of cut should be greater than the workhardened layer resulting from the previous cut (>0,12mm/.005"). 5. Program a ramp to vary depth of cut. 6. Feed greater than 0,12mm/.005 IPR. 7. Use strongest insert shape possible. 8. When possible, use round inserts in carbide grade KC5510™, KC5010™, or Kyon® grades. 9. Decrease depth to 1/7th of insert diameter for round inserts (i.e.: 1,90mm/.075" max. depth for 12,7mm/1/2" IC RNG45).  Depth-of-cut notch
Built-up edge	1. Increase speed. 2. Use grades KY1540™ or KY4300. 3. Use positive rake, sharp PVD coated grades KC5510 and KC5010. 4. Use flood coolant.  Built-up edge
Chipping	1. Use MG-MS geometry in place of MG-FS or ..GP geometries. 2. For interrupted cutting, maintain speed and decrease feed. 3. Use a tougher grade like KC5525.  Chipping
Torn workpiece surface finish	1. Increase speed and reduce feed rate. 2. Use a GG-FS or GT-HP geometry. 3. Apply KY1540 or KY2100™.  Torn workpiece surface finish
Workpiece glazing	1. Increase depth of cut. 2. Increase feed rate and decrease speed. 3. Reduce insert nose radius size.

High-Temperature Alloy Characteristics and Troubleshooting *(continued)*

Cobalt-Base, Heat-Resistant Alloys (150–425 HB) (≤45 HRC)

Wrought: AiResist 213, Haynes 25 (L605), Haynes 188, J-1570, Stellite
Cast: AiResist 13, Haynes 21, Mar-M302, Mar-M509, Nasa C0-W-Re, WI-52

Material Characteristics

- High forces at the cutting edge.
- High heat concentration in cutting area.
- High cutting speed may cause insert failure by plastic deformation.
- Cast material more difficult to machine than wrought.
- Relatively poor tool life.
- Small depths of cut are difficult.
- Rapid workhardening.
- Usually abrasive rather than hard.

Troubleshooting

Problem	Solution
Depth-of-cut notch	1. Increase toolholder lead angle. 2. Use a tougher carbide grade like KC5525™ or ceramic grades KY1540™, KY2100™, or KY4300™. 3. Use a 0,63mm/.025" or greater depth of cut. 4. Program a ramp to vary depth of cut. 5. Feed greater than 0,12mm/.005 IPR. 6. Use strongest insert shape possible. 7. Depth-of-cut should be greater than the work-hardened layer resulting from the previous cut (>0,12mm/.005").  Depth-of-cut notch
Built-up edge	1. Increase speed. 2. Use positive rake, sharp PVD coated grades KC5510™ and KC5010™. 3. Use ceramic grades KY1540 or KY4300.  Built-up edge
Chipping	1. Use MG-MS geometry in place of GG-FS or ..GP. 2. For interrupted cutting, maintain speed and decrease feed.  Chipping
Torn workpiece surface finish	1. Increase speed. 2. Reduce feed rate. 3. Use a GG-FS, GT-HP, or GT-LF geometry.  Torn workpiece surface finish
Workpiece glazing	1. Increase depth of cut. 2. Increase feed rate and decrease speed. 3. Reduce insert nose radius size.

High-Temperature Alloy Characteristics and Troubleshooting *(continued)*

Iron-Based, Heat-Resistant Alloys (135–320 HB) (≤34 HRC)

Wrought: A-286, Discaloy, Incoloy® 801, N-155, 16-25-6, 19-9 DL
Cast: ASTM A297, A351, A608, A567

Material Characteristics

- Relatively poor tool life.
- Small depths of cut are difficult.
- Rapid workhardening.
- Usually abrasive rather than hard.
- Tough and stringy chips.

