AEROSPACE
& PECM

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Aerospace manufacturing is increasingly defined by its invisible geometries….

…Such as the thermal microchannels within critical heat exchangers and the thin-walled geometries on nickel superalloy turbine blades and vanes. As propulsion systems and airframes are pushed toward higher efficiency, temperatures, and safety margins, performance is dictated by internal surfaces and features…. Many of which are difficult to machine or inspect.

1

PECM is ideal for **turbine blade and vane components** where internal surface quality, feature consistency, and defect avoidance are critical.

2

PECM's capabilities are adept for aerospace **thermal infrastructure** that relies on internal channels, microfeatures, or thin-walled geometries to manage heat efficiently.

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At-a-Glance: PECM & Aerospace Features

PECM delivers consistent, unique value for Aerospace applications.

Maintaining consistent channel geometry, ultra-smooth surfaces, and predictable flow behavior across tens of thousands of flight-critical components requires a process that **eliminates thermal distortion, taper, and geometry drift** across production runs.

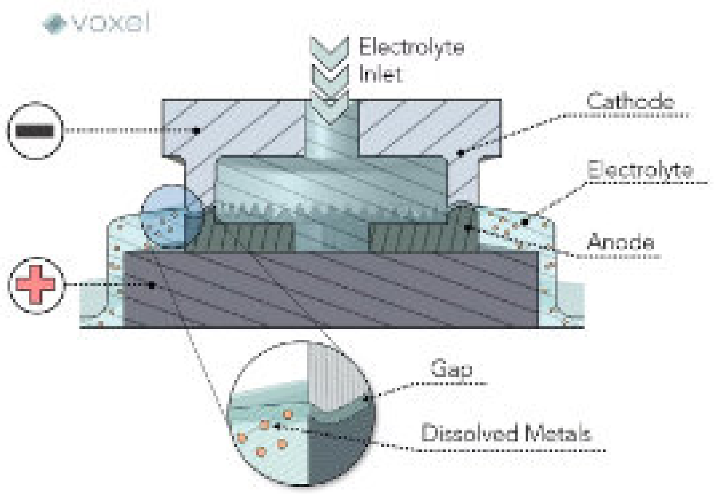
Voxel's PECM can act as a unique remedy for these aerospace manufacturing challenges.

PECM removes metal atom-by-atom, generating uniform internal surfaces and channel architectures in **nickel-based superalloys, stainless steels, titanium**, and other conductive materials used throughout aerospace propulsion and thermal systems, with **high scalability.**

PECM enables:

- **Micron-level channel uniformity** without taper, burrs or HAZ
- **<.2µm Ra internal surface finishes** on stainless, copper and nickel alloys
- **Repeatable multi-channel arrays** for thermal flow paths
- **Minimal tool wear**, supporting consistency across production

PECM **BASICS**



Unlike other material removal technologies such as electrical discharge machining (EDM), PECM is based on the principles of electrolysis. The machining operation involves a tool (the cathode) in the inverse shape of the desired workpiece (the anode).

As the tool moves towards the workpiece surface, it machines the workpiece into the complementary shape of the tool. This occurs as a pulsed DC current is applied, allowing for high precision and superior surface quality. At the same time, an electrolyte is pumped between the cathode and anode at high speed, removing dissolved metal and heat.

The result is an operation capable of producing a burr-free 3D shape with minimal tool wear in alloys that are difficult or impossible to machine through traditional methods. As PECM can produce parts in parallel with excellent repeatability, it is well-suited to high-volume and/or high-value production.

The PECM process has **4** factors:

- The **cathode**, or tool
- The **anode**, or workpiece
- The **electrolytic fluid,** and
- **The pulsed voltage**

Material **Compatibility**

PECM can most conductive materials, including but not limited to:

4140
A2 Tool Steel
Al MMCs
Aluminum 6061
Aluminum 7075
AMZ4
Brass
Bronze
CMSX-4
Cobalt Chrome
Copper
Ferrium C64
GaSb
Germanium
Haynes 230
Inconel 625
Inconel 718
Inconel 738
Inconel 740h
InSb
M4 Tool Steel
MarM247
Molybdenum
MP35N
NdFeB
Nickel
Nitinol
Nitronic 60
Pyrowear 53
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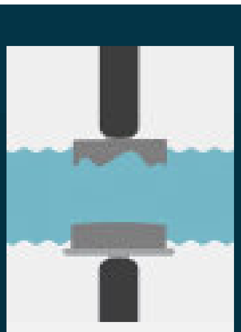
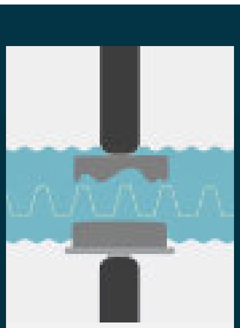
Stainless 440C
Ti Grade 2
Ti64
TiAl
Vit105



