Greenleaf®
Sustainable Productivity

Greenleaf Corporation is a leading supplier of industrial cutting tools, specializing in the manufacture of high-performance tungsten carbide and ceramic grade inserts and innovative tool-holding systems. Greenleaf continues to build on 75 years of innovation and the legacy established by its founder Walter J. Greenleaf, Sr., which centers on supplying customers with productive solutions to every metal-cutting situation.

Discover more at: **https://greenleafcorporation.com**

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MADE IN THE USA
Greenleaf Corporation is ISO 9001 Certified.

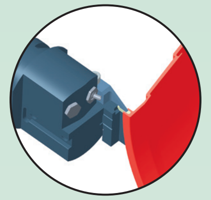
Greenleaf®
Sustainable Productivity

AEROSPACE
METALCUTTING SOLUTIONS

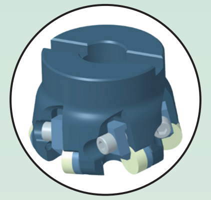
Take your machining to new heights

Greenleaf®
Sustainable Productivity

Casings p. 4

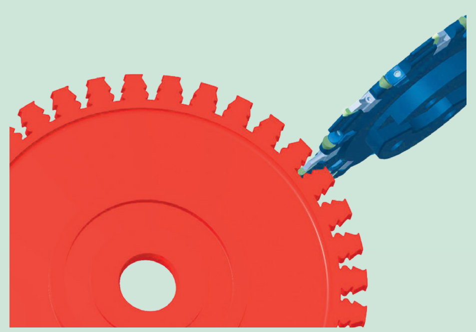


Greenleaf's support blade system utilizes 248 support blade combinations to meet the demanding features present on all aerospace casings (p. 5).



The fine-pitched Excelerator® milling range offers higher productivity with air/coolant lines through the cutter to the cutting edge. (p. 7).

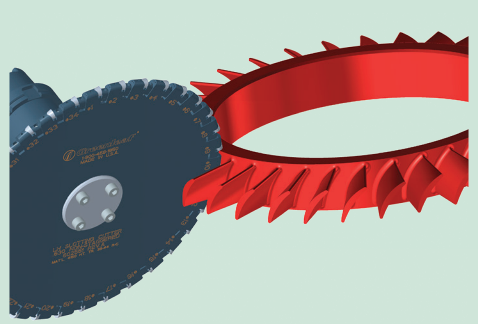
Discs p. 8

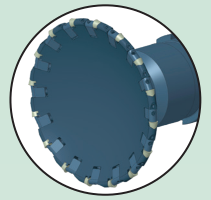


WG-700™ is particularly effective in finish turning of Rene alloys, and WG-600®, WG-700™, and XSYTIN®-1 can be used for rough turning (p. 9).

Greenleaf developed a slotting cutter and inserts to rough machine dovetail slots while eliminating the rough pre-broach operation, which results in up to 10 times higher productivity! (p. 10).

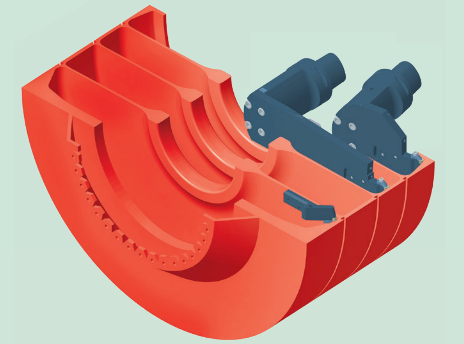
Blisks p. 12

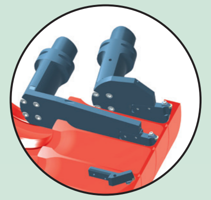




Greenleaf's curved slotting cutters work for rough slotting a blisk when a straight-thru slot is not an option while reducing cycle time and providing equipment cost savings (p. 13).

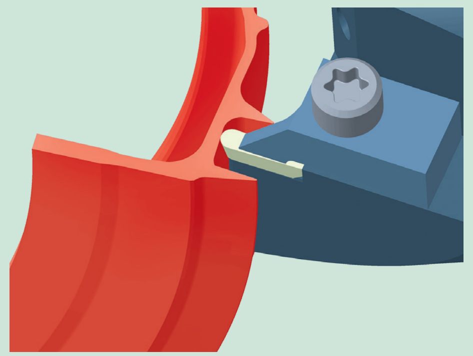
Spools p. 15

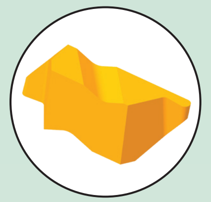




Greenleaf has decades of experience in designing special tooling to remove material from the most difficult-to-reach places, such as the internal diameter of spools (p. 15).

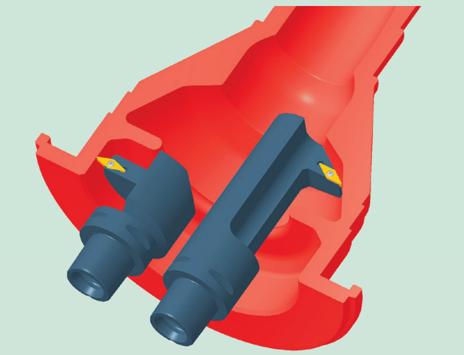
Rings and Seals p. 17

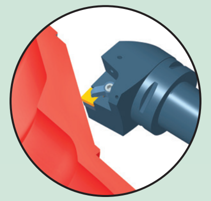




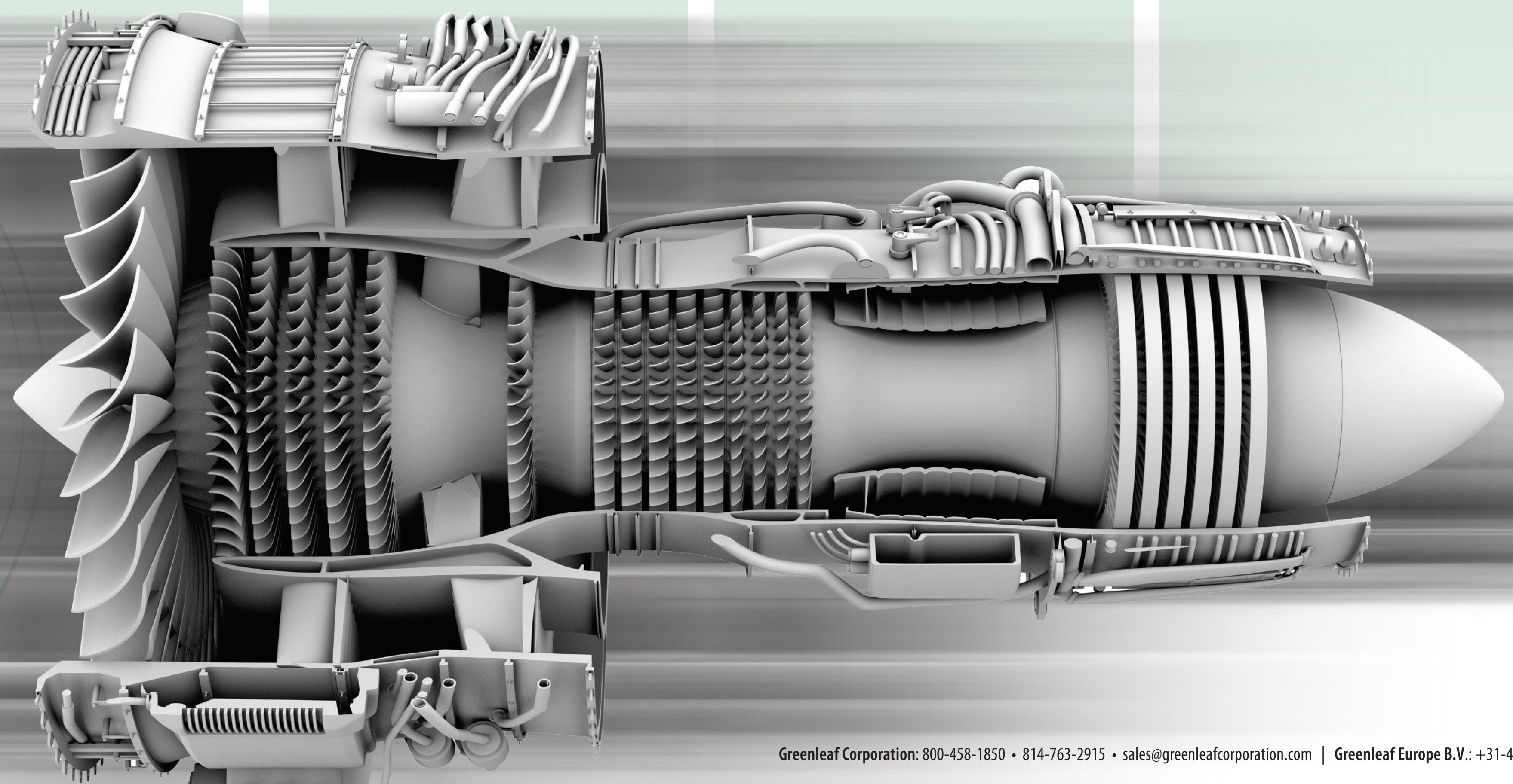
The Greenleaf Powerlock® grooving system of inserts and toolholders offers a complete line of carbide inserts that conform dimensionally to the industry-embraced notch-style system. (p. 17).

Shafts p. 18





In addition to developing productive and effective tools, Greenleaf can help develop unique strategies to achieve optimal cutting conditions for engine components in your machining environment (p. 18).



Application Support

Our commitment to quality and cutting-edge tools and inserts does not end with the purchase of Greenleaf products.

We work with our customers post-purchase to maximize throughput, minimize the need for capital investment, and reduce the overall cost per part without compromising part quality and process security.

The Greenleaf tooling advantage also lies in the experience and knowledge available to every sales engineer and customer from our technical support department. This team of applications engineers is available to provide recommendations for optimal cutting speeds and feeds and to assist in troubleshooting machining applications. All stages of machining heat-resistant alloys, special steels, and titanium alloys are addressable with Greenleaf tooling and expertise to your advantage.

We can help by:

- Reducing cycle times
- Developing solutions for difficult-to-machine materials
- Improving process security, eliminating rework and scrap
- Improving surface quality
- Devising a best-in-class machining process for high-volume parts
- Engineering custom solutions to address specific part/material/machining environment needs

Greenleaf Technical Support continually tests and gathers data on innovative tooling to develop the best techniques to maximize performance. Focusing on optimizing every application is a high priority for the technical support team so we can share that knowledge with customers.

Greenleaf tools and technical support expertise can significantly reduce costs and increase productivity.

Many components in commercial and military jet engines soaring through the skies today have likely been machined in some way by Greenleaf tooling and inserts. For decades, turbine engine manufacturers have benefited from cost and time savings through the application of Greenleaf's advanced metal-cutting solutions.

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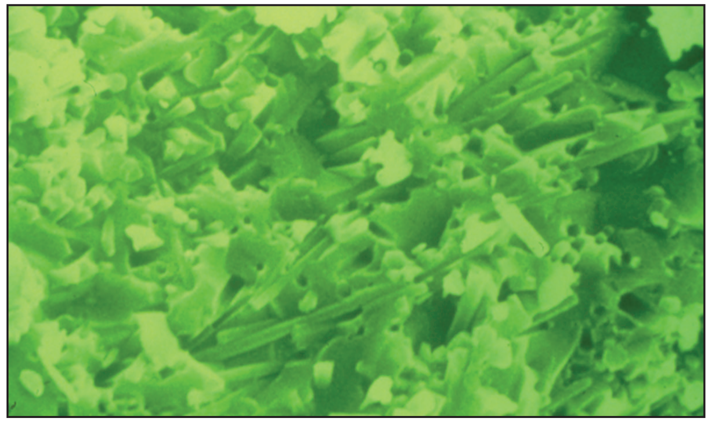
Pioneering Technology



SEM Photomicrograph 3000x

Greenleaf Corporation is a world leader in designing, manufacturing, and applying advanced tooling solutions to meet the unique challenges common to manufacturing jet engine components. High nickel alloys, stainless steels, and titanium alloys are all part of our daily application range.

