by David Jackson, president, Clean Imagineering LLC

SURFACE CONTROL

A dual-mode cleaning solution addresses laser contamination and thermal damage

Laser-based welding, cutting, machining and additive manufacturing enable high-precision production but routinely generate complex surface contamination. This includes metallic and non-metallic particulates, oxide scales and carbonaceous residues. Entrapped gases degrade surface integrity and dimensional control while also affecting downstream joining, coating, sealing and biocompatibility requirements.

Traditional post-process cleaning often requires water-based or solvent chemistries that introduce waste streams, drying delays and environmental compliance burdens. CO_2 composite spray technology presents a unique bimodal solution that addresses laser-induced contamination and thermal damage through two complementary operational modes:

Mode 1: Post-laser cleaning with a high-velocity, micronized CO_2 particles-in-air aerosol jet applied after laser processing as a dry, precision cleaning step that removes particulates, oxides and films without abrasives or liquids.

Mode 2: In-process cleaning and cooling integrated with the laser head to simultaneously manage the laser plume, suppress contamination formation, clean and cool adjacent surfaces during active laser operations, and improve surface quality and dimensional control in real time.

Recent polymer machining studies demonstrate the efficacy of this dual-mode approach: CO_2 composite spray at approximately 80 psi applied during 940-nm diode laser machining of fluorosilicone rubber (FSR), butyl rubber (NBR) and polyethylene (PE) yielded superior hole concentricity, kerf definition and a reported 100 to 140 percent reduction in kerf diameter relative to CO_2 gas-assisted baseline conditions.

Surfaces showed reduced charring, fewer heat-affected artifacts and cleaner edges across all polymer types, confirming simultaneous reductions in contamination and improved thermal process control.

In this laser application involving the machining or cutting of soft polymers, the CO_2 composite spray provides unique and controllable laser processing atmospheres in terms of cooling actions (due to micronized CO_2 particle sublimation cooling), cleaning actions (due to scouring surface impacts by the micronized CO_2 particles) and inerting actions (due to the inert chemistry of CO_2 gas). The low-cost, low-power diode laser used in this demonstration increased the kerf width because of poor heat management during laser processing.

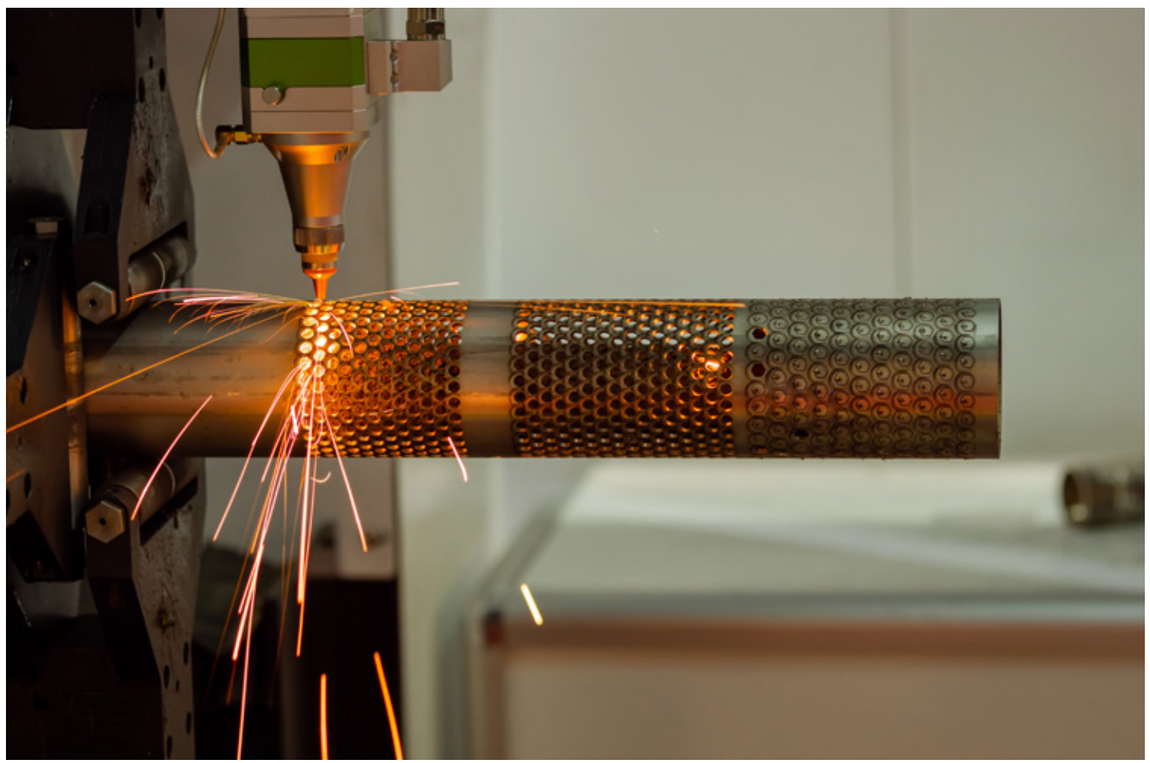
CO_2 gas assist alone is not sufficient for preventing the soft polymer from burning, ablating and spreading outward away from the laser beam cut path – as shown in the side-by-side pictures on page 37. Although a much more expensive high-pulse width laser would not necessarily require more effective cooling actions in this application, it would still benefit from the unique mechanical and chemical cleaning actions provided by the CO_2 composite spray. →

