Machinability

Machinability is the ease with which a given material may be worked with a cutting tool.

Machinability ratings (MR) provide an understanding of the severity of a metalworking operation in comparison to B1112 steel.

Factors affecting machinability include tool material, feeds, speeds, cutting fluids, and the microstructure, grain size, heat treatment, chemical composition, fabrication methods, hardness, yield strength, and tensile strength of the work piece.
Machinability (Tool Life)

The Taylor tool life equation describes the expected tool life of a cutting tool as a function of cutting speed:

\[ vT^n = C \]

- Cutting speed \([\text{m/min}]\) or \([\text{ft/min}]\)
- Inverse slope of the tool life (log/log) – constant for a given tool material
- Tool life \([\text{min}]\)
- Constant, y-intercept at \(T=1\) min, dependent on tool material, work material, cutting conditions
Machinability (Tool Life)

Tool life for coated and uncoated WC cermet cutting bits against 1045 steel
Machinability of Various Metals

Machinability Rating

Steel
- Low C
- Med C
- High C
- Free machining
- Alloy (1XXX - 8XXX)
- Tool

Stainless / superalloys
- Cast iron
- Titanium
- Aluminum
- Copper
- Brass
- Bronze

0 0.5 1.0 1.5 2.0
Machinability Rating

B1212

5
Materials Importance Over Time
Physical Properties of Metals

Strength
Elasticity / stiffness
Brittleness / ductility
Density
Conductivity (electrical and thermal)
Stability (chemical, corrosion, food safety)
Machinability / weldability
Cost
Combustibility
Melting point
Thermal expansion
Copper

- 2nd highest electrical conductivity (Ag is higher)
- Corrodes in air
- Hard to machine (often deforms rather than cuts)
- Antimicrobial

Y = 45 ksi
UTS = 50 ksi
H = B40
E = 17,000 ksi
## Types of Copper

<table>
<thead>
<tr>
<th>Identification</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>C10100 (oxygen free copper, OFE)</td>
<td>99.99% pure with less than 0.0005% O, expensive, used in high vacuum components as it does not outgas</td>
</tr>
<tr>
<td>C11000 (electrolytic tough pitch, ETP, ultraconductive copper)</td>
<td>Unalloyed, 99.9% pure, high ductility, corrosion resistance, poor machinability, excellent forming characteristics</td>
</tr>
<tr>
<td>C14500 (tellurium copper, TelCu)</td>
<td>Corrosion resistant, 0.5% tellurium, 1.0 MR</td>
</tr>
</tbody>
</table>
Brass

- Alloy of Cu and Zn (Zn ~5 – 50% by wt)
- Can be highly polished and easily plated (Au or Ag)
- Easily machined

\[
\begin{align*}
Y & = 45 - 57 \text{ ksi} \\
UTS & = 50 - 70 \text{ ksi} \\
H & = \text{B60 - B100} \\
E & = 14,500 - 18,500 \text{ ksi}
\end{align*}
\]
## Types of Brass

<table>
<thead>
<tr>
<th>Identification</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>230 (red brass)</td>
<td>Reddish in color, Cu (84-86%) / Zn (15%) / Fe (0.05% min) / Pb (0.06% min), high strength brass</td>
</tr>
<tr>
<td>260 (yellow / cartridge brass)</td>
<td>Used in shell casings, low MR, good formability and workability, Cu / Zn (28-32%) / Fe / Pb</td>
</tr>
<tr>
<td>353, 385, 360 (free machining, ultra-machinable brass)</td>
<td>Cu / Zn (35%) / Fe / Pb (2-4%), easily machinable, poor performance for forming operations</td>
</tr>
<tr>
<td>Alloy 485 (high-leaded naval)</td>
<td>Corrosion resistance via Sn, Cu (60%) / Zn (~40%) / Sn(0.7%)</td>
</tr>
</tbody>
</table>
Bronze

- Cu + Sn + other components
- Casts well (highly wetting / low viscosity) when melted
- Less brittle than Fe