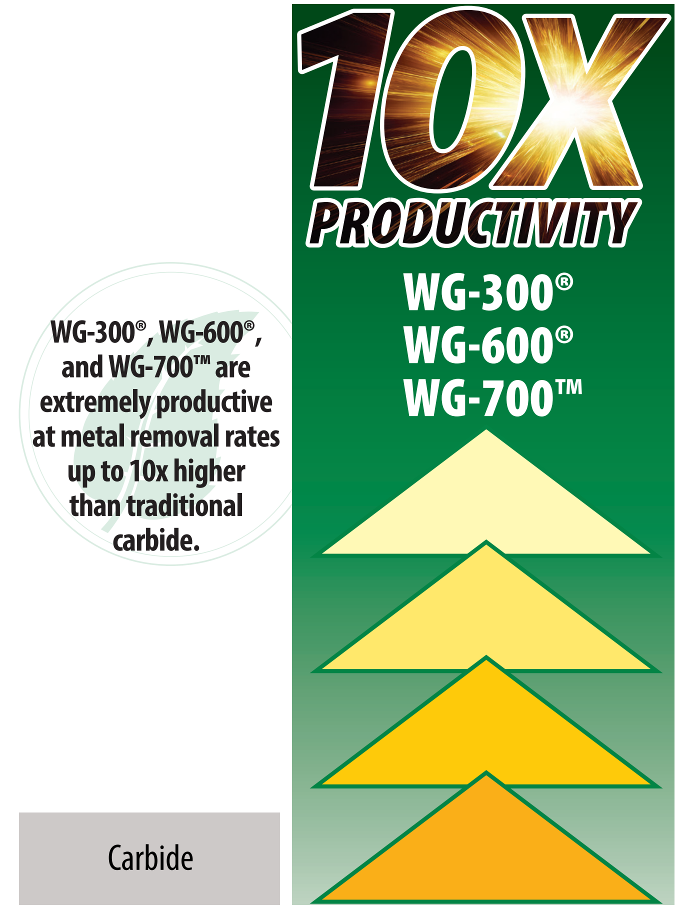
In 1985, Greenleaf pioneered the implementation of whisker-reinforced ceramic cutting tools in the aerospace industry with the introduction of WG-300®. This opened the door for many more materials to be machined at unprecedented speeds, marking a turning point in aircraft engine component manufacturing. Development of coated ceramics would follow, starting with the introduction of WG-600® in 2003 and then WG-700™ in 2011. All three of these whisker-reinforced ceramic grades are highly predictable and productive in machining nickel- and cobalt-based super alloys and other demanding materials at metal removal rates up to 10 times higher than traditional carbide.

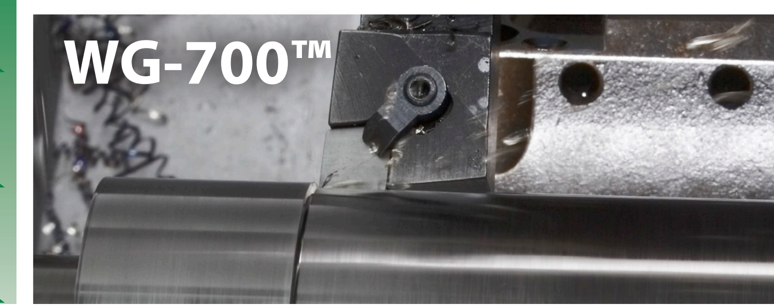
Greenleaf again transformed the aerospace industry manufacturing process in 2014 with the development of phase-toughened XSYTIN®-1, the first and only ceramic of its kind. XSYTIN®-1 is designed to meet the machining challenges of rough forgings and castings in high-strength alloy materials. The high strength and toughness of XSYTIN®-1 make it the ideal ceramic grade for maximizing productivity.

Greenleaf also offers advanced carbide grades specifically engineered for roughing and the precise finishing of aerospace alloys. A combination of high wear resistance, unique chipforms, and proven coatings allow for maximum tool life and cutting efficiency while providing excellent finish quality on these abrasive and difficult-to-machine materials.

Throughout all of manufacturing's diverse industry markets, there is a focus on being and remaining competitive, and the aerospace industry is no exception. The foundation of Greenleaf's innovations exists with this goal in mind by delivering maximum productivity for our customers while reducing their manufacturing costs. Providing cutting edge solutions with our advanced carbide and ceramic products, Greenleaf continues to tackle difficult aerospace manufacturing applications around the globe. From intake to exhaust, we have optimized tooling solutions available.

Greenleaf Corporation has a long history of innovation in the cutting tool industry, being one of the first to develop and market indexable cutting tool inserts in the 1960s and the first to develop and market whisker-reinforced ceramic inserts in 1985. Since then, Greenleaf's innovative developments have continued, with Greenleaf presently owning in excess of 70 pending or issued patents in North America, Europe, and Asia and numerous proprietary tools, tooling, and materials in its product offering. An up-to-date list of Greenleaf's patents and trademark registrations can be found at: www.greenleafcorporation.com.





The Road to Aerospace Tooling Innovations

1945

Greenleaf Corporation is formed by Walter Greenleaf, Sr. to market and sell standard and special tooling systems for metal cutting.

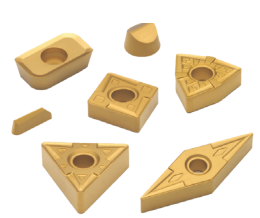
1960

Greenleaf Corporation patents its first indexable tooling systems and looks for local tool shops to license and manufacture the designs.

Unable to license their newly patented designs, **Greenleaf Corporation purchases a five-man tool shop in Saegertown, Pennsylvania** and begins to manufacture indexable turning and milling tools.

1969

Greenleaf introduces **CVD-coated carbide inserts** to the U.S. market – the first company to do so.



1985

Greenleaf introduces **WG-300®**, the world's first whisker-reinforced ceramic composite grade.

2003

WG-600®, the world's first coated whisker-reinforced ceramic insert, is introduced.

2007

Greenleaf Europe B.V. opens in Schimmert, The Netherlands.

2011

Greenleaf (Hunan) High-Tech Materials Co., Ltd. opens in Changsha, Hunan, China.

WG-700™, an optimized whisker-reinforced substrate morphology with enhanced nano-layered coating makes its debut.

2014

XSYTIN®-1, the first phase-toughened ceramic material, is introduced.

2017

Greenleaf's newly developed **dovetail slotting cutter and inserts** improve productivity tenfold.

2021-22

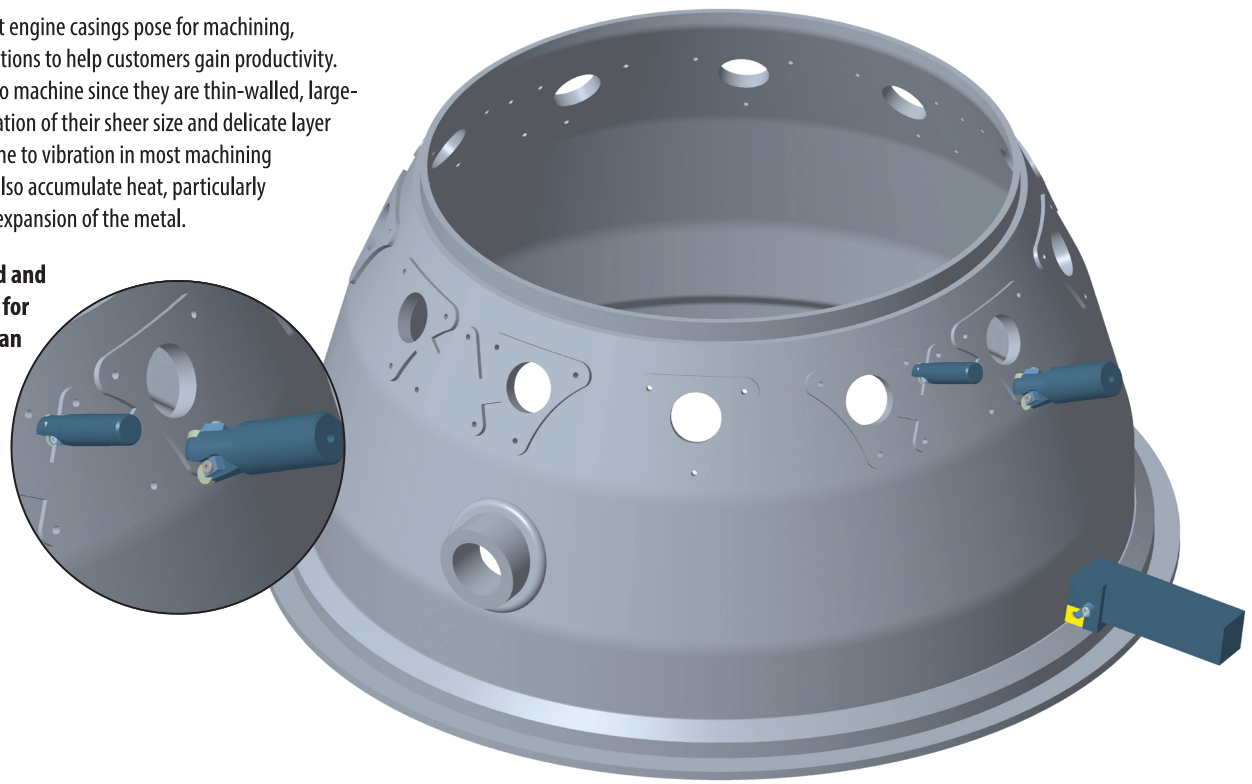
XSYTIN®-360 solid end mills reduce cutting forces and provide maximum material removal.

Greenleaf-360 solid end mills offer productivity and predictability in a variety of applications.

Casings

Despite all the challenges jet engine casings pose for machining, Greenleaf offers tooling solutions to help customers gain productivity. Engine casings are difficult to machine since they are thin-walled, large-diameter parts. The combination of their sheer size and delicate layer of material makes them prone to vibration in most machining operations. Engine casings also accumulate heat, particularly during milling, causing the expansion of the metal.

Greenleaf offers standard and special-designed tooling for machining casings that can help reduce vibrations and accelerate machining parameters.



Grade Recommendations for Common Materials

Common Materials	Material Group	Operation	Insert Grades: Primary	Insert Grades: Secondary
Astroloy Inconel 718 Nimonic Waspaloy	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Incoloy 909 Alloy A286 Jethete M152	Iron-based heat-resistant alloy	**Turning** — Forging scale removal	WG-300®	WG-700®
		Turning — Clean roughing	WG-600®	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Ti 6-4	Titanium alloy	**Turning** — Roughing	G-9230	G-915
		Turning — Finishing	G-9610	G-925
		Milling — Roughing	G-915	G-9230
		Milling — Finishing	G-9230	G-9610

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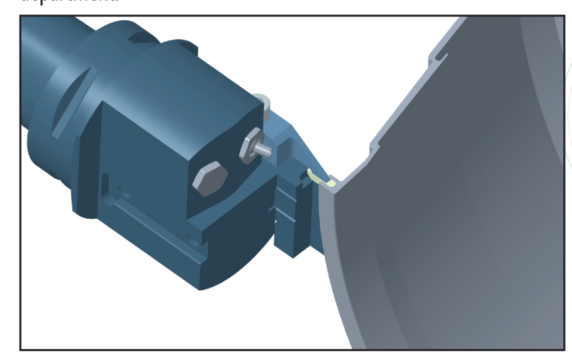
Rough Turning

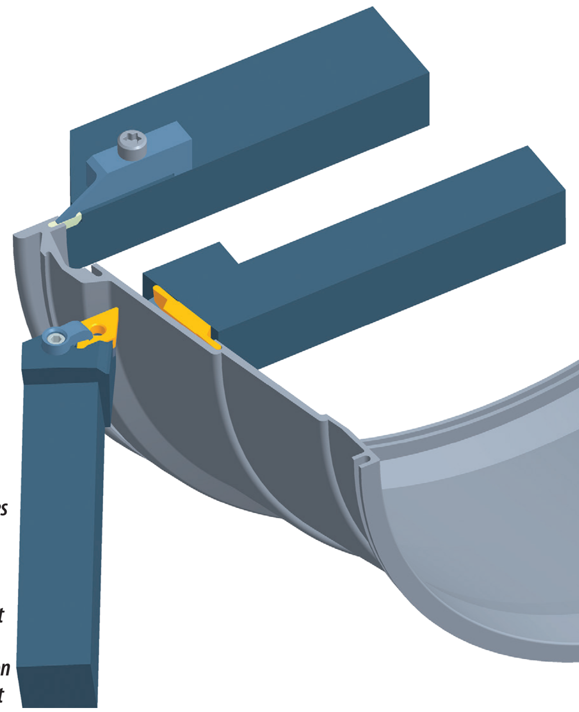
Greenleaf's insert grades are designed to provide customers with higher productivity and predictable tool life. XSYTIN®-1's strength, toughness, and resistance to thermal shock are proven to increase productivity without sacrificing process security when removing heavy scale. Roughing clean material can also benefit from the wear resistance of WG-300®, WG-600®, and WG-700™.

