The impact stress $\sigma$ required to fracture a brittle material in milling relates to the defect structure and sensitivity to crack propagation:

$$\sigma = \sqrt{\frac{2Er}{D}}$$

$E$: elastic modulus
$r$: defect or existing crack tip radius
$D$: particle size.

Accordingly, larger particles require less impact stress to fracture. As the particle size decreases during milling, the required stress to continue reducing the particle size increases, making prolonged milling less productive.

*Remember $W = g(D_f^{m} - D_i^{m})$ equation and results!*
Surface Area as a Shape Index

The specific surface area is expressed in terms of the area per unit mass ($m^2/g$). For monosized spheres, the area per sphere $A$ and the volume per sphere $V$ are:

$$A = \pi D^2, \quad V = \frac{\pi D^3}{6}$$

$$\Rightarrow \frac{A}{V} = \frac{\pi D^2 \cdot 6}{\pi D^3} = \frac{6}{D}$$

The weight $W$ of a solid particle is calculated from the particle volume and theoretical metallic density $\rho_m$.

$$W = \rho_m V, \quad \text{since surface area is the area per unit weight:}$$

$$S = \frac{A}{W}$$

$$\Rightarrow S = \frac{6}{D \rho_m} \quad \text{where } S \text{ is the specific surface area.}$$

A general form would be; $S = \frac{k_s}{D \rho_m}$ where $k_s$ is the particle shape factor.

A shape factor $k_s$ can be calculated for most geometric shapes. Consider a cylinder shaped particle with a length twice the diameter $D$.

\[\begin{align*}
A &= 2\pi D^2 + \frac{\pi D^2}{2} = \frac{5}{2} \pi D^2 \\
V &= \left(\frac{\pi D^4}{4}\right) 2D = \frac{\pi D^3}{2}
\end{align*}\]
Since \( W = \dot{S}_m V \), \( S = \frac{A}{V \dot{S}_m} = \frac{5\dot{S}_m}{\frac{3}{2} \frac{2}{3} \dot{S}_m} = \frac{5}{0.5} \dot{S}_m \)

\[ \Rightarrow k_s = 5.0 \]

**Gas Atominization**

The use of air, nitrogen, helium or argon for breaking up a molten metal stream. The liquid metal stream is disintegrated by rapid gas expansion out of a nozzle.

The main idea is to deliver energy (from a rapidly expanding gas) to the metal stream to form droplets.

Low temperature atomizers are generally in horizontal design shown below.
For high temperature metals, a closed, inert gas filled chamber is used to prevent oxidation. Below shown a vertical inert gas atomizer. In such units, the melt is prepared by induction melting and is poured into the nozzle.
The particle shape is spherical with a wide size distribution. As an example of typical operating parameters for a gas atomizer, is shown in the table below (for production parameters of a nickel-base superalloy powder). In practice, gas atomization is capable of production rates as high as 100 kg/min. The technique is applied to alloys of Al, Ni, Mg, Co, Pt, Cu, Fe, Au, Sn, Zn and Si.

<table>
<thead>
<tr>
<th>parameter</th>
<th>conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>alloy melting temperature</td>
<td>1400°C</td>
</tr>
<tr>
<td>melt temperature</td>
<td>1550°C</td>
</tr>
<tr>
<td>atomization gas</td>
<td>argon</td>
</tr>
<tr>
<td>gas pressure</td>
<td>2 MPa</td>
</tr>
<tr>
<td>gas flow rate</td>
<td>8 m$^3$/min</td>
</tr>
<tr>
<td>gas velocity at nozzle exit</td>
<td>100 m/s</td>
</tr>
<tr>
<td>gas-melt impingement angle</td>
<td>40°</td>
</tr>
<tr>
<td>metal flow rate</td>
<td>20 kg/min</td>
</tr>
<tr>
<td>mean particle size</td>
<td>120 μm</td>
</tr>
</tbody>
</table>
The atomization physics are described by the drawing shown below. As shown in the figure, the melt stream breaks into a sheet, and eventually droplets. Assuming sufficient superheating above the liquidus temperature, the final particle size will depend on the ligament diameter ($d_L$).
The ligament diameter $d_L$ depends on sheet thickness, $W$ and the gas velocity $V$; $d_L = 3 \left[ \frac{3 \sqrt{8W}}{(4\pi V)^{2/3}} \right]^{1/2}$

where $\gamma_m$ is the melt density and $\gamma$ is the surface energy.

The mean particle size may be linked to the atomization conditions. There is an operating parameter, Weber number $W_e$ which depends on the gas velocity $V$, gas density $\rho_g$, surface energy $\gamma_m$, and melt size as ligament diameter $d_L$,

$$W_e = \frac{\rho_g V^2 d_L}{(2\gamma_m)}$$

The atomized particle size $D$ is; $D : Kd \left[ 1 + \frac{M_m}{M_g} \right] \left( \frac{\rho_m}{\rho_g W_e} \right)$

where $K$ is an empirical constant, $d$ is the melt stream diameter, $M_m$ is the mass flow rate of the melt stream, $M_g$ is the mass flow rate of the gas, $\rho_m$ is the melt viscosity, and $\rho_g$ is the gas viscosity.

Most gas atomization is performed with $W_e$ below $10^3$. A lower ratio of mass flow rates (metal to gas) as well as larger Weber no (higher droplet velocity) contributes to smaller powders.