Common Tool Application Considerations

Problem	Solution
Depth-of-cut notch	1. Increase toolholder lead angle. 2. Use tougher grade like KC5525. 3. Use a 0,63mm/.025" or greater depth of cut. 4. Feed greater than 0,12mm/.005 IPR. 5. Increase coolant concentration. 6. Vary depth of cut. 7. Depth of cut should be greater than the workhardened layer resulting from the previous cut (>0,12mm/.005").  Depth-of-cut notch
Built-up edge	1. Increase speed. 2. Use positive rake, sharp PVD coated grades KC5510™ or KC5010™. 3. Use ceramic grades KY1540™ or KY4300™.  Built-up edge
Torn workpiece surface finish	1. Increase speed. 2. Reduce feed. 3. Increase coolant concentration. 4. Use a GG-FS, GT-HP, or GT-LF geometry.  Torn workpiece surface finish
Workpiece glazing	1. Increase depth of cut. 2. Increase feed rate and decrease speed. 3. Reduce insert nose radius size. 4. Use a GG-FS, GT-HP, or GT-LF geometry. 5. Use PVD grade KC5510 as your first choice.

NEW Cutting Tool Technologies

Grades KC5510™ and KC5525™

Kennametal's advanced PVD TiAlN coated carbide grades KC5510 and KC5525, in high positive rake geometries GG-FS and MG-MS, have overcome many of the problems associated with machining heat-resistant alloys and titanium materials. These new products are revolutionizing productivity in finishing and medium machining of super alloys.

Cutting speeds as high as 122m/min / 400 SFM can be attained with finishing grade KC5510. Typically, speeds can be doubled over a conventional PVD product with no impact on tool life (see Figure 1).

Grade KC5510 is an advanced PVD-coated, fine-grained tungsten carbide grade specifically engineered for the productive yet demanding machining of high-temperature alloys. The fine-grain tungsten carbide (6% cobalt) substrate has excellent toughness and deformation resistance. The advanced PVD coating allows for metalcutting speeds double those of conventional PVD-coated materials.

Grade KC5525 utilizes the same advanced PVD coating as grade KC5510, combined with a fine-grain tungsten carbide (10% cobalt) substrate. The higher cobalt content provides added security in interrupted cuts while the fine grain tungsten maintains deformation resistance.

In conjunction with grades KC5510 and KC5525, Kennametal has engineered two chip control geometries specifically designed for machining superalloys. The GG-FS geometry is precision ground for optimal performance in finish cuts where low forces are required and dimensional control is critical. The MG-MS geometry is designed for medium to heavy cuts and is precision molded for added economy. Both geometries are high positive.

CNGG-432 TiAlN Tool life: 7.5 minutes	Kennametal's CNGG-432FS KC5510 Tool life: 26.5 minutes

Figure 1: Comparison of a conventional TiAlN coated carbide insert versus Kennametal's advanced PVD grade (92m/min/300 SFM, 0,12mm/.005 IPR, 0,25mm/.010" doc, 718 INCONEL® 38 HRC)

DID YOU KNOW

Kennametal developed the KCS10™ upgrade with dedicated MP geometry, a first choice for medium and finishing applications in superalloys.

Features, Functions, and Benefits

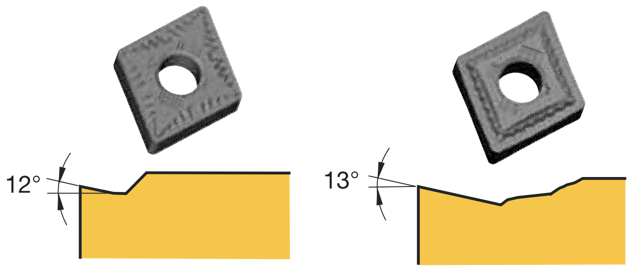
Feature	Function
• MP geometry	• Superior chip conrol
• Very positive geometry	• Minimized passive forces
• Thin PVD coating	• Allows high-cutting speeds • Extremely wear resistant
• State-of-the-art dies	• Provide tighter tolerances
• Chip control element across all edges	• Chip control across all edges