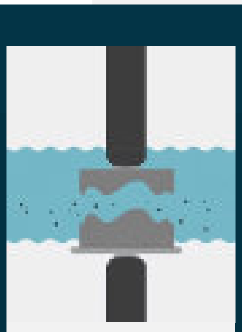
STEP 1

Cathode and anode are set up, and electrolyte is pumped between the two parts.



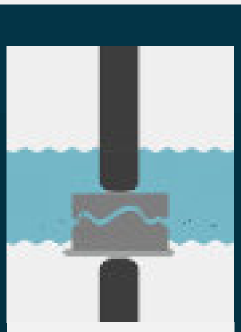
STEP 2

As the two pieces move together, a pulsed DC current is applied to the anode and cathode.



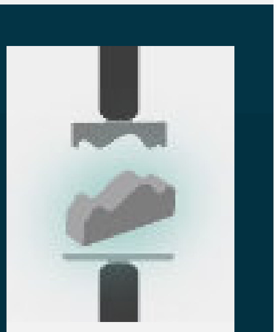
STEP 3

The flowing electrolyte removes heat and waste products from the gap.



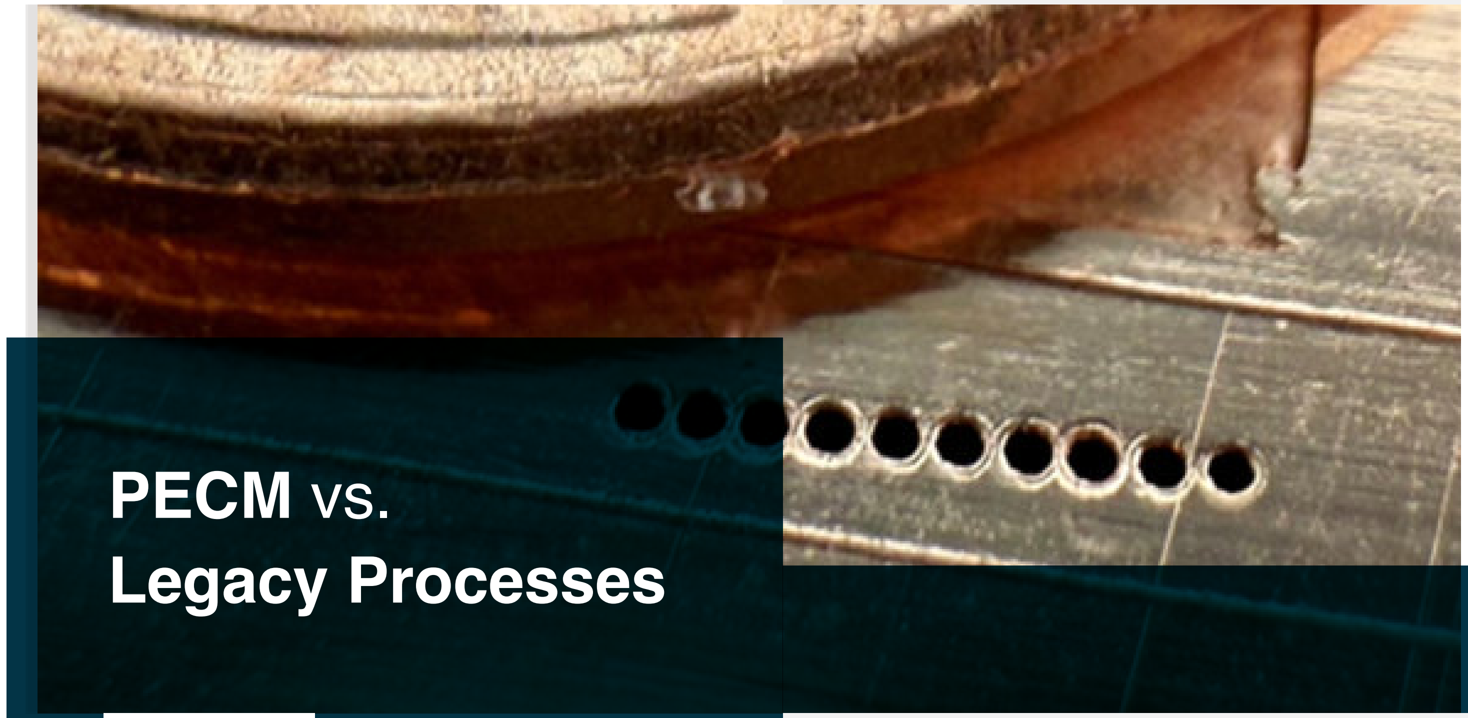
STEP 4

The workpiece is machined into the complementary shape of the cathode tool.



STEP 5

Part is complete with no need for secondary process, burr removal or polishing.



PECM vs. **Legacy Processes**

Design agency is limited by heat and/or contact-based material removal processes.

Conventional processes have inherent limitations, including…

Burrs & Tool Vibration

Contact-based machining introduces cutting forces that create **burrs, edge rollover,** and **vibration-driven surface damage**, notably on thin features and tight internal geometries.

Heat-affected Zones / Recast Layers

Thermal processes leave **HAZ, microcracks,** or **recast layers** that alter material properties, reducing fatigue or corrosion resistance.

Limited Repeatability

Repeatability degrades as tools wear and get replaced. **Dimensional drift, inconsistent finishes,** and **increased inspection** affect high-volume production.

Manufacturers are forced to compromise new designs to meet these limitations.

WHY CHOOSE PECM?

The unique properties of Voxel's pulsed electrochemical machining technology allow it to avoid many of the aforementioned issues:

☑ Non-contact machining produces **no burrs** or **tool vibration**, allowing machining of sensitive areas

☑ Non-thermal machining leaves **no HAZ** or **recast layers**, leaving **superfinished surfaces**

☑ PECM allows **part-to-part/ feature-to-feature repeatability**, significantly less tool wear

PECM IS FUNDAMENTALLY DIFFERENT

By utilizing electrochemistry instead of contact or heat, PECM removes material atom-by-atom, allowing smoother surface finishes, higher tolerances and improved repeatability– enabling manufacturers to explore new designs into production.