Surface cleanliness is increasingly recognized as a critical process parameter rather than a cosmetic concern.

When extended to metal welding, cutting and additive manufacturing, CO_2 composite spray reduces rework and scrap, eliminates dependencies on chemical and water-based cleaning, supports real-time quality feedback, and enables manufacturers to align with sustainability and circular-economy commitments through CO_2-powered process integration.

The contamination challenge

Laser-based processes, including cutting, welding, drilling, surface structuring, powder-bed fusion and micro-machining, are foundational across transportation, aerospace, energy, medical device, electronics and specialty manufacturing sectors. These processes deliver high energy density and precision, enabling fine features, high-aspect-ratio structures, and reproducible geometry that mechanical or conventional thermal processes cannot match.

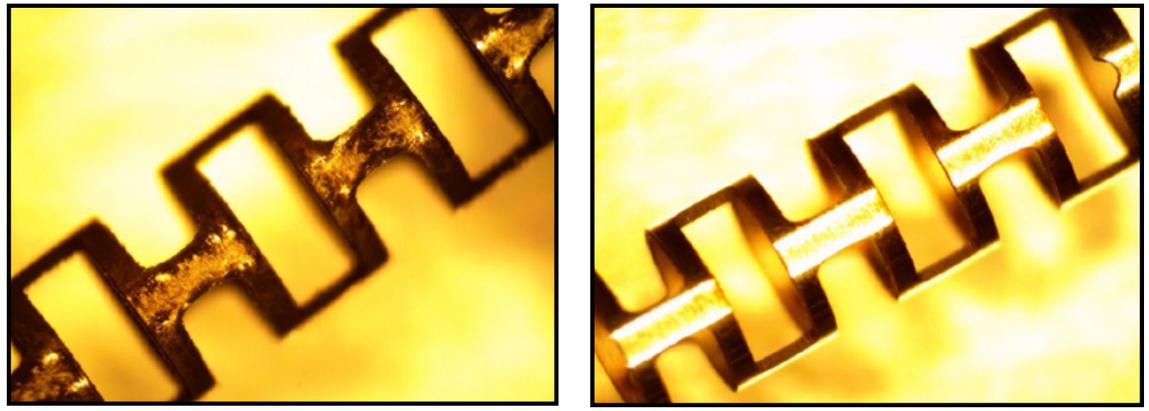


While laser processes enable high-precision manufacturing, they can generate surface contaminants that are difficult and time-consuming to remove.