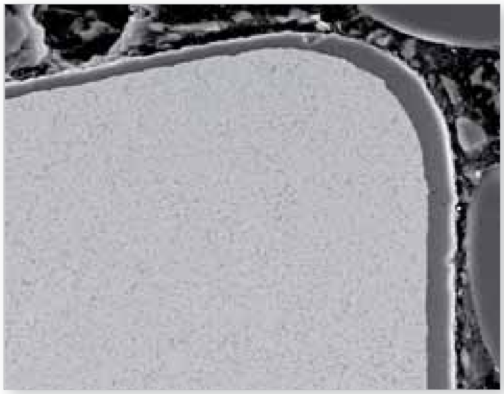
NEW Cutting Tool Technologies *(continued)*

Grades KC5510™ and KC5525™

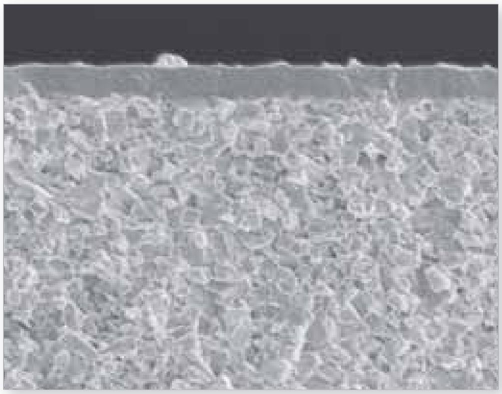
GG-FS finishing sharp

MG-MS medium sharp





Micrograph cross-section of the cutting edge.



The higher cobalt content provides added security in interrupted cuts while the fine-grain tungsten maintains deformation resistance.

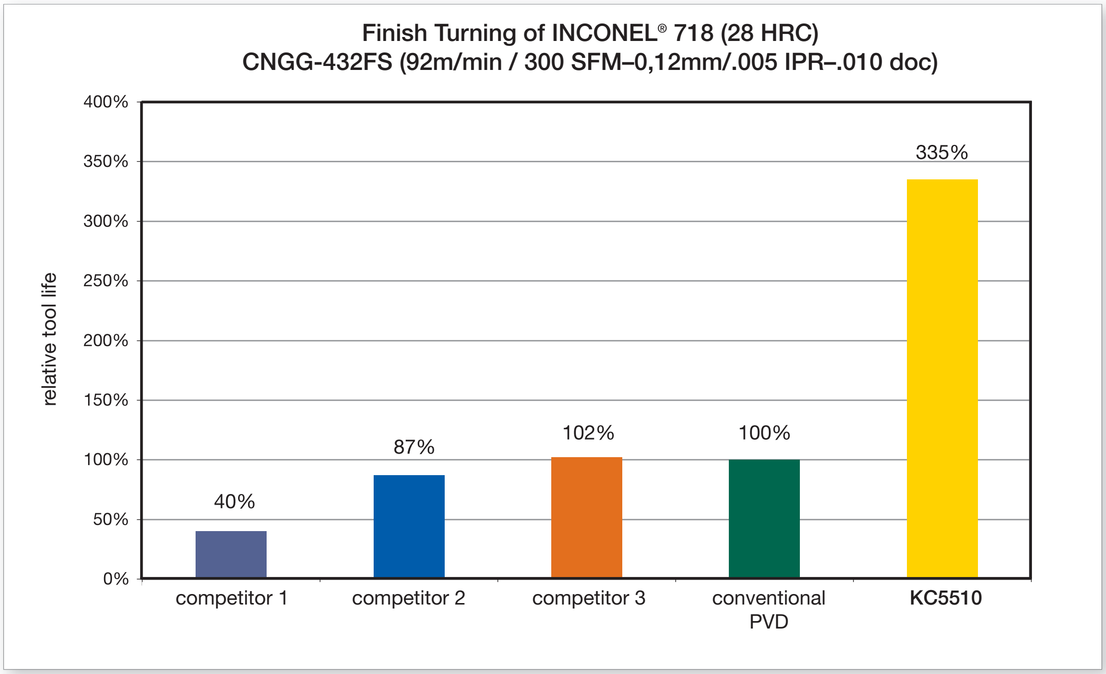


Figure 2: Kennametal's advanced PVD grade KC5510 compared to best-in-class competitive grades.

Medium Machining of INCONEL® 718

Grades KC5510™

In developing these products, Kennametal conducted extensive metalcutting tests internally and in conjunction with our customers. In more than 100 tests, these new high-performance products outperformed the competition 95% of the time.