Process Specs

☑ Cut Surface Area

3500-7000mm2 in slower cuts; 1750-3500 in faster cuts. Larger surfaces may require multiple operations or higher-amperage equipment while smaller surfaces can potentially be run in-parallel

☑ Wall Thickness

Less than 50μm, with no maximum. .075mm (.003in) has been achieved in 2D blind or through features, minimum feature size is a wall of <25μm

☑ Slot Channel

•Top: 50μm (.002in) minimum
•Bottom: 20μm (.0008in) minimum
•Slot: 30 to 50μm
•Internal: 150μm (.006) minimum is most common, although 75μm (.003in) has been achieved in an ideal case

☑ Surface Finish

.005μm Ra to .4μm Ra, depending on the material

☑ Durability

Cathodes will have a lifetime exceeding thousands of parts

☑ Aspect Ratio

No minimum, capable of exceeding 300:1, depending on the feature size and electrode fabrication method

☑ Corners & Radii

•Top: 50μm (.002in) minimum; Bottom: 20μm (.0008in) minimum
•Minimum inside 90 corner radius, pocket bottom: 15-25μm possible; 25-50μm is more typical
•Minimum outside 90 corner radius, pocket top: 50μm standard
•Internal: 150μm (.006) minimum is most common, although 75μm (.003in) has been achieved in an ideal case

☑ Process Speed

Tends to be a step change in speed with geometry size, depending on the ability to flow electrolyte through the part's features.
Minimum blind feature (e.g. a slot): .5mm, speeds of .1-2μm/s
Feature of 2+mm: speeds of 15-30+ μm/s
More NRE yields more opportunity to improve speeds

☑ Depth Tolerance

Depends on parallelism of the workpiece. Generally, the depth can be controlled to +/- 5μm or less

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Industry **Outlook**

Commercial aviation is under mounting pressure to reduce emissions while still growing demand for reliable, affordable global travel. Industry roadmaps and international frameworks increasingly point toward long-term decarbonisation targets, with sustainable aviation fuels (SAF) and efficency improvements both playing major roles in near and mid-term progress [1].