However, the fundamental strength of laser processing – intense localized heating and rapid material interactions – also creates conditions that can lead to surface contamination. The molten pool, vapor plume and high-temperature interfaces generate particulates, oxides and decomposed organic residues that can persist on finished surfaces and degrade downstream operations.

Surface cleanliness is increasingly recognized as a critical process parameter rather than a cosmetic concern. Residual contamination from laser operations affects:

- *Coating adhesion and durability:* Particulates and oxide scales prevent intimate contact between substrate and coating, reducing adhesion strength and promoting premature failure.
- *Bonding and joining integrity:* Metallic bonds, brazing and adhesive joining all require clean, oxide-free surfaces. Laser-generated contaminants, however, can cause weak interfaces and fatigue failures.
- *Sealing performance:* In aerospace and automotive applications, contaminated surfaces prevent effective seal formation, compromising pressure integrity and component life.
- *Biocompatibility and corrosion resistance:* Medical implants and stents must be particle- and oxide-free to ensure osseointegration, electrical performance and long-term corrosion resistance. Furthermore, laser-generated residues can trigger inflammatory responses and accelerate degradation.
- *Electrical and optical performance:* In electronics and photonics, micro-scale particulates and films degrade conductivity, signal and light transmission, and thermal management. →



Mode 1: Before and after CO_2 composite spray cleaning following laser processing.

Regulatory and customer specifications are tightening allowable contamination limits, prompting manufacturers to integrate contamination control into the laser process itself rather than relying solely on post-hoc cleaning.

Approaches and limitations

Most laser-based manufacturing operations address post-process contamination a few ways.

- Aqueous ultrasonic cleaning is effective but requires deionized water rinsing, drying, wastewater treatment and disposal, and secondary waste management. The process also faces lengthy cycle times, being non-selective, and risk of corrosion if rinsing and drying operations are incomplete.
- Solvent wiping or vapor degreasing removes organic films but leaves particle residue; it is increasingly restricted due to VOC emissions and worker exposure concerns.
- Abrasive blasting or brushing risks surface damage, particularly on soft metals and coatings and is not suitable for delicate or micro-features.
- Plasma cleaning is capital-intensive, requires secondary gas supplies, is ineffective for particulate matter and is not readily integrated into high-volume workcells.

A dry, immediate and selective in-situ cleaning solution that also reduces contamination during laser processing would address these limitations and provide a competitive advantage in high-reliability, volume-sensitive applications.

Contamination types

Recent analysis of laser welding, cutting and machining contamination profiles identifies five primary laser-induced contaminant classes, each with distinct formation mechanisms and removal challenges:

1. Metallic and non-metallic particulates

- *Process spatter and ejected droplets:* Laser-induced vaporization and melting cause molten material to be expelled from the interaction zone at high velocity. Fine metallic droplets cool rapidly, solidify and redeposit on nearby surfaces as hard, adherent spatter. →

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- *Micro- and nano-scale particles:* Rapid solidification of vaporized material generates particles in the 0.1-micron to 10-micron range that remain suspended in the plume and gradually settle or are entrained in cooling flows, eventually adhering to substrate surfaces and adjacent tooling.

- *Non-metallic inclusions:* In multi-phase or coated materials, residues from fillers, plating and interlayer materials (including silicates, carbides and polymeric binders) may be ejected and redeposited, compromising surface homogeneity.

2. Oxide layer formation

- *Surface oxidation at elevated temperature:* When molten or heated metal surfaces are exposed to oxygen (from air or ineffective shielding), they rapidly form oxide scales: FeO, Fe_2O_2, Al_2O_2, Cr_2O_2 and analogues in alloys.

- *Oxide thickness and composition variation:* Oxide growth depends strongly on alloy chemistry, peak temperature, cooling rate and shielding gas effectiveness. Poorly shielded regions exhibit thick, brittle, discolored oxide films that alter surface wetting, hardness and subsequent adhesion.

- *In polymers, carbonization and incomplete oxidation:* High-temperature decomposition of polymers can yield carbonized residues and partially oxidized char layers that adhere tenaciously to edges and adjacent surfaces.