$Y = 21 - 55 \text{ ksi}$
$UTS = 35 - 120 \text{ ksi}$
$H = B65 - B170$
$E = 96,000 - 120,000 \text{ ksi}$
# Types of Bronze

<table>
<thead>
<tr>
<th>Identification</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>C863 (Manganese bronze)</td>
<td>High strength variant, Cu (60-80%) / Al (3-8%) / Fe (2-4%) / Mn (2-5%) / Zn (~25%)</td>
</tr>
<tr>
<td>C932 (Bearing bronze)</td>
<td>Used in bushings and bearings, highly machinable, Cu (81-85%), Sn (6-8%), Pb (6-8%), Zn (2-4%)</td>
</tr>
<tr>
<td>C954 (Aluminum bronze)</td>
<td>High strength and corrosion resistance, tarnish resistant, used in marine applications, Cu (83%), Fe (3-5%), Al (10-11.5%)</td>
</tr>
</tbody>
</table>
Cast Iron

- Fe + C + Si
- Brittle
- Low melting point
- Highly machinable
- Often cast

Y = 33 - 108 ksi
UTS = 25 - 135 ksi
H = B130 - B450
E = ~130,000 ksi
## Types of Cast Iron

<table>
<thead>
<tr>
<th>Identification</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>A48, Grey cast iron</td>
<td>Moderate hardness (B260), machine tool bases, cylinder blocks, Fe / C (3.4%) / Si (1.8%) / Mn (0.5%)</td>
</tr>
<tr>
<td>A47, Malleable iron</td>
<td>Low hardness, gears, crankshafts, Fe / C (2.5%) / Si (1%) / Mn (0.55%)</td>
</tr>
<tr>
<td>Ni-hard type 2</td>
<td>High strength applications, Fe / C (3%) / Si (2%) / Mn (1%) / Ni (20%) / Cr (2.5%)</td>
</tr>
</tbody>
</table>
Steel

- Low / medium / high carbon steel – general formula is Fe + C + other trace components
- Steel alloys
- Malleability and ductility largely determined by carbon content
Steel Production

**Continuous casting**

**Hot rolling**

Cold rolling = room temperature, work hardening, high quality surface finish

Hot rolling = high temperature, no work hardening, scaly finish
Low Carbon / Mild Steel

- 0.05 – 0.30% C
- Poor corrosion resistance
- Common structural material, car body panels, cans
- Low cost

**Mechanical Properties**

- Yield Strength ($Y$): 50 – 80 ksi
- Ultimate Tensile Strength ($UTS$): 60 – 80 ksi
- Hardness ($H$): B120
- Elastic Modulus ($E$): 30,000 ksi
Medium Carbon Steel

- 0.30 – 0.59% C
- Balance of ductility, strength, and wear resistance
- Railroads, crankshafts

Y = ~100 ksi
UTS = 115 ksi
H = B170 – B210
E = 30,000 ksi
High Carbon Steel

- 0.60 – 0.99% C
- Strong and hard
- Springs, knives, blades, piano wire

Y = ~150 ksi
UTS = 100 - 140 ksi
H = >B200
E = 30,000 ksi
# Steel and Alloy Steel Designations