Yet, even as SAF scales, fuel efficiency directly affects operating cost, range, and total fuel volume required– meaning the physics and manufacturability of high-efficiency engines are critical from both an ecomonical and ecological framework.

In commercial aerospace, these pressures and aspirations collide with a manufacturing-driven reality that can be particularly unforgiving. Unlike many industrial sectors, aerospace components must meet stringent certification, reliability, and lifecycle requirements while operating in environments defined by extreme temperatures, cyclic loading, and long service intervals. Small deviations in material condition, surface quality, or internal geometry can develop consequences over thousands of flight cycles, meaning manufacturing variability is not merely a cost issue, but a performance and safety concern that shapes what designs are considered viable in the first place.

At the same time, the aerospace supply chain is being asked to deliver increasingly complex components at higher production rates without sacrificing repeatability. Advanced engines and thermal systems rely on internal features that are difficult to machine, difficult to inspect, and often impossible to rework once a part is complete. **As designs push toward tighter tolerances, thinner walls, and more aggressive internal architectures, manufacturers must balance innovation against risk**—particularly when the features that govern performance are hidden from view and embedded deep within flight-critical hardware.

Problem 1: **Thermal Efficiency** vs. **Temperature Limits**

For modern turbofan engines, efficiency gains aren't found in software– rather, they are rooted in thermodynamics and hardware: increasing overall pressure ratio and turbine inlet temperature (TIT) remains one of the most powerful pathways to higher thermal efficiency [2].

However, this progress comes with a familiar tax: higher temperatures upstream and deeper in the hot section drive an escalating need for **improved cooling flows and more aggressive high-temperature materials**, as blades and vanes must survive extreme environments for thousands of cycles without losing integrity [2, 3].

Fundamentally, this is where aerospace becomes increasingly defined by its invisible geometries.

The performance and durability of turbine blades and vanes, in fact, are governed not only by external aerodynamics, but by internal cooling passages, micro-scale turbulators (such as ribs, pin fins, dimples, etc.) and carefully shaped film-cooling holes that meter air and form protective cooling films across hot surfaces. [4, 5, 6]

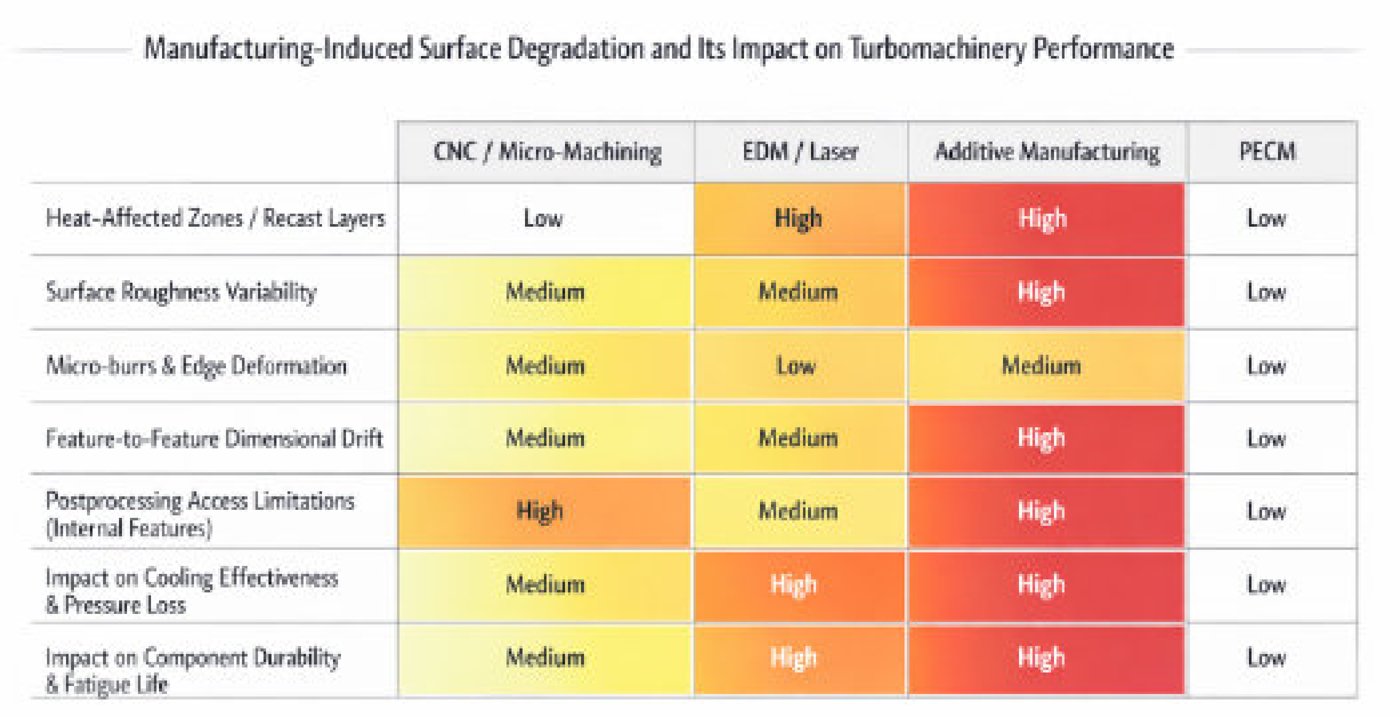
Seemingly insignificant changes in internal channel design tangibly affect heat transfer, temperature gradients, and the mass flow of cooling air required, thereby directly influencing engine efficiency and component life [6,7].