Figures 3–5 document tool life in minutes, helical cutting length in meters/feet, and volume of metal removed in cu³/min for grade KC5510 CNGG-432FS and CNMG-432MS. Materials machined were 152mm/6" diameter bars of INCONEL 718 (39 HRC) and Ti-6Al-4V (30 HRC). Feed rates and depths of cut employed in these internal tests are indicated in the test results. End-of-tool-life criteria used are 0,30mm/.012" flank-wear, nose wear, or depth of cut, and 0,10mm/.004" crater depth. Use this metalcutting data as a benchmark for planning your machining operations to realize optimum economy. Calculate the helical cutting length based on the feed rate, workpiece diameter, and length of cuts. Determine the optimum cutting speed from data in the following charts.

Finishing of INCONEL 718

Note that when machining INCONEL 718, grade KC5510 in CNGG432-FS geometry delivers tool life as high as ~50 min at 60m/min / 200 SFM, 0,12mm/.005 IPR, and 0,12mm/.005" doc (Figure 3). This insert can be run even at 122m/min / 400 SFM, with good tool life. For carbide tools, these speeds represent a 100%+ improvement in productivity over conventional PVD-coated tools.

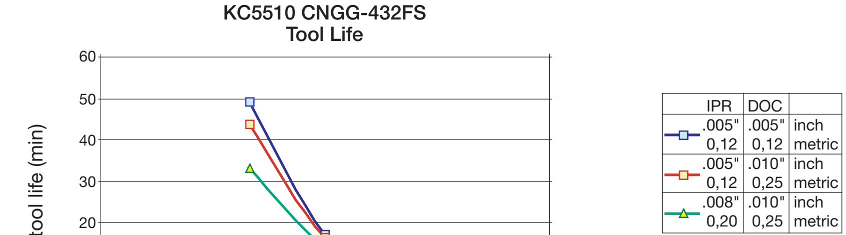


Figure 3: Tool life for INCONEL 718

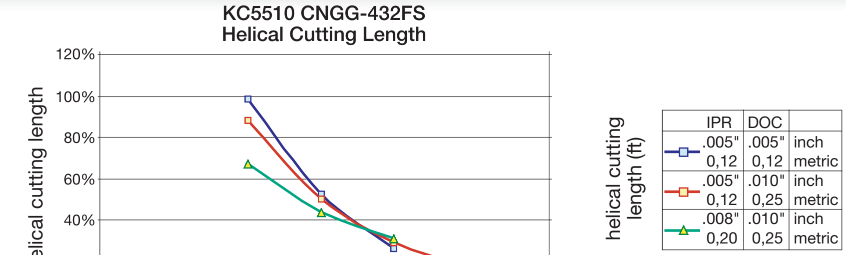


Figure 4: Helical cutting length for INCONEL 718

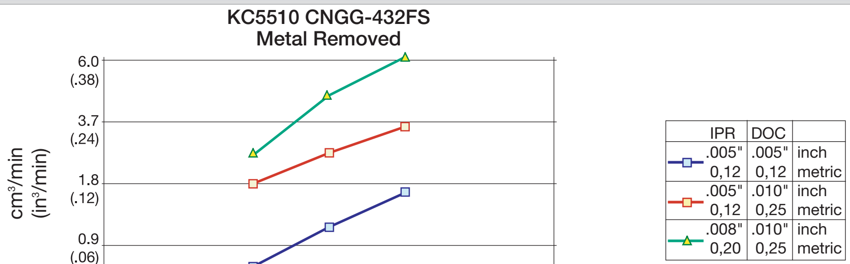


Figure 5: Cubic inches of material removed cutting INCONEL 718

(continued)

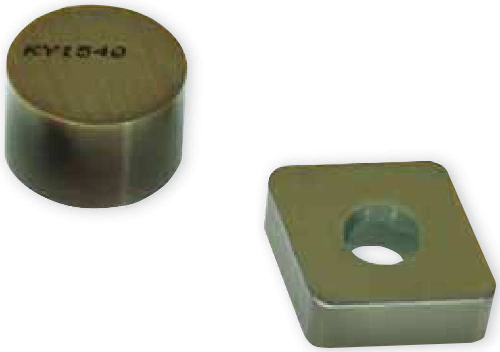
Medium Machining of INCONEL® 718 *(continued)*