Turning and Grooving

Greenleaf's advanced tooling system for grooving, profiling, and cut-off operations provides every specific application with unsurpassed support. The rigidity of this system ensures the longest tool life and highest metal removal rates with both carbide and ceramic inserts. Support blade systems pair qualified shanks and blades, providing 248 configurations for the use of cut-off, round V-bottom, and full- and flat-nosed grooving inserts.

Another unique offering for grooving and profiling of thin-walled aircraft engine components are double-edged ceramic inserts designed to produce smaller features that nevertheless can be grooved or profiled at ceramic speeds. Available on a build-to-order basis in various configurations and sizes in WG-300®, these ceramic inserts fit in the same tools as carbide Powerlock® inserts. Both tooling and inserts are available in standard and custom configurations designed by Greenleaf's engineering department.

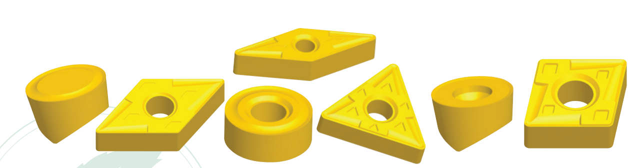




In nickel-based alloy casings, XSYTIN®-1 provides unprecedented resistance to crack growth caused by vibration, resulting in outstanding process security and repeatability. Its strength allows the machining of large-diameter parts at lower speeds approaching the range of carbide, reducing the likelihood of encountering vibration and the risk associated with turning a large part at high RPM.

Finish Turning

Whisker-reinforced and coated WG-600® and WG-700™ inserts excel at finishing nickel-based heat-resistant alloys because of their inert, tough substrate and their uniquely wear-resistant and lubricious coatings.



TurboForm® chipforms are Greenleaf's solution when it comes to finish turning with carbide. A very positive chipform reduces tool pressure allowing for a better surface finish at increased speeds. Carbide grades G-925, GA5026, G-9230 and G-9610 offer high wear resistance for high-speed machining of abrasive and difficult-to-machine materials.

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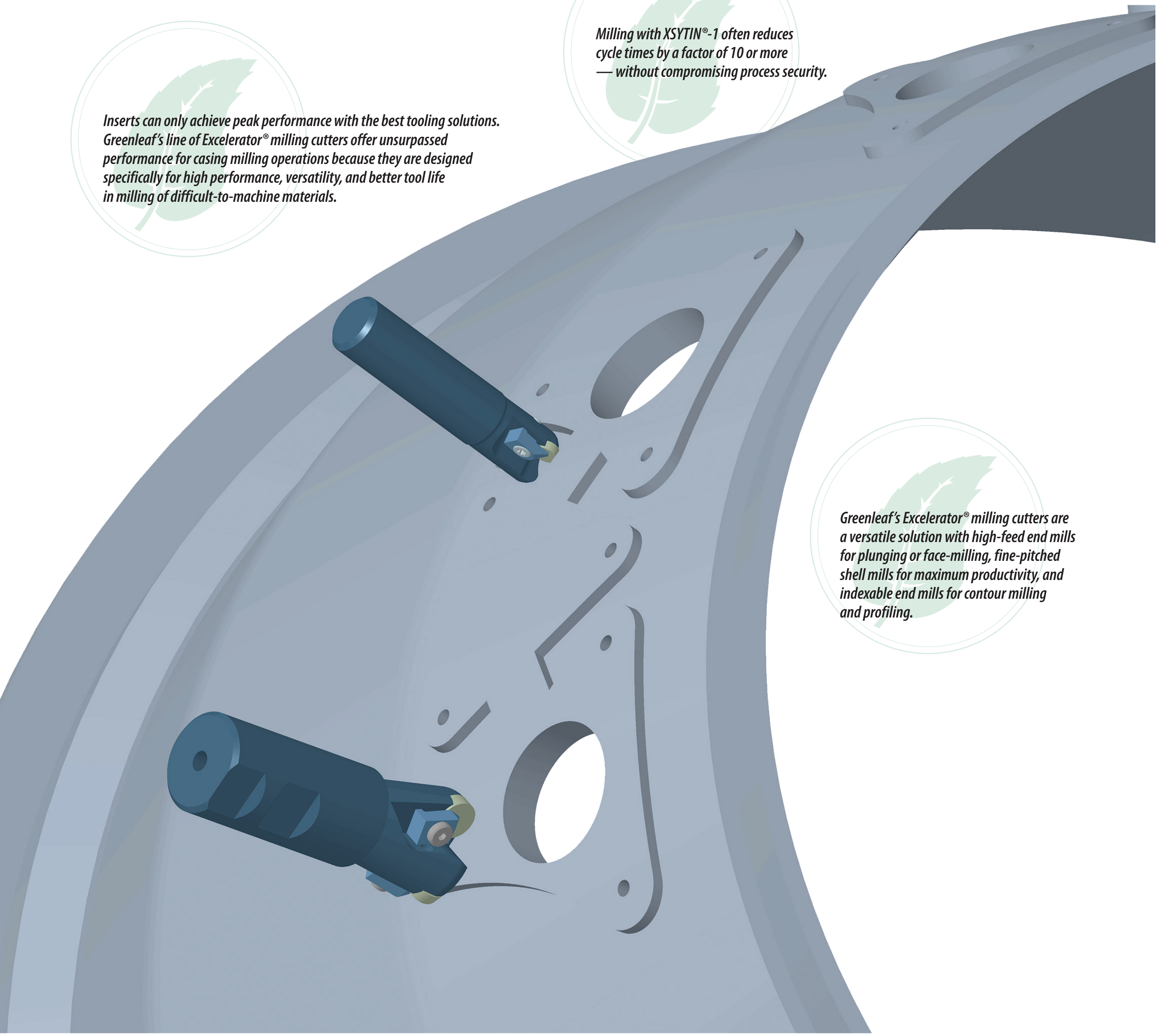
Casings

Rough Milling

Milling heat-resistant alloys with carbide inserts can be a very time-consuming task. When milling casings with ceramic inserts (available in multiple grades and geometries) at optimal cutting conditions, the wear is predictable, heat evacuation is stable, and with the right tooling strategy, material expansion is not a risk factor. Using ceramic inserts for rough milling applications offers dramatic productivity gains without compromising process reliability.

Milling with XSYTIN®-1 often reduces cycle times by a factor of 10 or more — without compromising process security.

Inserts can only achieve peak performance with the best tooling solutions. Greenleaf's line of Excelerator® milling cutters offer unsurpassed performance for casing milling operations because they are designed specifically for high performance, versatility, and better tool life in milling of difficult-to-machine materials.



Greenleaf's Excelerator® milling cutters are a versatile solution with high-feed end mills for plunging or face-milling, fine-pitched shell mills for maximum productivity, and indexable end mills for contour milling and profiling.

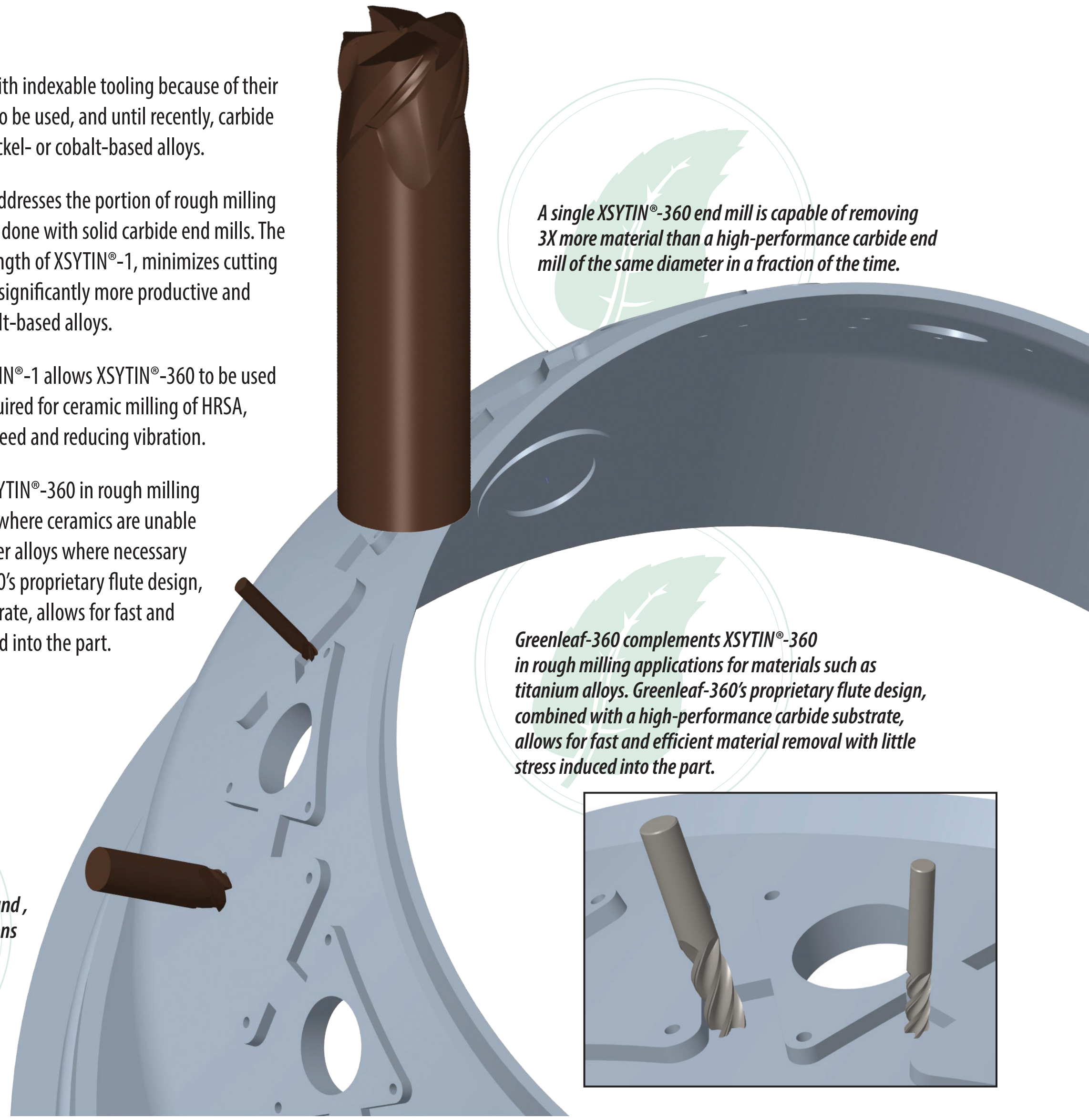
Rough Milling

Many features on a casing cannot be addressed with indexable tooling because of their shape or size. Consequently, solid end mills have to be used, and until recently, carbide was the only cost-effective choice for roughing nickel- or cobalt-based alloys.

XSYTIN®-360 is a solid ceramic product line that addresses the portion of rough milling in nickel- or cobalt-based casings that is currently done with solid carbide end mills. The unique flute geometry, made possible by the strength of XSYTIN®-1, minimizes cutting forces and extends tool life to make XSYTIN®-360 significantly more productive and cost-effective than solid carbide in nickel- or cobalt-based alloys.

The very high transverse rupture strength of XSYTIN®-1 allows XSYTIN®-360 to be used at lower cutting speeds than what is typically required for ceramic milling of HRSA, lowering the requirements on machine spindle speed and reducing vibration.

Greenleaf-360 carbide end mills complements XSYTIN®-360 in rough milling applications for materials such as titanium alloys where ceramics are unable to be applied and in nickel- and cobalt-based super alloys where necessary spindle speed may not be available. Greenleaf-360's proprietary flute design, combined with a high-performance carbide substrate, allows for fast and efficient material removal with little stress induced into the part.



A single XSYTIN®-360 end mill is capable of removing 3X more material than a high-performance carbide end mill of the same diameter in a fraction of the time.