The same is true externally: film-cooling hole geometry and surface condition can be sensitive to roughness, partial blockage, and manufacturing variability, meaning the real-world result deviates substantially from what design engineers originally intended. [8]

Meanwhile, the materials keep getting tougher. Nickel-based superalloys (often in single-crystal form for high-pressure turbine hardware) remain foundational because they retain mechanical strength at temperatures that would cripple conventional alloys, enabling continued efficiency increases through hotter, harder-running cores [13–14].

At the same time, metal matrix composites (MMCs) are being deployed in commercial hot-section components (for example, shrouds and other parts), illustrating the industry's push to extend temperature capability and reduce cooling penalties [15–16].

But whether the material is a nickel-based superalloy or a CMC, the burden still falls on controllable internal features and surface conditions: cooling effectiveness, flow losses, and local hot spots are governed by the geometry and finish of internal passages and holes, and **those are manufacturing problems as much as they are design problems** [11–12, 17–18].



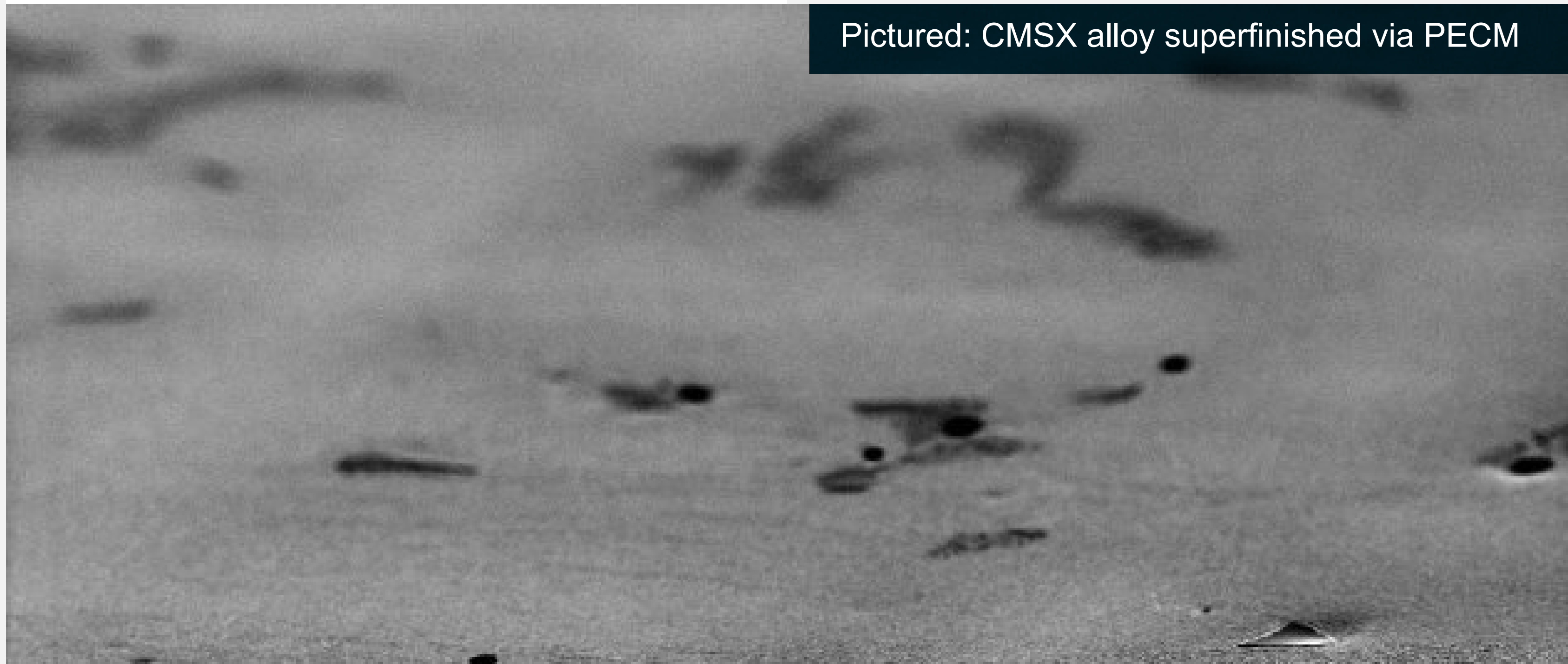
Manufacturing-Induced Surface Degradation and Its Impact on Turbomachinery Performance

