# WATERJET CUTTING

The ultra-high-pressure cold-cutting process — physics, machine anatomy, cutting parameters, abrasive science, history & applications on one poster

| | |
|---|---|
| **6,000 bar** | 87,000 psi — the pressure that cuts |
| **≈ 900–1,000 m/s** | jet speed ~3× the speed of sound (Mach 3) |
| **±0.05 mm** | positioning accuracy & repeatability |
| **300 mm** | cut depth — thick steel, stone, armour |

## THE BASICS
## WHAT IS WATERJET CUTTING?

Waterjet & abrasive waterjet (AWJ) is a **cold machining** process: a **cold jet of water** pressurised to up to **6,000 bar** is forced through a tiny jewel orifice at supersonic speed and **erodes material** by mechanical impact — no melting, no burning, no tool that touches the part. Because cutting is done by the erosion force of the jet rather than by heat or a blade, the material structure is left unchanged, edges stay stress-free, and there is nothing to go dull.

Pure water cuts **soft** materials: foam, rubber, food, paper, plastic, leather and insulation. Adding a stream of **garnet abrasive** (AWJ) turns the jet into a precision eroding tool that slices **hard metals** (steel, titanium, Inconel, aluminium), **stone & marble**, **glass**, **ceramics** and **fibre composites** (CFRP, Kevlar) up to **300 mm** thick — all in a single pass, cool and burr-free.

- **No heat-affected zone (HAZ)** — the part stays below ≈ 90°C throughout
- **No tool wear** — water & garnet are consumables, never resharpened
- **No thermal distortion** — edges are cold-cut, flat and true
- Works on **any material** or stack, starting from any point, no pilot hole

First used by paper and mining industries in the 1930s; the abrasive waterjet arrived in 1983 and unlocked hard-metal cutting, making waterjet the most material-versatile process in modern manufacturing.

## MACHINE ANATOMY
## THE CUTTING HEAD — COMPONENT FLOW

**Abrasive flow path, top to bottom — the heart of the machine:**

- **Intensifier pump** — compresses water to 6,000 bar (or a direct-drive crank to 3,500)
- **HP water line** — armoured tube carries the pressurised water from pump to head
- **Orifice (jewel)** — sapphire/ruby/DLC nozzle, Ø 0.08–0.5 mm, forms the coherent jet
- **Venturi mixing chamber** — the jet's vacuum sucks garnet in from the side inlet
- **Focusing tube** — tungsten-carbide tube, Ø 0.5–1.5 mm, aligns and trains water + garnet
- **High-speed jet** — exits at ≈ 900 m/s, concentrated onto the workpiece surface
- **Workpiece → catch tank** — water and spent garnet collected safely below the table

**Abrasive hopper + metering valve** — gravity-fed garnet (0.2–1.0 kg/min) through a hose into the mixing chamber; an air purge line and sieve keep the flow constant so the cut never starves. The whole head rides on the CNC gantry and can tilt for bevels.

## PHYSICS
## HOW IT WORKS — THE PHYSICS

- **Energy conversion** — the pump compresses water, storing energy as pressure; that stored energy is then released as kinetic energy in the high-speed jet. Water is nearly incompressible, so the energy is delivered with little loss.
- **Bernoulli** — $v = \sqrt{(2P/\rho)}$: at 4,000 bar the jet exits ≈ 900 m/s; at 6,000 bar ≈ 1,000 m/s (~Mach 3). Doubling the pressure raises speed by only $\sqrt{2}$ but boosts momentum and cutting power sharply.
- **Venturi vacuum** — the fast jet drags the surrounding air, creating a low-pressure zone that sucks garnet in through the side inlet and mixes it uniformly into the stream.
- **Momentum & erosion** — abrasive grains strike the surface at high pressure and shallow angles; the impact causes micro-chipping and fatigue, eroding material away — millions of impacts per second remove the kerf.
- **Kerf** — the slot removed, ≈ focusing-tube Ø + 0.2 mm (≈ 1 mm wide).
- **Taper** — the kerf narrows through the thickness of the part (0.5–1° per 25 mm) as the jet loses energy.
- **5-axis tilt** — the head tilts to ±60° (A/C axes) to compensate taper and to cut true bevelled edges for welding joints.

Result: a cold, burr-free, near-net cut with **Ra 3–12 µm** finish, independent of material hardness, reflectivity or thermal properties — only the jet's momentum and the garnet's hardness matter.

## PURE VS ABRASIVE
## PURE WATERJET vs ABRASIVE (AWJ)

| Feature | Pure waterjet | Abrasive waterjet (AWJ) |
|---|---|---|
| Cut medium | Water only | Water + garnet |
| Materials | Foam, rubber, food, paper, leather, insulation, soft plastics | Steel, Ti, Inconel, stone, glass, ceramics, CFRP/composites |
| Max thickness | ≈ 25 mm (soft materials) | to 300 mm (steel 150–200 mm) |
| Cut mechanism | Droplet impact erosion (fine, clean) | Abrasive particle erosion (micro-chipping) |
| Edge finish | Clean, striation-free, melt-free | Ra 3–12 µm; slight taper on thick cuts |
| Running cost | Low — water + electricity only | Medium — garnet ≈ US$0.3–1.5/kg |

**Rule of thumb:** if it can be cut wet by a thin blade or knife, try pure water; if it is hard, thick, or metallic, add garnet. AWJ cuts almost unbreakable and temperature-sensitive materials that would damage any other process.