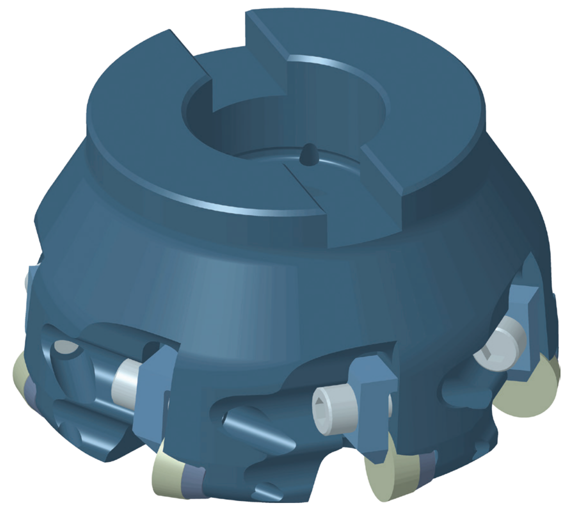
Greenleaf-360 complements XSYTIN®-360 in rough milling applications for materials such as titanium alloys. Greenleaf-360's proprietary flute design, combined with a high-performance carbide substrate, allows for fast and efficient material removal with little stress induced into the part.

XSYTIN®-360 end mills can be reground, and special flute length configurations can be produced on request, making better use of the raw material.

Finish Milling

The fine-pitched Excelerator® milling range offers air/coolant directed on edge and higher productivity as a direct result of more teeth. This feature makes it possible to use the same tools from start to finish, first roughing with ceramics and ultimately semi-finishing or finishing with carbide.

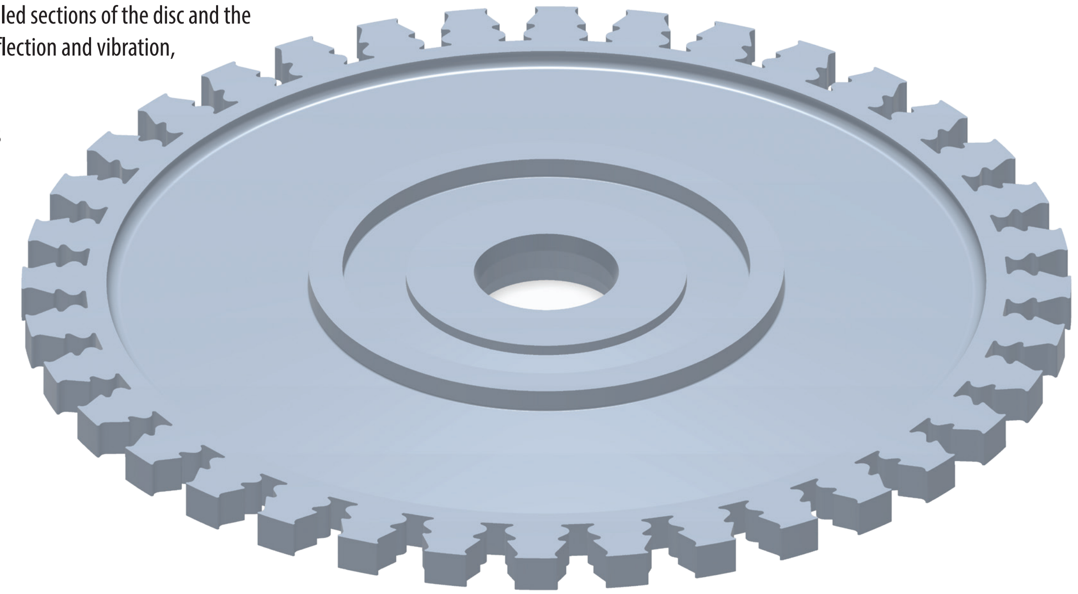
With positive cutting action, reliable performance, and coolant through on edge, Greenleaf's FMRPF face mills and WSRPF end mills are particularly well-suited for semi-finishing or finishing with carbide where solid carbide end mills are not required.



Discs

Greenleaf produces special-designed solutions for difficult-to-reach geometries for grooving applications on discs. In addition, we have developed special slotting cutters for roughing portions of the disc that are typically broached. Since discs are one of the heaviest parts and are located in the hottest part of the engine, the materials are extremely difficult to manufacture. The thin-walled sections of the disc and the long reach required for the tooling can cause deflection and vibration, which can lead to quality concerns.

Greenleaf recognizes these issues and uses its nearly eighty-plus years of design experience to provide innovative solutions for cost efficiency and reliability.



Grade Recommendations for Common Materials

Common Materials	Material Group	Operation	Insert Grades	
			Primary	Secondary
Astroloy, IN100, Inconel 718, Inconel 718 Plus, MERL 76, N18, Nimonic, René 104, René 61, René 65, René 88, René 95, RR1000, Udimet 720, Waspaloy	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Alloy A286	Iron-based heat-resistant alloy	**Turning** — Forging scale removal	WG-300®	WG-700®
		Turning — Clean roughing	WG-600®	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Ti 6242, Ti 6246, Ti 6-4, Ti 834	Titanium alloy	**Turning** — Roughing	G-9230	G-915
		Turning — Finishing	G-9610	G-925
		Milling — Roughing	G-915	G-9230
		Milling — Finishing	G-9230	G-9610

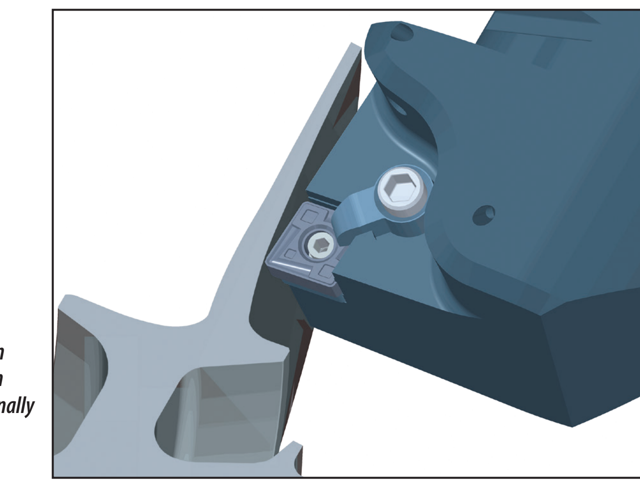
Rough Turning

The primary reason that round inserts are the best choice for ceramic rough-turning of nickel- or cobalt-based heat-resistant alloys is that most ceramics tend to develop a depth-of-cut notch, which a round shape (especially with low radial engagement) resists best. Next-generation nickel-based disc alloys designed for higher operating temperatures lead to the generation of significantly higher cutting forces than Inconel 718 when machined. Together with the heat, abrasiveness, and strain-hardening, this calls for strength and notching resistance that few ceramic grades on the market possess.

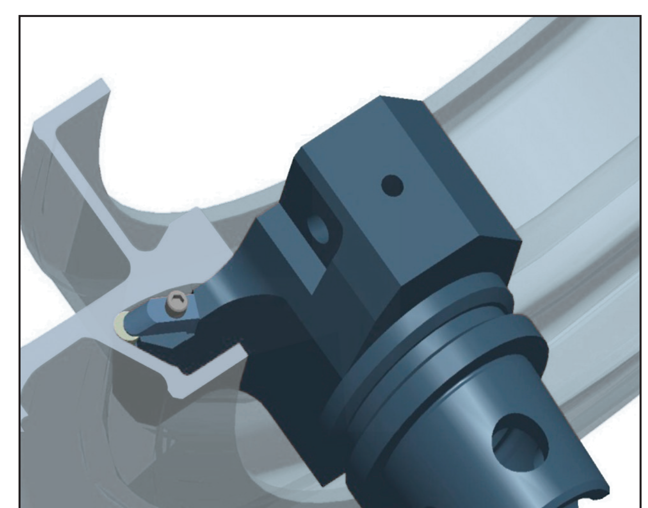
Going beyond other ceramic grades, XSYTIN®-1 is an efficient and highly reliable solution that embraces and overcomes the challenges of roughing in next-gen HRSAs.

Finish Turning

Finish turning of turbine discs has traditionally been reserved almost exclusively for carbide because of the extremely stringent requirements of the surface structure of the finished component. Nevertheless, Greenleaf has been successful in implementing both carbide and ceramic grades in finishing of aircraft engine discs.



Our coated carbide grades paired with the TurboForm® (TF) chipform can extend tool life with the positive and reinforced edge of TF. This chipform minimizes grain distortion and residual stresses resulting in an exceptionally clean surface.



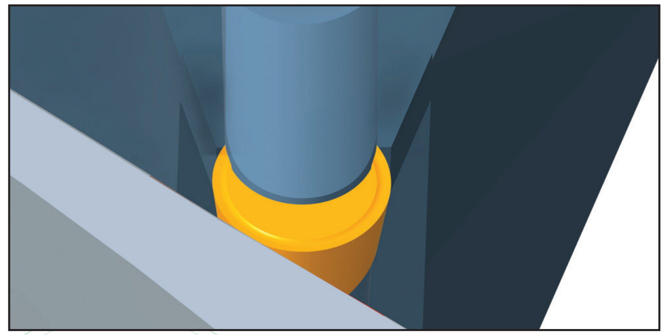
Greenleaf's experience with ceramic machining of heat-resistant alloys has resulted in the effective use of WG-600® and WG-700™ in finishing applications. WG-700™ is particularly effective in finish-turning of Rene alloys, and both WG-600® and WG-700™ can be used for roughing. Higher speed and consistent tool life will deliver higher productivity from these grades.

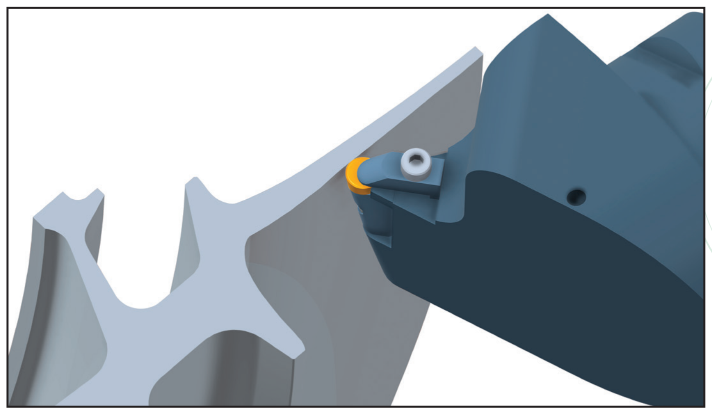
Discs

Microstructure

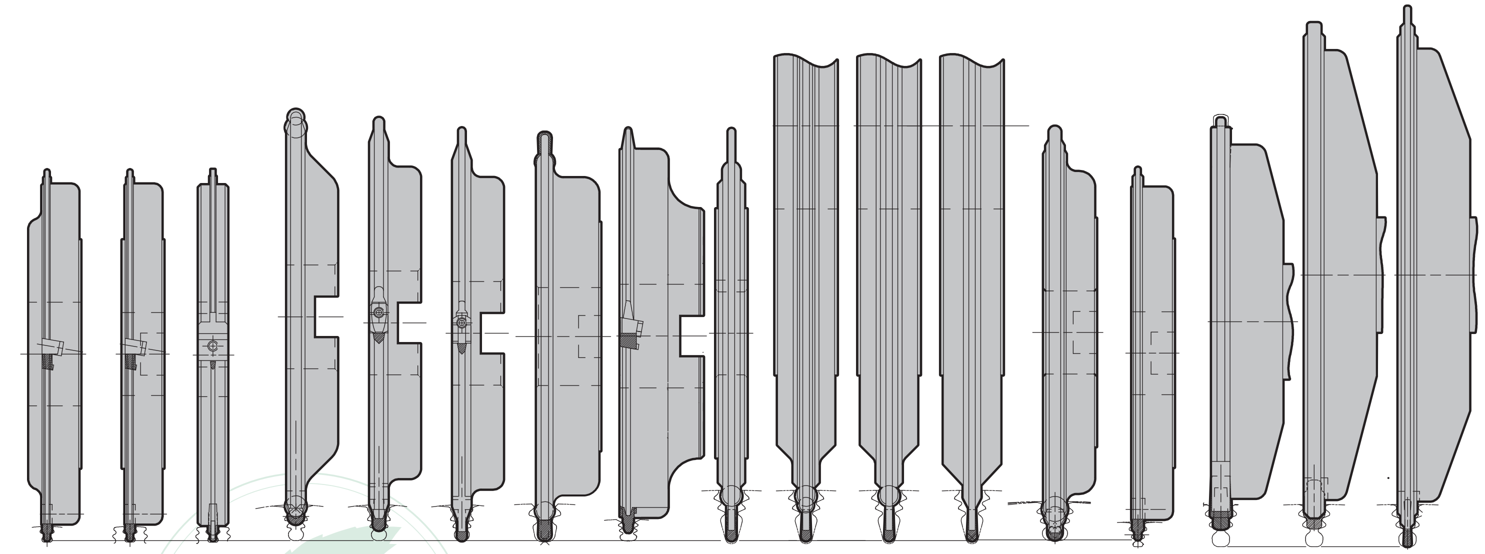
Greenleaf is one of the only companies in the world whose ceramic inserts are certified at multiple OEMs for finishing critical rotating components in aircraft engines.