3. Carbonaceous and organic residues

- *Thermal decomposition of lubricants and coatings:* Oils, greases, paint strippers and other surface treatments decompose when exposed to laser heating, generating carbon films and soot that adhere to the workpiece and nearby surfaces.

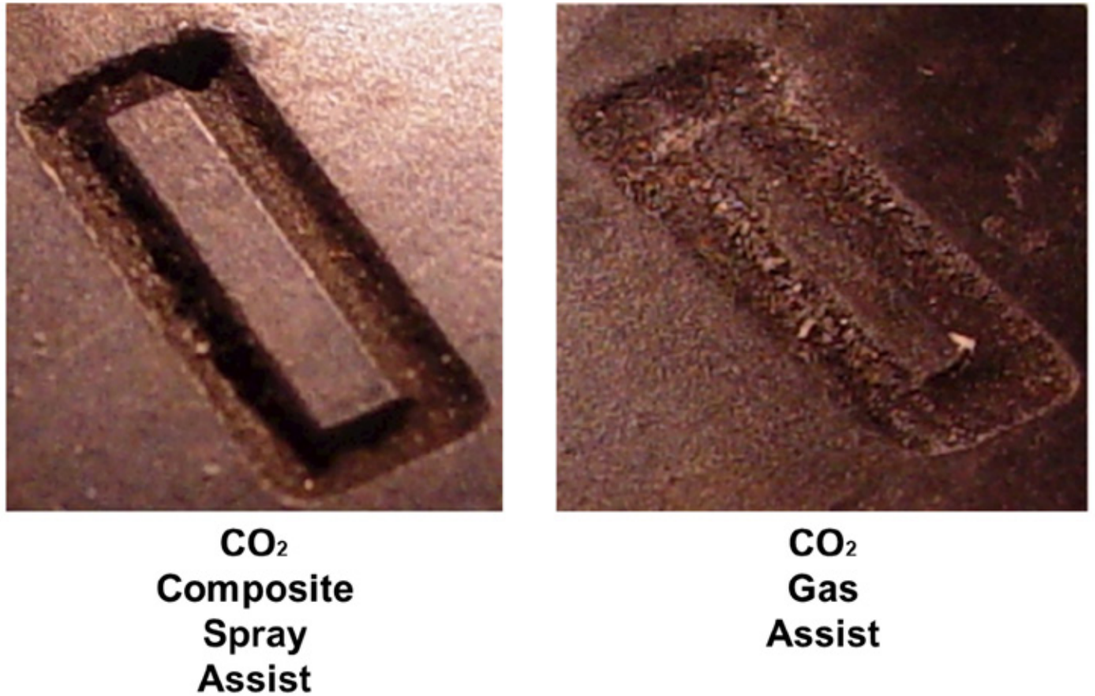
- *Pyrolysis of polymer materials:* In laser cutting or ablation of polymers, partial melting and incomplete vaporization generate cross-linked, tar-like residues that are difficult to remove without solvents.

- *Burning of organic fillers and fibers:* In composite and reinforced polymer cutting, ablated fiber fragments and decomposed resin can create darkened, brittle regions along cut edges.

4. Entrapped gases and porosity

- *Gas bubble formation in melt pools:* Hydrogen, nitrogen and oxygen become trapped in resolidifying weld metal during keyhole welding, creating porosity and surface blisters that are stress concentration sites for fatigue and crack initiation.