## CUTTING PARAMETERS
## KEY CUTTING PARAMETERS

| Parameter | Typical value | Effect on the cut |
|---|---|---|
| Water pressure | 3,000–6,000 bar | ↑ pressure = faster, cleaner, thinner kerf |
| Orifice Ø | 0.08–0.5 mm | smaller = finer jet but slower feed |
| Focusing tube Ø | 0.5–1.5 mm | sets the kerf width (≈ tube Ø + 0.2 mm) |
| Abrasive flow | 0.2–1.0 kg/min | ↑ garnet = faster cut (has a limit) |
| Traverse speed | 0.5–6 m/min | slower = smoother finish (Ra 3–12 µm) |
| Standoff distance | 1–3 mm | larger = more flare, more taper |
| Garnet mesh | 80 std (50–220) | finer mesh = smoother, slower |
| Piercing | pressure ramp + slow feed | clean start hole, no blow-out |

Tune **pressure** for speed and **abrasive** for finish; pierce first with a low pressure 'ramp' before ramping to full cut speed to avoid blasting a ragged hole through the part.

## WHY GARNET
## GARNET — THE ABRASIVE

- **Why garnet?** Almandine garnet — Mohs hardness 7.5–8, sharp angular crystals, SG ≈ 4.1 — it is harder than nearly every workpiece, so it erodes the part, and it shatters on impact to expose fresh cutting edges.
- **Mesh sizes:** 50 = fast roughing · 80 = standard all-round · 120 = finer edge · 220 = micro-finish (finer mesh gives a smoother kerf at lower speed).
- **Rate & cost:** metered at 0.2–1.0 kg/min and ≈ US$0.3–1.5/kg — the single biggest running cost of AWJ after power.
- **Recycling:** spent garnet is filtered, dried and re-sieved; recoverable 3–5× before it breaks down and is disposed of.
- **Alternatives:** olivine, copper slag or crushed glass cut the cost but give a less consistent, slightly rougher cut.
- **Feeding:** a gravity hopper + metering valve keeps flow constant so the cut never starves or floods mid-job.

## THE MACHINE
## MACHINE ANATOMY — KEY COMPONENTS

**HP pump** — two designs: **intensifier** uses a slow, large hydraulic ram to squeeze a small-diameter piston, multiplying pressure to 6,000 bar (pulses, needs an attenuator/damper); **direct-drive crank** uses a motor-driven crankshaft on ceramic triplex plungers, reaching ≈ 3,500 bar, more efficient & smoother — the choice is pressure range vs flow & running cost.

**Water plant** — filtration plus **reverse osmosis (RO)** removes minerals and particles so the tiny orifice and high-pressure seals are protected and the jet stays coherent; some plants add a softener and a 5-micron filter.

**Abrasive feed** — a hopper holds garnet; a metering valve doses it precisely through the delivery hose to the cutting head at 0.2–1.0 kg/min.

**CNC gantry** — servo-driven X/Y/Z axes plus a tilt (A/C) head; traverse speed to **20 m/min**, positioning & repeatability **±0.05 mm**; runs G-code from CAD/CAM with programmed pierce height, taper compensation and nesting.

**Catcher system** — a water tank under the table absorbs the jet's remaining energy so it dissipates safely; spent garnet settles as sludge for recycling.

## STRENGTHS
## ADVANTAGES

- ✓ **Cuts almost any material** — metals, stone, glass, composites, food
- ✓ **No HAZ / no distortion** — cold process, no fire risk
- ✓ **No tool wear / no cutting force** — nothing to re-sharpen
- ✓ **±0.05 mm accuracy**, Ra 3–12 µm edges, near-net shape
- ✓ **Small kerf** (≈1 mm) — material-efficient, stack sheets & cut stacks
- ✓ **No start hole needed** — pierce anywhere, start mid-material
- ✓ **Any thickness** — to 300 mm, one pass, no heat
- ✓ **Eco bonus** — water + recyclable garnet, no toxic fumes

## TRADE-OFFS
## LIMITATIONS

- ✗ **Taper & striations** on thick or fast cuts — needs 5-axis tilt to fix
- ✗ **Slow for thin metal** — laser / plasma are much faster on sheet
- ✗ **High capital cost** — pump, CNC gantry & water plant are pricey
- ✗ **Garnet is a consumable** — ~US$0.3–1.5/kg, continuous spend
- ✗ **Loud** — 85–100 dB, needs a sound enclosure
- ✗ **Wet process** — parts must be dried; rust & splash management
- ✗ **Can't cut** tempered/brittle glass or some ceramics (shatter)
- ✗ **Pump maintenance** — seals, check-valves & orifices wear