Since discs are a critical rotating component, they have requirements for surface structure unlike any other engine components. The coating of WG-600® combined with the high-shear geometry of the GF1 chipform allows us to finish-machine discs, casings, and other components at ceramic speeds but with the surface quality (roughness, depth of white layer, magnitude of residual stresses) of carbide.





Compared to CBN, WG-600® V-bottom round inserts with the GF1 chipform excel in every category: they reduce cycle time, significantly reduce the cost of tooling per part, and result in a superior surface that is more uniform with lower residual stresses.



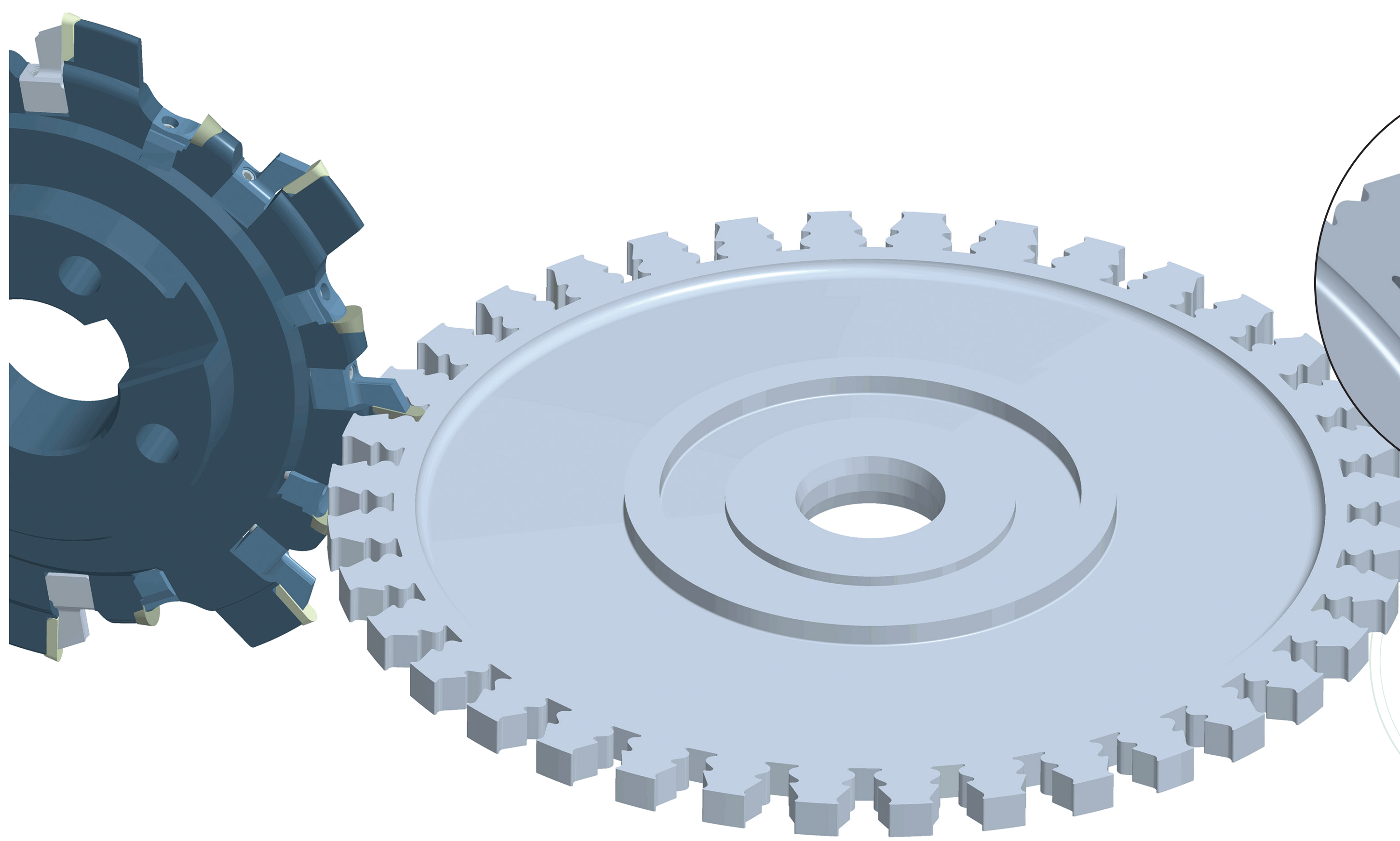
When custom solutions are needed, Greenleaf's engineering department is well versed in designing unique configurations for our customers' turbine disc slotting needs.

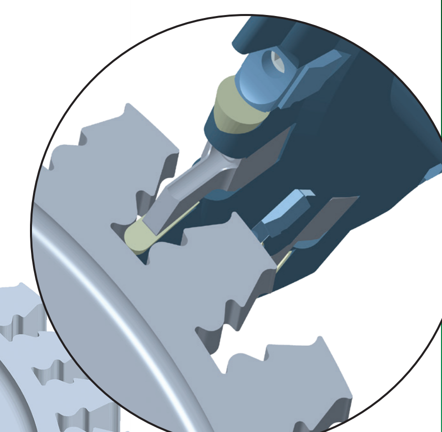
Turbine Disc Slotting

For efficient and successful disc slotting, the part and fixture must be as rigid as possible. Conventional (up) milling with a light feed of 0.0025 IPT (0.0635 mm/t) is recommended with ceramic inserts. After completing a slot, it is not recommended to feed back through the slot.

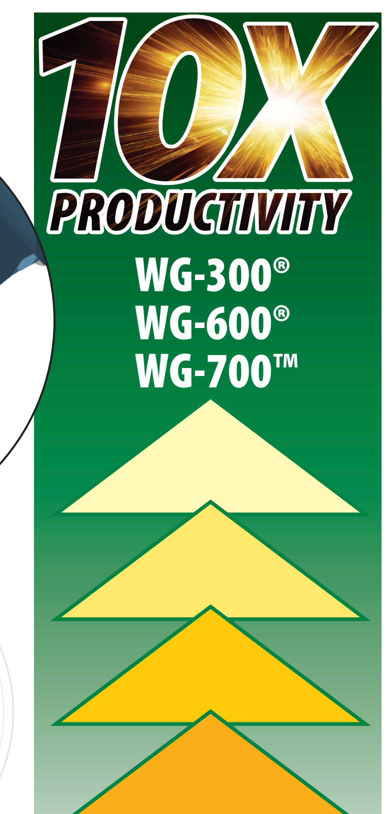
A complete form can be generated with just one insert, or roughed out using multiple inserts. This is an alternative to the current rough broach operation.

Slotting Cutter & Inserts
U.S. Patent Nos. 8,267,625 & 9,073,131





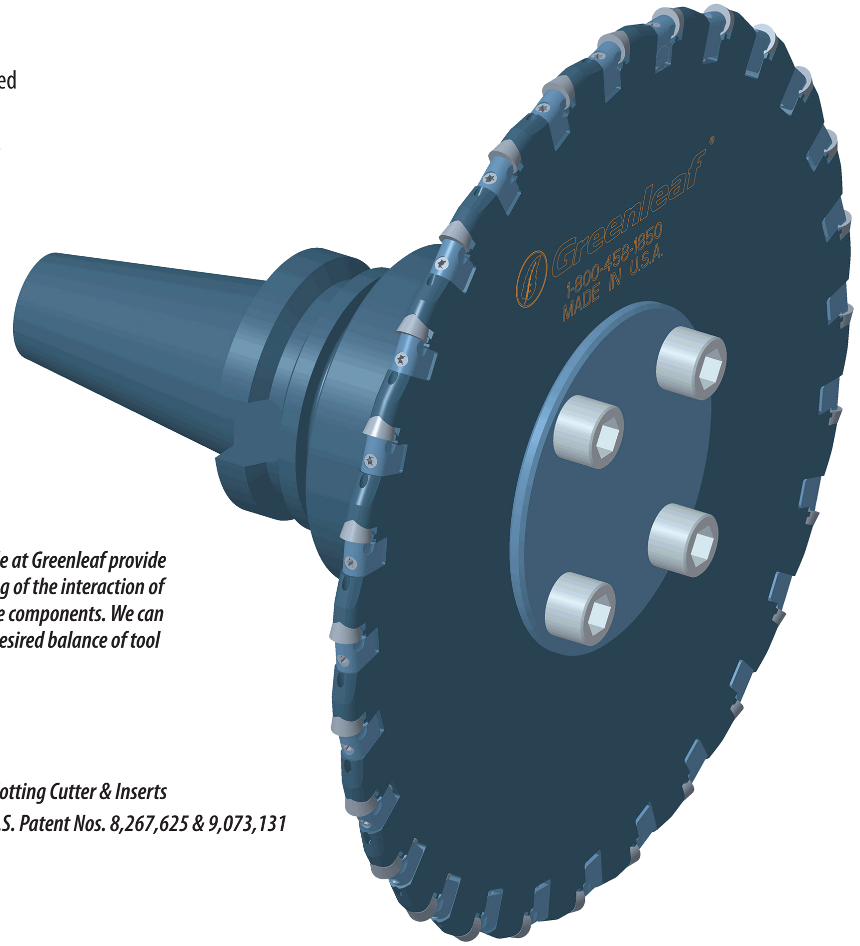
Greenleaf developed a slotting cutter and inserts to rough machine dovetail and fir tree slots while eliminating the rough pre-broach operation.



Blisks

Greenleaf's continuous focus on helping customers overcome operational constraints led to the development of special-designed cutters for rough milling blades on blisks. These unique solutions offer the customer improved methods that utilize the capabilities of advanced machine centers to remove material between blades more efficiently. Using these innovative tools along with our solid tooling solutions, customers can rely on Greenleaf to provide them with a complete tooling solution.

The technology and experience available at Greenleaf provide extensive knowledge and understanding of the interaction of ceramic slotting tools and their machine components. We can help optimize the process to reach the desired balance of tool life and cycle time.



Slotting Cutter & Inserts
U.S. Patent Nos. 8,267,625 & 9,073,131

Grade Recommendations for Common Materials

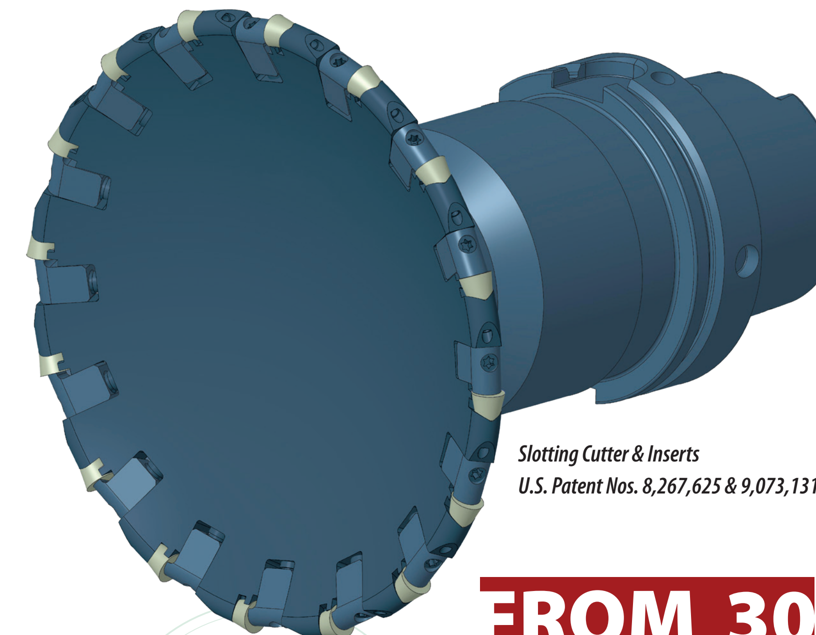
Common Materials	Material Group	Operation	Insert Grades	
			Primary	Secondary
Inconel 718 Inconel 718 Plus	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Ti-17 Ti 6-4	Titanium alloy	**Turning** — Roughing	G-9230	G-915
		Turning — Finishing	G-9610	G-925
		Milling — Roughing	G-915	G-9230
		Milling — Finishing	G-9230	G-9610

Rough Slotting

Using a slotting cutter to remove the material between the blades of a blisk can be a challenging operation as fixturing and vibration-dampening measures are critical. The right cutting path, or how the tool engages and disengages with the part, is essential to the operation's success.