- *Sealed gas pockets:* In additive manufacturing, incomplete →



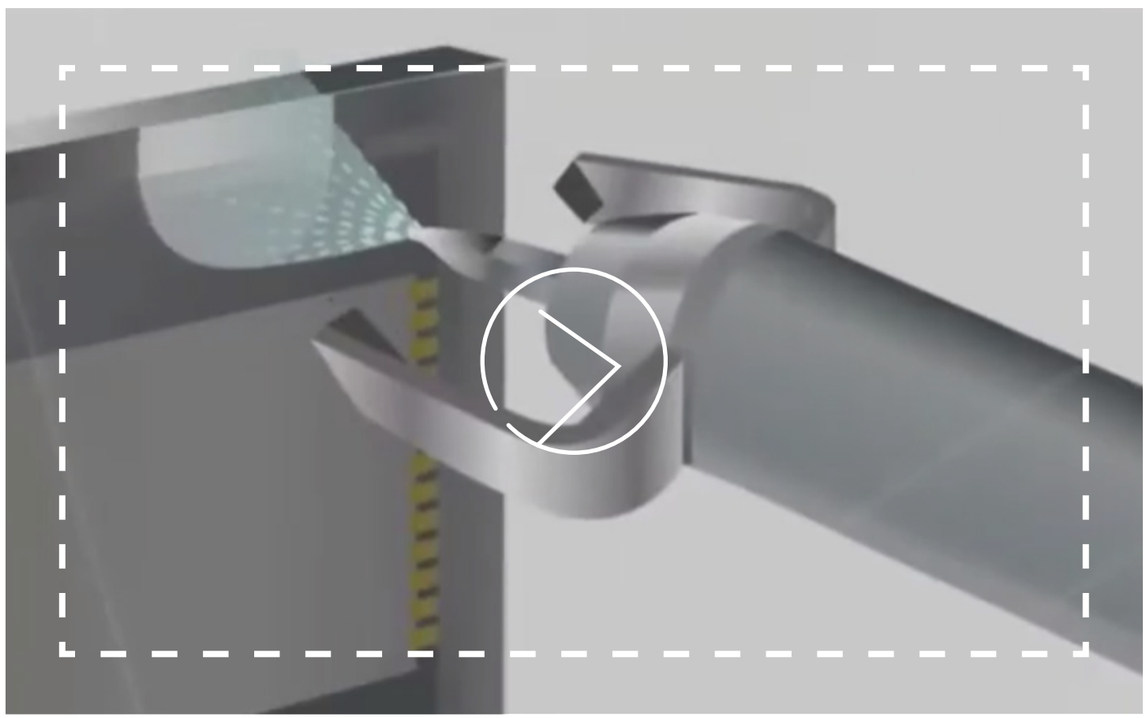
Mode 2: CO_2 composite spray cleaning – cooling during laser processing.

degassing can leave sealed voids within or near the surface layer, compromising mechanical properties and biocompatibility.

5. Multilayer and composite residues

- *Adhesive and interlayer persistence:* Laser cutting and welding of laminated structures, coated metals and composite materials can leave adhesive, plating or interlayer residues along cut edges and weld seams.

- *Differential ablation:* Varying laser absorption and vaporization rates between adjacent materials can create residue boundaries and contamination pockets.



Watch the video to learn more about Clean Imagineering's CO_2 composite spray technology.

Process-specific contamination

The severity and type of laser-induced contamination depend on several controllable and inherent factors:

- *Laser power and focus:* Higher energy density increases vaporization and spatter; tighter focus narrows the contamination zone but increases thermal gradients.

- *Assist gas flow and composition:* Inert shielding (argon, nitrogen) reduces oxidation but does not actively remove particles. Reactive assist gases (oxygen, air) can intentionally accelerate oxidation for some materials but require careful control.

- *Scan speed and interaction time:* Slow speeds increase dwell time and thermal load, promoting oxide growth and pyrolysis; fast speeds reduce thermal damage but may increase spatter if energy density is not optimized.

- *Material surface condition:* Oils, coatings and contaminants present before laser processing decompose under high heat, contributing to carbonaceous contamination in the plume.

- *Wavelength and pulse characteristics:* In polymers, UV and short-wavelength lasers tend to produce cleaner ablation with fewer pyrolytic residues; longer wavelengths and longer pulse durations increase thermal decomposition.

These mechanisms underscore that post-laser cleaning alone is insufficient. An integrated approach that suppresses contamination formation while simultaneously removing incipient particles offers superior results and process robustness. ●

Clean Imagineering LLC →