	CNC / Micro-Machining	EDM / Laser	Additive Manufacturing	PECM
Heat-Affected Zones / Recast Layers	Low	High	High	Low
Surface Roughness Variability	Medium	Medium	High	Low
Micro-burrs & Edge Deformation	Medium	Low	Medium	Low
Feature-to-Feature Dimensional Drift	Medium	Medium	High	Low
Postprocessing Access Limitations (Internal Features)	High	Medium	High	Low
Impact on Cooling Effectiveness & Pressure Loss	Medium	High	High	Low
Impact on Component Durability & Fatigue Life	Medium	High	High	Low

Problem 2: **Manufacturing Constraints** & **Design Conservatism**

Conventional manufacturing can produce many of these features, but with tradeoffs that intensify as geometries shrink and requirements tighten. Some processes scale quickly (such as laser-based processes) but introduce thermal side effects or surface damage that may demand secondary operations; other methods (such as CNC) offer precision but tend to struggle with deep, high-aspect-ratio internal features or consistent feature-to-feature repeatability. The net effect is that aerospace designers and manufacturers often respond rationally: they back away from aggressive cooling architectures or ultra-tight internal features when variability and inspection risk rise, especially when the part's performance is governed by surfaces and passages that are difficult to measure directly [19–20].

Additive manufacturing is a band-aid; it can create complex manifolds and internal channels needed for thermal designs, but **overwhelmingly struggles to produce adequate surface quality**— as-built



Pictured: CMSX alloy superfinished via PECM roughnesses amongst more advanced methods can still yield 10–20 μm surfaces. Additionally, as AM scales to meet higher volumes, **manufacturers may sacrifice laser scanning strategies, powder sizes, and layer thicknesses to make parts quicker with inferior tolerances** [21].

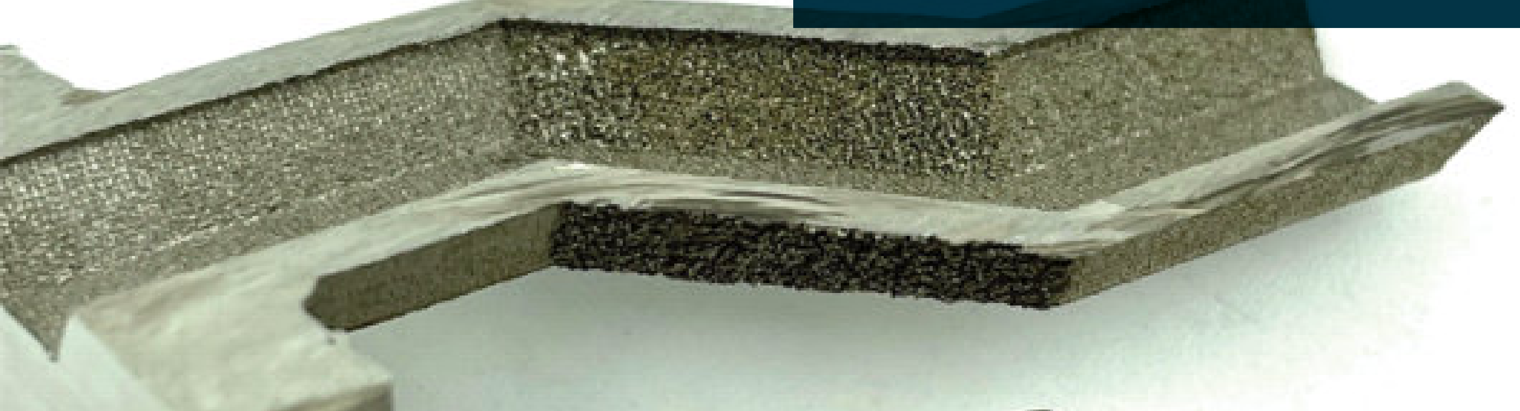
As efficiency targets continue to rise, manufacturers will feel growing pains in the form of temperature limits, cooling penalties, yield risk, and verification challenges. By and large, these limitations come from hardware and infrastructure: engine architectures are being pushed toward higher pressure ratios and higher firing temperatures, while simultaneously acknowledging cooling air availability and component durability as major constraints [4–7].