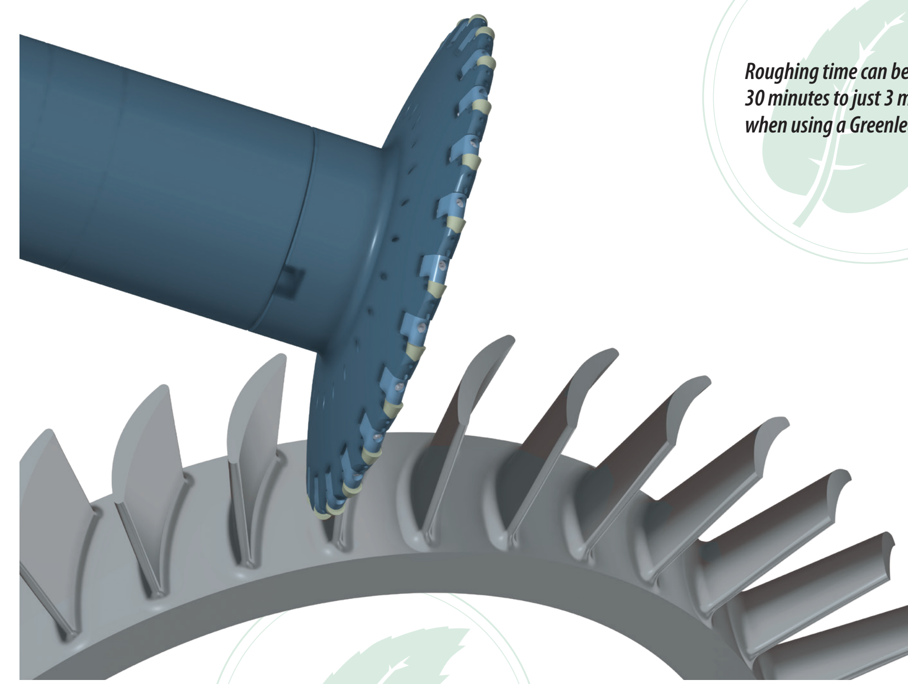
The choice of tool for rough slotting blisks depends first and foremost upon the material being machined. For example, nickel-based alloys are readily machinable with ceramics, while titanium-based alloys are not. In both cases, round positive inserts are ideally suited for maximizing the rate of metal removal while maintaining process security and stability.

Greenleaf's curved slotting cutters are the roughing solution for blisks with tightly curved blades, where using a straight slotting cutter is not an option. Our custom-designed slotting cutters and inserts provide time and capital equipment cost savings for rough-slotting blisks.



Slotting Cutter & Inserts
U.S. Patent Nos. 8,267,625 & 9,073,131

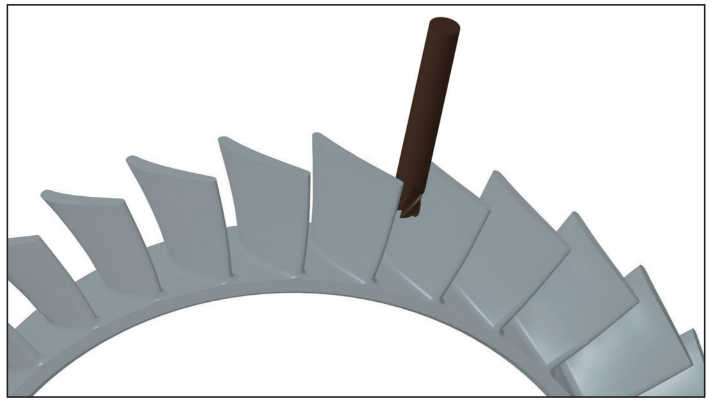
Roughing time can be reduced from 30 minutes to just 3 minutes per slot when using a Greenleaf blisk mill cutter!



Greenleaf slotting cutters accept both carbide and ceramic insert options, providing customers with a productivity advantage for various materials.

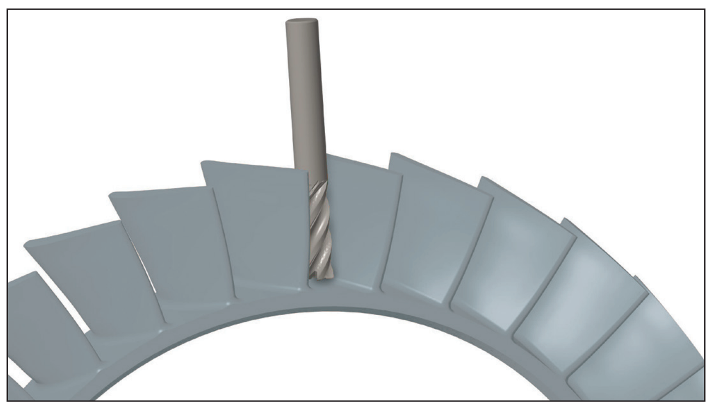
Blisks

Using slotting cutters, and curved slotting cutters in particular, requires a very specific machine, fixture, and part configuration that may not always be available. Solid end mills are then the best solution.



Rough Milling

XSYTIN®-360 solid ceramic end mills allow much of the rough machining of blades in a nickel-based blisk to be sped up considerably. Having the strength to handle full-slotting operations means that XSYTIN®-360 can be implemented from the very first stages of roughing, offering higher tool life and drastically lower cycle times than solid carbide end mills.



Rough and Finish Milling

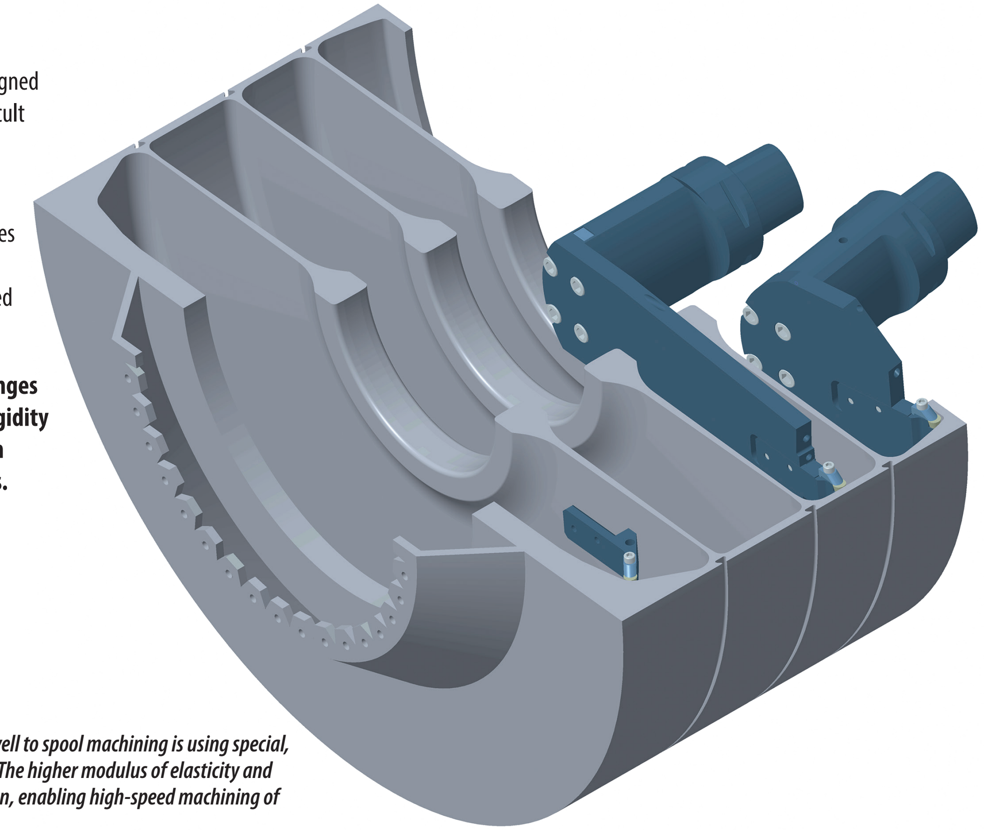
Greenleaf-360 solid carbide end mills address titanium alloy blisk machining operations where XSYTIN®-360 cannot be applied and in nickel-based alloys where surface speed is limited. Greenleaf-360 also offers extended shank length capabilities over XSYTIN®-360, allowing for the effective completion of long-reach applications. An excellent combination of strength, toughness, and heat resistance enables high-performance machining capability from roughing to finishing with extended tool life and predictability.

Spools

Greenleaf uses their decades of experience in specially designed tooling solutions to develop rigid tools needed for the difficult applications found in manufacturing spools.

Since spools are manufactured from forged blanks or as welded assemblies and have thin walls when finished, issues with chip evacuation, deflection, and vibration need to be addressed. In many applications, modular tooling is required to allow access to cut the internal features on the parts.

Greenleaf's engineering team recognizes the challenges and designs the special modular tools to have the rigidity and strength to resist deflection and vibration when subjected to cutting forces in unfavorable directions.



One solution that lends itself particularly well to spool machining is using special, more rigid, 'no-chat' materials for tooling. The higher modulus of elasticity and density reduce deflection and limit vibration, enabling high-speed machining of difficult-to-reach regions of the spool.

Grade Recommendations for Common Materials

Common Materials	Material Group	Operation	Insert Grades	
			Primary	Secondary
Inconel 718 René 61 René 88 René 104	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925

Scallops

Greenleaf solid end mills minimize cutting forces with the macro- and micro-geometry that helps maintain the sharp edge of the tool. Cutting scallop features requires a tool with a sharp edge to maintain stability during the cutting operation on the thin flanges. Any imbalance in the cutting forces can lead to deflection and vibration, reducing tool life and resulting in poor surface finish.

Greenleaf solid end mills offer manufacturers the solutions needed for these difficult forms typically found on discs, seals, spools, and casings.

Greenleaf-360 provides a comprehensive solution for roughing in jet-engine disc-scalloping applications. The high-quality carbide substrate enables maximum strength and rigidity, allowing heavier feed rates for roughing operations. At the same time, the unique flute geometry and coating facilitate superior surface finish and reduced cutting forces.

Tooling Recommendations for Common Materials

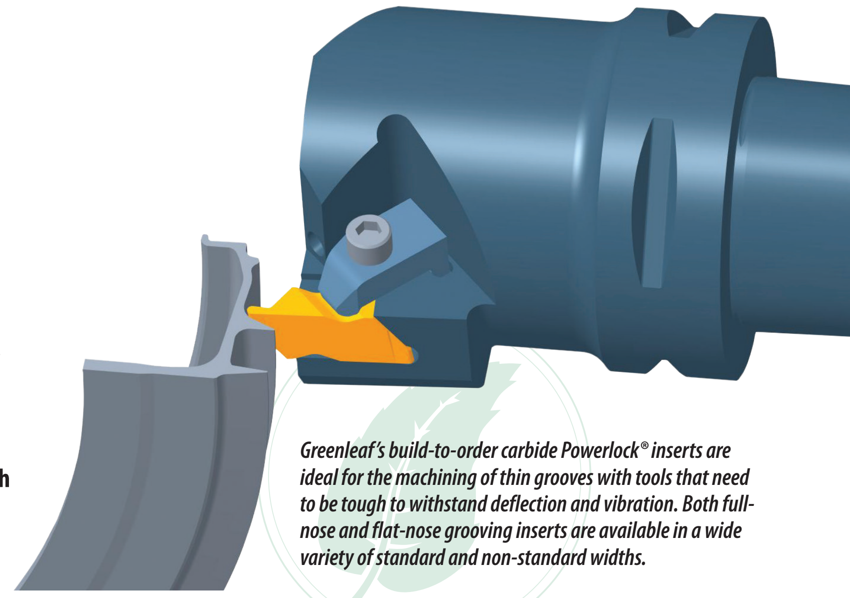
Material Group	Operation	Solid End Mills	
		Primary	Secondary
Iron-based heat-resistant alloy	**Milling** — Roughing	Greenleaf-360	XSYTIN®-360
	Milling — Finishing	Greenleaf-360	
Nickel-based heat-resistant alloy	**Milling** — Roughing	XSYTIN®-360	Greenleaf-360
	Milling — Finishing	Greenleaf-360	
Titanium alloy	**Milling** — Roughing	Greenleaf-360	
	Milling — Finishing	Greenleaf-360	

Rings and Seals

Greenleaf works with OEMs and subcontractors to optimize the machining process from forged or rolled blank to finished component. Our understanding of part requirements, machining environments, and potential deformation in a ring or seal allows us to minimize cycle time while ensuring the finished component is within tolerance.