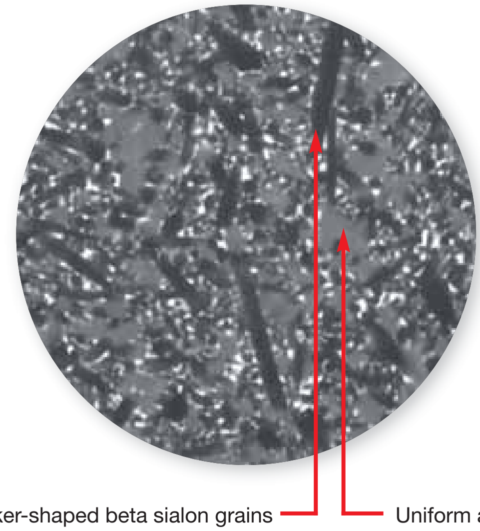
KY4300™ is the Benchmark

Compared to KY1540, KY4300 can be expected to perform with lower wear levels and offer higher speed capabilities. KY1540 has advantages in toughness and depth-of-cut notch resistance, but the excellent wear resistance of KY4300 will produce better surface finishes, cut with lower forces, and enable higher speeds versus the sialon grades.

KY1540™ is Proven

- In turning and milling applications.
- As a cost-effective replacement for expensive whisker ceramic cutting tools.
- In a broad range of high-temp alloy applications including:
  - — INCONEL® products and other nickel-based materials.
  - — Stellites and other cobalt-based materials.
- In a wide variety of machining conditions, including interrupted cuts and applications involving scale.





Whisker-shaped beta sialon grains enhance fracture toughness.

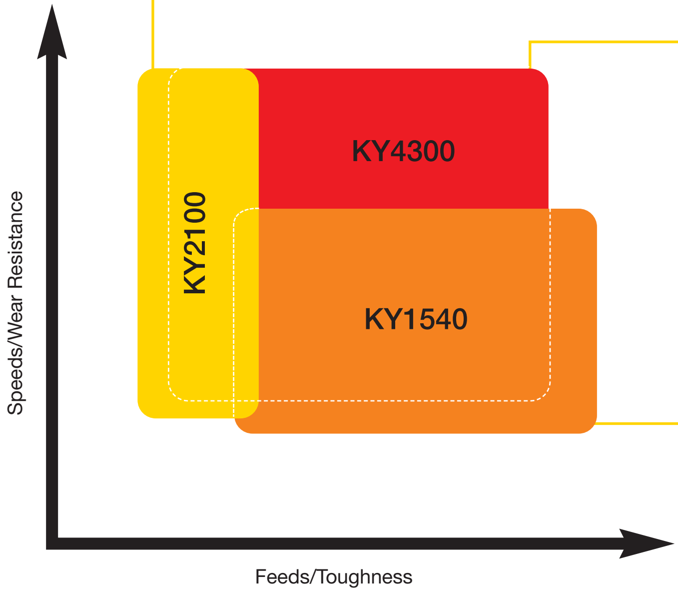
Uniform alpha sialon grain size and composition enhance hardness.

(continued)

Medium Machining of INCONEL® 718 *(continued)*

KY2100™ • Excellent Finisher

- Extremely wear-resistant.
- Ideal for high-speed turning and milling applications.
- Well-suited for finishing cuts involving a broad range of high-temperature alloys.
- Excellent for turning of hardened high-temperature alloys (>48 HRC).



KY4300™ • Benchmark

- Excellent surface finish, lower cutting force, higher speeds.
- Silicon carbide whiskers deliver longer tool life and increased toughness.

KY1540™ • Proven

- Long, consistent tool life.
- Excellent toughness and depth-of-cut notch resistance.
- Performs in a wide variety of machining conditions, including interrupted cuts and applications involving scale.