Geometry and scale are at the heart of these growing pains: when internal surfaces and microfeatures directly govern performance, manufacturers often respond by backing away from aggressive new geometries, as the risk of variability is increased at scale. This shows up as larger safety margins, lower cooling feature densities, thicker walls, and more forgiving tolerances, **ultimately resulting in a widening gap between what can be designed and what does get designed.**

This "**design conservatism**" is especially true in turbine cooling hardware where internal passages, ribs, pin fins, and film-cooling holes push into sub-millimeter scales, and where small amounts of roughness or contamination can cause flow instability, hot spots, or accelerated damage [9–12].

However, the market continues to demand efficiency improvements, and the conventional high-throughput processes manufacturers rely on to produce more complex-geometry components increasingly introduce structural side effects. While postprocessing can mitigate some issues, these methods struggle to uniformly reach deep internal microfeatures without altering geometry. Ultimately, that combination (tight internal features and hard-to-verify surfaces) increases the likelihood of throttling performance, durability drift, or shortened service life when engines are run continuously at high utilisation [19–21].

That is why commercial aerospace propulsion increasingly rewards manufacturing processes that can deliver internal microfeatures and surface integrity at scale, particularly in turbine hardware and thermal systems where performance, efficiency, and durability are governed by invisible geometry [22–23]. ■



Pictured: Cross-section of additive S-shaped component machined internally via PECM

Working With Voxel

Voxel is a uniquely specialized contract manufacturer deploying critical parts in production environments via PECM with applied R&D.

☑ Driven by Co-Development

Voxel embeds with our customers throughout the product lifecycle, creating value through **IP, licensing,** and **production contracts.**

☑ Unique Capabilities

Our applied R&D enables machining of challenging **features, materials,** and **surface conditions** impractical or impossible with legacy processes.

☑ Production-Ready Success

Voxel's PECM-based processes are engineered for **repeatability** and **parallelization**, supporting the transition from early development to reliable, high-volume production with minimal process rework.

Voxel is not organized around selling a process or executing to a fixed print, but to work **alongside** engineering teams as manufacturing constraints are discovered, challenged and rewritten via continued, applied R&D. We engage early-on when materials, internal features, or surface requirements are still fluid, creating unique **partnerships** from qualification to production and beyond.

At our core is Voxel's proprietary application of PECM: continuously advanced through applied R&D and feedback. By vertically integrating electrolyte chemistry, cathode design, tooling and process control, we enable unique **internal geometry machining, superfinished surfaces** and **material machining** methodology**.**

Partnership **Roadmap**

1 **Engagement**
Start a conversation about your goals and challenges; share relevant examples.

2 **Discovery & Qualification**
Assess project fit by reviewing geometry, materials, and production targets.

3 **Solution Shaping**
Define a clear manufacturing path via transparent discussion of requirements and risk.

4 **Proposal & Negotiation**
Review detailed scope, pricing, and assumptions; refine terms for alignment.

5 **Commitment**
Formalize partnership, assign resources, and establish communication channels.

6 **Feasibility**
Validate manufacturability via PECM trials, inspection, and parameter tuning.

7 **Repeatability**
Demonstrate consistent part quality across multi-part runs with documented controls.

8 **Scalability**
Prepare tooling, capacity and throughput for cost-effective, high-volume production.

9 **Ramp-Up**
Launch initial production runs: optimizing for speed, quality and delivery assurance.

10 **Full Production**
Deliver reliable, efficient supply while supporting long-term improvement & growth.

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Contact our **Team**

WHY VOXEL?