Both rings and seals are highly susceptible to distortion and warping. To meet the strict tolerances of features on these components, finding ways to reduce the cutting forces and the tendencies to distort is crucial.

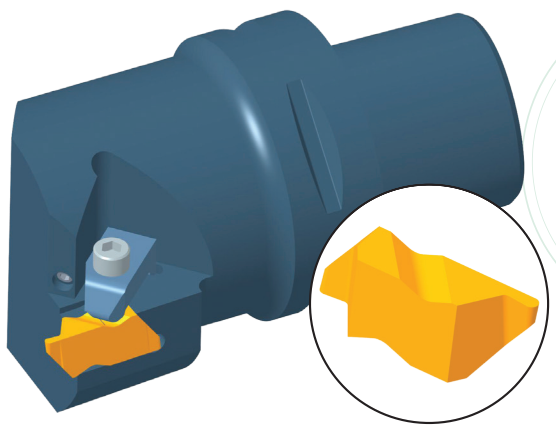
Greenleaf produces standard and custom solutions for the grooves found on rings and seals that, although they may be relatively thin, are still tough enough to withstand deflection and vibration.



Greenleaf's build-to-order carbide Powerlock® inserts are ideal for the machining of thin grooves with tools that need to be tough to withstand deflection and vibration. Both full-nose and flat-nose grooving inserts are available in a wide variety of standard and non-standard widths.

Grade Recommendations for Common Materials

Common Materials	Material Group	Operation	Insert Grades	
			Primary	Secondary
Jethete M152	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Inconel 718 Inconel 718 Plus Rene 65 Waspaloy	Iron-based heat-resistant alloy	**Turning** — Forging scale removal	WG-300®	WG-700®
		Turning — Clean roughing	WG-600®	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Ti 6-4	Titanium alloy	**Turning** — Roughing	G-9230	G-915
		Turning — Finishing	G-9610	G-925
		Milling — Roughing	G-915	G-9230
		Milling — Finishing	G-9230	G-9610

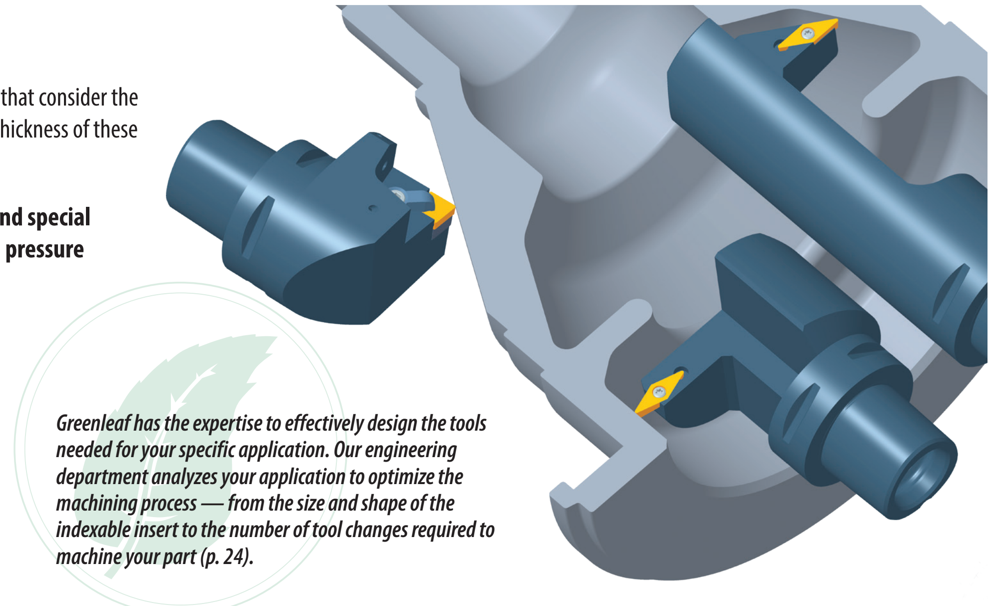


The Greenleaf Powerlock® grooving system of inserts and toolholders offers a complete line of carbide inserts that conform dimensionally to the industry-embraced notch-style system. Using advanced 2D & 3D modeling software coupled with Finite Element Analysis, Greenleaf has the ability to provide custom Powerlock® tooling solutions designed specifically for customer parts.

Shafts

Greenleaf's technical experience provides customers with solutions that consider the issues present when machining shafts. Due to the length and wall thickness of these components, the parts are prone to deflection and vibrations.

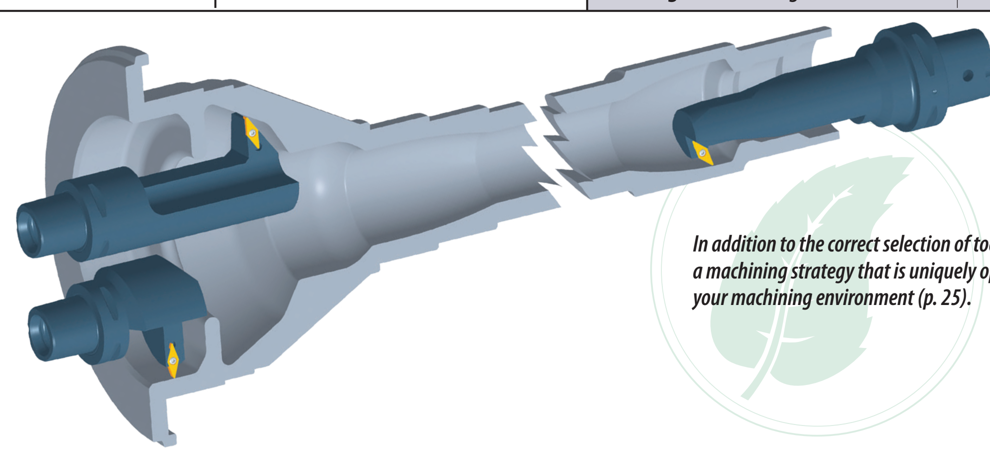
Greenleaf develops tooling packages using both standard and special designs to utilize insert geometries that will reduce cutting pressure and provide optimal tool life.



Greenleaf has the expertise to effectively design the tools needed for your specific application. Our engineering department analyzes your application to optimize the machining process — from the size and shape of the indexable insert to the number of tool changes required to machine your part (p. 24).

Grade Recommendations for Common Materials

Common Materials	Material Group	Operation	Insert Grades	
			Primary	Secondary
AerMet 100 F1E Maraging 250 Maraging 300 ML340 SuperCMV	Maraging steel	**Turning** — Forging scale removal	XSYTIN®-1	G-9230
		Turning — Clean roughing	XSYTIN®-1	G-9230
		Turning — Semi-finishing	XSYTIN®-1	G-925
		Turning — Finishing	G-925	GA5026
		Milling — Roughing	XSYTIN®-1	G-915
		Milling — Finishing	G-9230	G-925
Inconel 718	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Ti-17	Titanium alloy	**Turning** — Roughing	G-9230	G-915
		Turning — Finishing	G-9610	G-925
		Milling — Roughing	G-915	G-9230
		Milling — Finishing	G-9230	G-9610



In addition to the correct selection of tools, Greenleaf can help you devise a machining strategy that is uniquely optimized for your component in your machining environment (p. 25).

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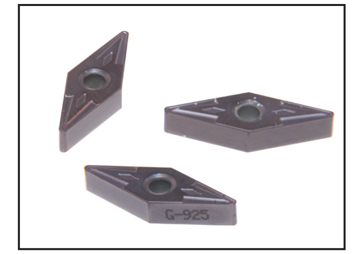
Technical Reference – Grades

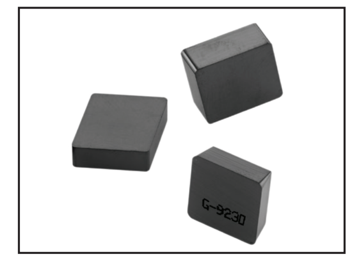
Carbide Grades



G-925

A multi-layered PVD-coated carbide grade specifically designed for machining difficult aerospace materials such as titanium and nickel-based alloys, G-925 exhibits excellent resistance to notching and deformation. Its application is best suited to run at moderate to high speeds with a moderate feed rate.

- PVD-coated sub-micron carbide for turning and milling high-temperature alloys, titanium and stainless steel
- Resists notching and deformation at moderate to high cutting speeds



G-9230

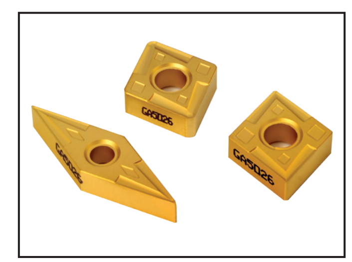
This PVD-coated carbide grade developed for medium to heavy machining of heat-resistant alloys and titanium alloys has excellent wear resistance and toughness, making it the right choice for cast and forged machining conditions. G-9230 is the go-to grade when it comes to milling slots in blisks.

- PVD-coated carbide for cast and forged scale conditions
- High wear resistance and toughness

G-9610

G-9610 is a PVD-coated carbide grade designed for turning titanium-based alloys. The wear-resistant, chemically stable, and very smooth and lubricious coating protects the heat-resistant, sub-micron substrate and allows for higher speeds and extended tool life in continuous cuts.

- Highly resistant to built-up edge (BUE), chemical wear, abrasive wear, and loss of hardness at high temperatures
- Best applied at higher speeds and moderate feed rates
- Also performs well in finish turning of nickel- and cobalt-based alloys



GA5026

A high-speed MT-CVD coated carbide grade developed for turning nickel- and cobalt- based super alloys, GA5026 has exceptional resistance to notching and deformation common in aerospace materials. Its application ranges are high speeds and light feeds.

- MT-CVD coated sub-micron carbide for high-speed turning of nickel- and cobalt-based super alloys and stainless steels
- Exceptional resistance to notching and deformation

Greenleaf-360

The full Greenleaf-360 solid carbide end mill line offers a complete solution for applications ranging from rough to finish milling of various aerospace components, providing exceptional productivity and process stability. Utilizing a proprietary flute design combined with a high-performance carbide substrate, Greenleaf-360 allows for fast and efficient material removal with little stress induced into the workpiece. In addition, Greenleaf-360 complements the XSYTIN®-360 ceramic end mill line for milling applications in materials such as titanium alloys where ceramics are unable to be applied and in nickel and cobalt-based super alloys where necessary spindle speed may not be available.

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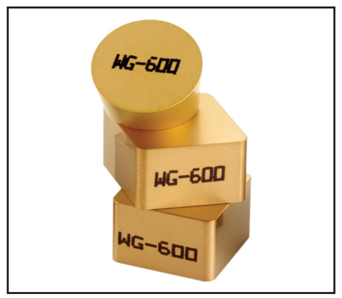
Technical Reference – Grades

Ceramic Grades

WG-300®

WG-300® is an uncoated, whisker-reinforced ceramic with excellent wear and shock resistance at high surface speeds. WG-300® is extremely effective at machining nickel- and cobalt-based super alloys, and other common aerospace materials at metal removal rates up to 10 times higher than carbide. WG-300® excels at removing clean material at a high level of productivity while also maintaining predictability.