Experimental data gives the following relation:

$$D = \frac{C}{V} \left( \frac{\gamma_m}{\rho_m} \right)^{0.22} \left( \frac{\rho_m}{\rho_m} \right)^{0.57}$$

$C$ is a nozzle geometry constant, $\gamma_m$ is the melt surface energy, and $\rho_m$ is the melt density.
Water Atomization

Water atomization is the most common technique for producing elemental and alloy powders from metals which melt below 1600°C. An example of a water atomizer geometry is shown below. High pressure water jets are directed against the melt stream, forcing disintegration and rapid solidification.

The process is similar to gas atomization, except for the rapid quenching and differing fluid properties. Because of rapid cooling, the powder shape is irregular and rough, with some oxidation. Synthetic oils or other nonreactive liquids can be used instead of water to have better control of particle shape and oxidation.
Pressure is the main process control variable in water atomization. Higher water pressures result in higher water velocities and smaller particle sizes. In one set of experiments, a steel was atomized at a water pressure of 1.7 MPa giving 117 μm mean particle size, whereas 13.8 MPa resulted in mean particle size of 42 μm. Pressures up to 150 MPa can be used in water atomization, resulting in 5 μm size range.

The table below provides a contrast between water and gas atomization. Two big differences are in the powder shape and the surface contamination. In many situations, if an oxide coating is detrimental, then it can be removed by heating in hydrogen after atomization.

The operating variables for water atomization have significant effect on the resulting powder characteristics. In practice, atomization rates as high as 400 kg/min can be achieved, using velocities up to 230 m/s. The melt can be the desired final composition.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Gas Atomization</th>
<th>Water Atomization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size, μm</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Particle shape</td>
<td>Spherical</td>
<td>Nodular, irregular</td>
</tr>
<tr>
<td>Agglomeration</td>
<td>Some</td>
<td>Little</td>
</tr>
<tr>
<td>Apparent density, %</td>
<td>55</td>
<td>35</td>
</tr>
<tr>
<td>Cooling rate, °C/s</td>
<td>$10^2$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Segregation</td>
<td>Slight</td>
<td>Negligible</td>
</tr>
<tr>
<td>Oxide content, ppm</td>
<td>120</td>
<td>3000</td>
</tr>
<tr>
<td>Fluid pressure, MPa</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Fluid velocity, m/s</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Low</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Mathematical models linking the particle size in water atomization with the operating parameters have similarities to those of gas atomization. A high pressure, or high water velocity, causes a decrease in the mean particle size.

\[ D = \frac{\beta \ln(P)}{[V \sin(\alpha)]} \]

where \( \beta \) is a constant which incorporates both material and atomizer design effects, \( P \) is the atomizer pressure, \( V \) is the water velocity, and \( \alpha \) is the angle between the melt stream and the water nozzle.

**Centrifugal Atomization**

The rotating electrode concept is shown below and an example of resulting powder is shown in the figure.
The consumable electrode is the anode and rotates at velocities up to 50,000 RPM. Like gas atomization, centrifugal atomization is often performed under an inert gas to protect the powder from oxidation.

Assuming the centrifugal force is balanced by the surface tension force of the particle on the rim of the rotating device gives a relation between the expected particle size $D$ and the operating parameters.

$$D = \left( \frac{A}{w} \right) \sqrt{\frac{\gamma}{\rho \ln R}}$$

$A$: process dependent constant,
$w$: angular velocity,
$\gamma$: surface energy of the melt,
$\rho$: density of the melt,
$R$: radius of the electrode.

According to this model, smaller particles are generated with faster rotation rates, larger rotational diameters, and lower surface energy liquids.

However, if there is insufficient superheating, solidification will form ligamental particles before spheroidization.
Another model for the mean particle size \( D \) by centrifugal atomization is:

\[
D = \frac{M_m^{0.14}}{w^{0.64}} \left( \frac{S}{S_m} \right)^{0.43}
\]

- \( M_m \): melt rate
- \( w \): angular velocity
- \( S \): surface energy of the melt
- \( S_m \): melt density

The benefits of rotating electrode process are:

- powder cleanliness
- spherical shape, which is good for high packing density and good flow rate
- uniform particle size
- no contamination

The disadvantages:

- low production rate
- high equipment and processing cost
- coarse particle size

(If tungsten cathode is used, W-contamination may be observed)
Atomization Limitations

Atomization is generally limited to impact velocities less than the speed of sound. This determines the heat extraction, particle size, and energy efficiency of all atomization techniques.

The energy efficiency for atomization is low. As the flow rate of atomization fluid increases, there is a minimal decrease in the final particle size. The process efficiency decreases as both flow rate and pressure increase.

In the case of water atomization, attempts to use very high pressures to form smaller particles show a diminishing return. Unfortunately, the desire for small powders cannot be satisfied by just higher pressures. Creating smaller particles requires Weber numbers in \(10^3\) to \(10^4\) range, which requires high gas densities and velocities, possibly using rocket nozzle technologies.

An alternative concept is to use 2-stage atomization. The primary melt stream is atomized using gas, plasma or centrifugal techniques and before the droplets freeze they are collided with a secondary atomization stage to generate finer particles.
Water atomization generally provides a more homogeneous microstructure as compared to other techniques, but water greatly increases the oxygen level of the powder.

Surface oxidation and an irregular particle shape are common problems with high alloy powders produced by water atomization.

Precious metals may have only 50 ppm oxygen after atomization, but alloys containing reactive metals such as Cr, Ti, or Al will routinely exhibit up to 2000 ppm of oxygen.

Inert gas atomization can generate oxygen levels below 100 ppm with proper handling, although the smaller powders contain higher oxygen levels.