Voxel integrates our **PECM technology** with **unique process expertise** to enable **repeatable**, production-rate manufacturing of complex metal parts for critical industries.

WHY NOW?

Engaging with Voxel early creates **leverage**: our applied R&D and production teams can influence geometries, surfaces, and material strategies, ultimately enabling **higher-performance parts**, **smoother qualification** and a more **direct path to production**.

GET IN TOUCH WITH OUR ENGINEERS:

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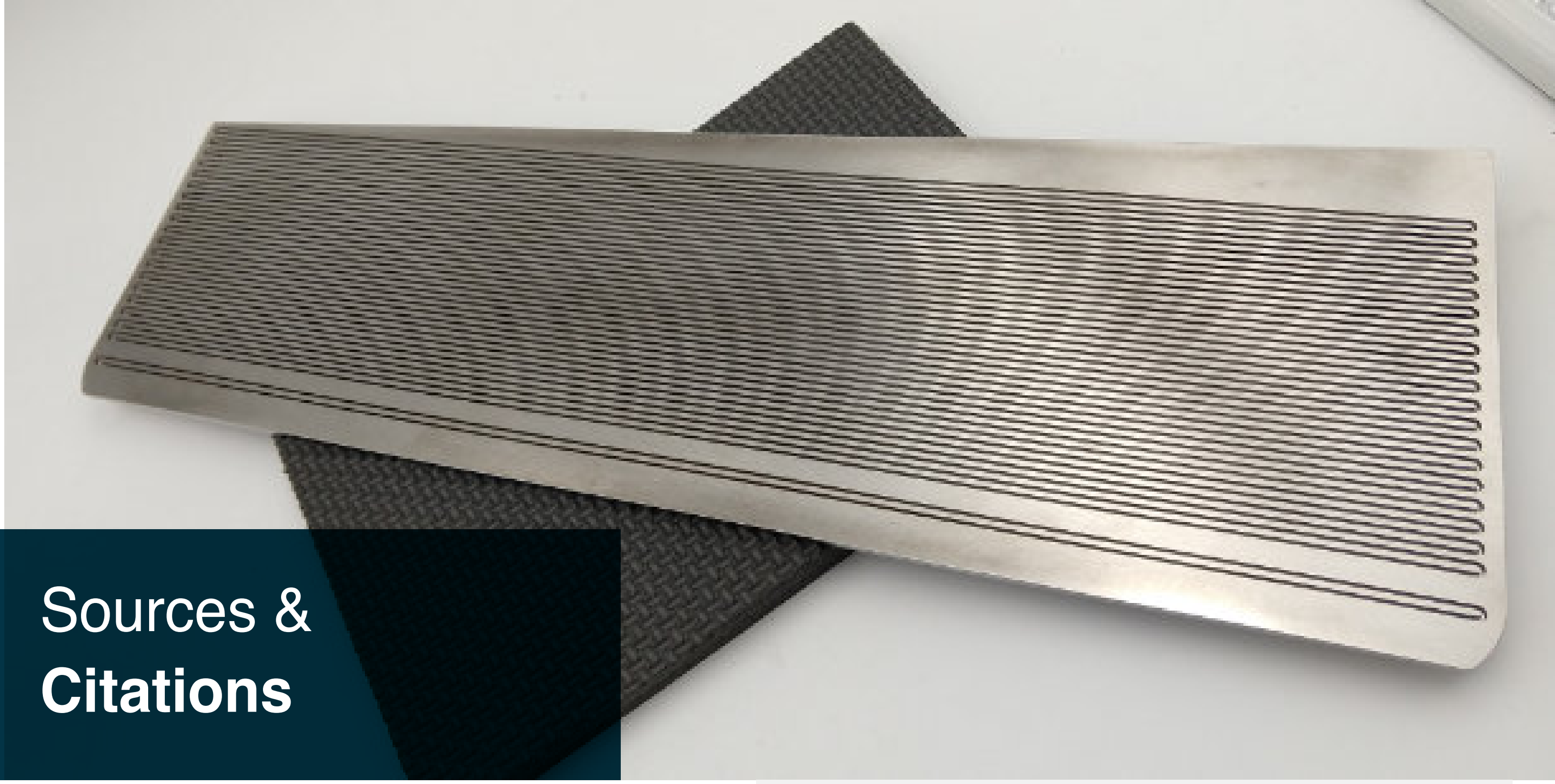

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