- Whisker-reinforced Al_2O_3 ceramic for machining nickel- and cobalt-based super alloys and hard steels
- Excellent thermal and shock resistance at very high surface speeds
- A top choice worldwide for milling, grooving, and turning difficult-to-cut, non-ferrous materials



WG-600®

This coated whisker-reinforced ceramic offers longer tool life and better performance over uncoated ceramics at higher cutting speeds. WG-600® has all the qualities of WG-300® but also demonstrates excellent thermal and wear resistance at very high surface speeds. WG-600®also excels at finishing heat-resistant alloys because of the unique wear-resistant and lubricious coating. WG-600® has been proven to beat CBN in every category in aerospace applications. It runs faster, has a higher tool life, and produces a superior machined surface.

- Coated whisker-reinforced Al_2O_3 ceramic for machining nickel- and cobalt-based super alloys and hard steels
- Excellent thermal and wear resistance at very high surface speeds
- Extended tool life over uncoated whisker-reinforced ceramics

WG-700™

A whisker-reinforced ceramic with a unique high-speed coating, WG-700™ has all the great qualities of WG-300® as well as adding a high-performance coating. WG-700™ is ideal for machining common aerospace materials, especially Rene alloys. WG-700™ also excels at finishing heat-resistant alloys because of the unique wear-resistant and lubricious coating. It provides a higher speed and a consistent tool life that delivers higher productivity.

- Coated whisker-reinforced Al_2O_3 ceramic featuring improved toughness and unique friction-reducing coating
- For machining nickel- and cobalt-based super alloys and other difficult-to-machine materials
- Exceptional tool life with metal removal rates up to 10 times greater than carbide

XSYTIN®-1

A phase-toughened ceramic capable of extreme feed rates, XSYTIN®-1 is one of the only ceramic grades that retains a sharp edge and is resistant to notching. It has unprecedented toughness and strength that allows for slower speeds with high feed rates in aerospace applications. Because of these qualities, XSYTIN®-1 is a first choice for machining interrupted cuts as well as scale and abrasive materials. It is also ideal for milling due to its inherent toughness.

- Phase-toughened ceramic capable of extreme feed rates
- Ideal for use in interrupted cuts, scale, and milling
- For machining rough forgings and castings of high-strength alloy materials

XSYTIN®-360

Produced from XSYTIN®-1, XSYTIN®-360 boasts the same high transverse rupture strength, resistance to thermal shock, and fracture toughness. The ability to withstand high bending moments translates favorably to performance in full slotting or side-milling with a high depth of cut. It allows XSYTIN®-360 to be applied in conditions where other ceramic end mills would fail due to instability or excessive mechanical stress. Resistance to thermal shock and high fracture toughness is reflected in slower crack propagation due to thermal cycling or mechanical impact, which translates into higher tool life and predictable wear. XSYTIN®-360 also features a unique high-shear flute macro- and micro-geometry that breaks up harmonics, reduces cutting forces and aids with chip evacuation to significantly extend too life, but preserves enough toughness to withstand roughing cuts in high-strength alloys. XSYTIN®-360 can be applied in nickel- and cobalt-based alloys, steel, cast iron, and other challenging materials.

- Excellent performance in full slotting and high-depth-of-cut side milling
- Predictable, reliable wear
- Unique flute geometry reduces cutting forces and extends tool life
- For use in any material that is machinable with ceramics

Technical Reference – Materials

Nickel-based alloys

All nickel-based heat-resistant alloys found in a modern aircraft engine are designed to maintain higher strength at elevated temperatures by resisting oxidation and the movement and stacking of dislocations. Unlike iron austenite, nickel austenite is stable at room temperature and does not undergo a phase transformation until melting. Broadly speaking, all nickel-based alloys in an aircraft engine can be separated by application into ones for rotating and non-rotating parts.

Alloys for rotating parts are designed for high-temperature tensile strength. As such, toughness is less of a requirement while hardness is one of the most important. All rotating nickel-based parts are aged. When using ceramics or the right microgeometry in carbide to create sufficient plasticization, chips shear off well and flank wear is predictable in both continuous and interrupted cuts. Higher resistance to abrasive wear (hardness, fracture toughness) is required than when machining the same alloys in the solution-treated condition.

Alloys for non-rotating parts are designed to resist creep, higher stress-rupture strength, and toughness/ductility at high temperatures. Solution treatment and aging cycles can vary significantly from rotating to non-rotating parts, while the composition of the alloys vary less. Machining these alloys typically requires sharper tools and can be done at higher cutting speeds because less heat is generated in the shear zone. Higher chip thickness is also recommended to facilitate chip breaking and prevent the rewelding of chips. Built-up edge and chip sticking are common patterns of tool wear.

XSYTIN®-1 and whisker-reinforced ceramics are exceptionally well-suited for all stages of machining of nickel-based alloys.

Cobalt-based alloys

Cobalt-based alloys are also austenitic but are typically only strengthened through solid solution of such alloying elements as tungsten (W) and molybdenum (Mo) and hardened through the formation of carbides. As a result, they show lower stress rupture strength than nickel-based alloys until around 930°C, at which point carbide strengthening overtakes precipitation strengthening because of the higher stability of carbides beyond 930°C.

Cobalt-based alloys are only used for non-rotating parts operating at the highest temperatures, most often found around the combustion chamber. The higher quantity of carbides and lower overall hardness means that cobalt-based alloys are more abrasive, and the chip does not shear as well as it does in aged nickel-based alloys. Ceramic machining of cobalt-based alloys requires toughness, while carbide machining (noting that cobalt is the binder in a standard tungsten-carbide cutting tool) is done at low speeds and with extra care to preserve the coating and prevent the interaction of the substrate with the workpiece.

XSYTIN®-1 shows outstanding productivity and tool life in turning and milling cobalt-based alloys at speeds ranging from 650 to 2600 SFM (200 to 800 m/min).

Iron-based alloys

Iron-based alloys in aircraft engines are used in applications that either require high wear resistance (bearings) or toughness, strength, and resistance to oxidation at moderate temperatures. Most commonly, these are low-carbon (lath) martensitic or precipitation-hardening austenitic steels.

Duplex-hardening steels (M50, M50NiL, 33CrMoV12-9, RBD) used for applications requiring wear-resistance (bearings) are martensitic and follow a secondary hardening process, such as carburization or nitriding, which raises the surface hardness and introduces compressive stresses. The removal of the carbide- or nitride-rich skin is an operation typically carried out through grinding. In contrast, Greenleaf alumina-based ceramics have the hardness and resistance to abrasive wear necessary to instead remove the skin in turning.

Ultra high-strength maraging steels are quenched (sometimes cryogenically) to form the low-carbon martensitic matrix, tempered to improve toughness and ductility, and then aged to increase strength through precipitation hardening (final condition of Maraging 200–350, ML340, AerMet, SuperCMV). Steels in this class are abrasive and ductile despite the high hardness and extremely high strength. These properties make machining particularly difficult, requiring cutting tool materials with exceptional combinations of toughness, wear-resistance, and strength, such as XSYTIN®-1.

Precipitation-hardening stainless steels (15-5PH, 17-4PH, 17-7PH, etc.) are fully austenitic, fully martensitic, or austenitic-martensitic in microstructure. Due to ductility and high-temperature strength, PH stainless steels require positive cutting tools with resistance to abrasive wear and a plentiful supply of coolant at the cutting edge.

Greenleaf whisker-reinforced ceramics have been successfully implemented in the machining of a number of PH stainless steels.

Technical Reference – Materials

Titanium alloys

All Ti alloys in service in an aircraft engine are used for their resistance to corrosion, and higher specific strength than steel or Ni-based alloys in a wide range of temperatures. The main challenges in machining any Ti alloy stem primarily from its ductility, low thermal conductivity, and the subsequent lack of plasticization because of low heat transfer from the shear zone to the workpiece.

Common titanium alloys exist mostly as a combination of two phases – Alpha (hexagonal close packed) and Beta (body-centered cubic).

Alpha or near-alpha alloys (e.g. Ti-834, Ti-6242, Ti-6246) are not significantly alterable through heat treatment, are easy to weld, have low-medium tensile strength, lower ductility, good high-temperature creep strength, and excellent properties at cryogenic temperatures. These alloys are less ductile than alpha-beta or near-beta titanium alloys, with better chip formation.

Alpha-beta alloys (e.g. Ti-6Al-4V) are heat treatable with medium-high strength, and high-temperature creep strength below that of alpha alloys. These alloys offer an excellent combination of tensile strength and toughness but have a thermal conductivity that is 60% lower than that of commercially pure titanium. Machinability has been likened to a 'wet sponge'– going through a large region of elastic and plastic deformation before the chip shears off and springs back, producing a cyclical, torn chip.

Beta or near-beta alloys (e.g. Ti-555-3, Ti-5Al-4Cr-4Mo-2Zn-2Zr also known as Ti-17) are the most heat treatable, with higher ductility and toughness at the expense of a narrower range of service temperatures. These alloys can be aged to attain very high tensile strength and are the most abrasive of the three types of Ti alloys and most difficult to machine.

G-925, G-9230, and G-915 have won a number of benchmarks at aircraft engine OEMs for all stages of alpha-beta and near-beta titanium machining – from the removal of forging scale to finishing. In addition, G-9610 has shown a marked improvement in tool life and productivity in continuous cuts of titanium alloys. It is a clear favorite for operations requiring higher heat resistance or extended cut time.

Grade Recommendations for Common Materials

Common Materials	Material Group	Operation	Insert Grades	
			Primary	Secondary
Astroloy, IN100, Inconel 718, Inconel 718 Plus, MERL 76, N18, Nimonic, René 104, René 61, René 65, René 88, René 95, RR1000, Udimet 720, Waspaloy	Nickel-based heat-resistant alloy	**Turning** — Forging scale removal	XSYTIN®-1	WG-300®
		Turning — Clean roughing	XSYTIN®-1	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
Alloy A286, Incoloy 909, Jethete M152	Iron-based heat-resistant alloy	**Turning** — Forging scale removal	WG-300®	WG-700®
		Turning — Clean roughing	WG-600®	WG-300®
		Turning — Semi-finishing	WG-600®	WG-300®
		Turning — Finishing	WG-600®	GA5026
		Milling — Roughing	XSYTIN®-1	WG-300®
		Milling — Finishing	G-9230	G-925
AerMet 100, F1E, Maraging 250, Maraging 300, ML340, SuperCMV	Maraging steel	**Turning** – Forging scale removal	XSYTIN®-1	G-9230
		Turning – Clean roughing	XSYTIN®-1	G-9230
		Turning – Semi-finishing	XSYTIN®-1	G-925
		Turning – Finishing	G-925	GA5026
		Milling – Roughing	XSYTIN®-1	G-915
		Milling – Finishing	G-9230	G-925
Ti-17, Ti-6242, Ti-6246, Ti-834	Titanium alloy	**Turning** — Roughing	G-9230	G-915
		Turning — Finishing	G-9610	G-925
		Milling — Roughing	G-915	G-9230
		Milling — Finishing	G-9230	G-9610

Custom Engineered Solutions

Special Design

Greenleaf proudly offers special and custom-engineered products. Customers from around the world benefit from the collective knowledge and experience of a tenured engineering staff, and they use our capabilities to address specific and complex requirements. We offer single-tool to full-component-layout solutions for roughing and finishing operations using standard and custom insert geometries. From small job shops to aerospace industry giants, Greenleaf has saved customers countless machining hours with our unique design, application, and manufacturing experience featuring advanced ceramic and carbide insert grades.

Consider special design tooling when standard tooling is simply not capable of meeting part or machine requirements or when the need for increased metal removal rate is justified. When special design tooling is employed, customers often experience a reduction in scrap and the replacement of many tools with just a single tool. The improvements in cutting tool materials, paired with Greenleaf-designed tooling systems to enhance performance, continue to provide engine manufacturers the productivity they need to meet their specific challenges.

Advanced Modeling

Greenleaf uses advanced computer solid modeling and analysis software that allows us to fine-tune our custom tool designs to your unique part configuration and application. Computer-Aided Design (CAD) with advanced hardware and software enables fast turnaround of proposal drawings and finished detail drawings for tools as they enter our dedicated manufacturing facilities. This analysis proves extremely beneficial for aerospace tooling solutions, considering the need for lightweight engines (and therefore fuel savings) that require tooling on thin-walled components. Greenleaf can model strength before use and simulate the strength of tooling for an optimized design.