## TIMELINE
## HISTORY — PAPER MILLS TO 6,000 BAR

| Era | Milestone |
|---|---|
| 1930s–50s | Low-pressure jets used for paper cutting & cool coal mining |
| 1958 | Dr. Norman Franz (U. Michigan) pioneers ultra-high-pressure jets for wood |
| 1971 | McCartney Mfg. sells the first commercial waterjet systems (paper & cardboard) |
| 1979 | Flow Systems installs industrial systems; Boeing adopts waterjet for aerospace |
| 1983 | Dr. Mohamed Hashish invents the abrasive waterjet (AWJ) — hard-metal cutting unlocked |
| 1990s | 5-axis CNC heads, 4,000 bar intensifiers & CAD/CAM integration arrive |
| Today | 6,000 bar pumps, robotic & micro waterjets (kerf < 0.1 mm), lights-out automation |

From trimming cardboard in paper mills (1930s) to slicing aerospace titanium & Inconel at 6,000 bar today — the same erosion physics scaled up ~30× in pressure and armed with garnet. Flow Systems brought waterjet into industry in the late 1970s, and Hashish's abrasive jet in 1983 turned it into a true metal-cutting machine.

## COMPARE
## WATERJET vs LASER vs PLASMA vs CNC MILL

| Criterion | Waterjet | Laser | Plasma | CNC mill |
|---|---|---|---|---|
| HAZ | None (cold) | Small HAZ (thermal) | Large HAZ (heat) | None (mechanical) |
| Edge quality | Good–excellent | Excellent | Fair–rough | Excellent |
| Kerf width | ≈ 1 mm | 0.2–0.4 mm | 2–5 mm | Cutter Ø |
| Thin steel | Slow–medium | Very fast | Fast | Slow |
| Thick steel | Best (to 300 mm) | Poor (limited) | Good | Good |
| Materials | Any (non-galling) | Metal, wood, plastic | Metal only (conductive) | Most |
| Cut force | None (no contact) | None | None | Tool contact |
| Heat treatment | None — cold | Anneals/re-casts edge | Hardens edge | Minimal |
| Environment | Wet, noisy, clean | Fumes, optics | Glare, fumes | Chips, coolant |
| Cost per part | Medium | Low at volume | Low | Medium |

Waterjet wins where **cold**, **thick**, or **any material** matters; laser wins on **speed & fine kerf** in thin sheet; plasma wins on **cheap thick steel**; CNC mill wins on **3D shapes & finish**.

## WHERE IT'S USED
## MATERIALS & APPLICATIONS

- **Aerospace** — Ti, Inconel, CFRP panels; no HAZ preserves fatigue life of hot-section metals
- **Stone** — marble inlay & mosaic, granite countertops, slate engraving
- **Food** — frozen & baked slicing without crushing, smearing or bacterial transfer
- **Gaskets** — rubber, cork, PTFE, even sticky urethane foams cut clean
- **Armour** — no heat-hardened edge on armour plate, preserves ballistic properties
- **Glass** — signage, lettering & decorative shapes; the jet keeps the glass cool
- **Foam** — thick, stacked sheets cut in a single pass for packaging & furniture
- **Electronics** — PCB depaneling without conductive dust, heat or mechanical shock
- **Metal fabrication** — nesting complex shapes from plate, starting mid-sheet with no pilot hole

Because it is **material-agnostic**, one waterjet machine can replace several dedicated cutters — switching from steel to glass to food involves no tool change, only a programme.

## VOCABULARY & REFERENCE
## GLOSSARY — KEY TERMS · FORMULAS & NUMBERS

**HAZ** — heat-affected zone — avoided since waterjet is cold
**Taper** — kerf narrowing through the thickness
**Focusing tube** — WC tube that aligns water + garnet
**Traverse speed** — table feed rate (0.5–6 m/min)
**Intensifier** — hydraulic booster pump to 6,000 bar
**AWJ** — abrasive waterjet (water + garnet)
**Kerf** — width of the cut slot (≈ 1 mm)
**Orifice** — jewel nozzle (ruby/sapphire) that forms the jet
**Standoff** — nozzle-to-part gap (1–3 mm)
**Garnet** — natural almandine abrasive, Mohs 7.5–8
**Venturi** — vacuum that feeds abrasive into the jet
**5-axis** — tiltable head (±60°) for taper compensation

**FORMULAS:** Bernoulli $v = \sqrt{(2P/\rho)}$ · Pump power = P × Q (pressure × flow) · Cutting rate rises with power · Abrasive mass flow 0.2–1.0 kg/min · Jet exit ≈ Mach 3 at 4,000 bar · Standoff 1–3 mm · Kerf ≈ tube Ø + 0.2 mm · Taper ≈ 0.5–1° per 25 mm · Water is incompressible — the jet stores ≈ 1 GJ/m³ of energy.