<table>
<thead>
<tr>
<th>SERIES</th>
<th>STEEL TYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1XXX, 11XX</td>
<td>Plain carbon (non alloy) steel</td>
</tr>
<tr>
<td>13XX</td>
<td>Manganese steel</td>
</tr>
<tr>
<td>2XXX</td>
<td>Nickel alloy steels</td>
</tr>
<tr>
<td>23XX</td>
<td>3.5% Nickel</td>
</tr>
<tr>
<td>25XX</td>
<td>5.0% Nickel</td>
</tr>
<tr>
<td>3XXX</td>
<td>Nickel/Chrome steels</td>
</tr>
<tr>
<td>4XXX</td>
<td>Molybdenum steels</td>
</tr>
<tr>
<td>40XX</td>
<td>Carbon/Moly</td>
</tr>
<tr>
<td>41XX</td>
<td>Chrome/Moly</td>
</tr>
<tr>
<td>43XX</td>
<td>Chrome/Moly/Nickel</td>
</tr>
<tr>
<td>46XX or 48XX</td>
<td>Moly/Nickel</td>
</tr>
<tr>
<td>5XXX</td>
<td>Chromium alloy steels</td>
</tr>
<tr>
<td>51XX</td>
<td>Low Chromium content</td>
</tr>
<tr>
<td>52XX</td>
<td>Medium Chromium content</td>
</tr>
<tr>
<td>53XX</td>
<td>High Chromium content</td>
</tr>
<tr>
<td>6XXX</td>
<td>Chromium/Vanadium alloy steels</td>
</tr>
<tr>
<td>86XX or 87XX</td>
<td>Nickel/Chromium/Moly alloy steels</td>
</tr>
<tr>
<td>92XX</td>
<td>Manganese/Silicon alloy steels</td>
</tr>
<tr>
<td>LETTER</td>
<td>STEEL TYPE</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>A</td>
<td>Air-hardening steels</td>
</tr>
<tr>
<td>D</td>
<td>Die steel alloys</td>
</tr>
<tr>
<td>F</td>
<td>Carbon/Tungsten alloys</td>
</tr>
<tr>
<td>H</td>
<td>Hot work alloys</td>
</tr>
<tr>
<td>L</td>
<td>Low alloy</td>
</tr>
<tr>
<td>M</td>
<td>Molybdenum alloys</td>
</tr>
<tr>
<td>O</td>
<td>Oil hardening steels</td>
</tr>
<tr>
<td>P</td>
<td>Mold steel alloys</td>
</tr>
<tr>
<td>S</td>
<td>Shock resistant alloys</td>
</tr>
<tr>
<td>T</td>
<td>Tungsten alloys</td>
</tr>
<tr>
<td>W</td>
<td>Water hardening steel</td>
</tr>
</tbody>
</table>
Comparison of Steel Properties

- Low carbon steel (0.15% C)
- Mild steel (0.18% C)
- Mild steel (0.26% C)
- Medium carbon steel (0.44% C)
- Chrome / moly
- Cr / Mo / Ni (0.40% C)
- Cr / Mo / Ni (0.20% C)

Legend:
- UTS (ksi)
- Y (ksi)
- $ (Price)
- density
Stainless Steel

A NON-RUSTING STEEL.
Sheffield Invention Especially Good for Table Cutlery.

According to Consul John M. Savage, who is stationed at Sheffield, England, a firm in that city has introduced a stainless steel, which is claimed to be non-rusting, unstainable, and unmar responsible. This steel is said to be especially adaptable for table cutlery, as the original polish is maintained after use, even when brought in contact with the most acid foods, and it requires only ordinary washing to cleanse.


- Minimum 10% Cr by mass
- Corrosion-resistant
- Higher strength
- Higher cost
- Hard to machine

St. Louis Gateway Arch (1965)
Austenitic Stainless Steel

- Over 70% of stainless steel
- Highly corrosion resistant
- <=0.15% C and >=16% Cr + Ni + Mn
- Difficult to weld
- Face centered cubic structure
Martensitic Stainless Steel

- Strong / tough
- Magnetic
- Body centered cubic structure
- Austinite at high temperatures converts to martensite
# Types of Stainless Steel

<table>
<thead>
<tr>
<th>Identification</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>303 (aus)</td>
<td>304 + S + P, free machining, difficult to weld</td>
</tr>
<tr>
<td>304 or 18/8 (aus)</td>
<td>Most common grade, forks, knives, weldable, corrodes in saltwater environments, 18% Cr and 8% Ni</td>
</tr>
<tr>
<td>316 (aus)</td>
<td>Marine grade, Mo provides corrosion resistance, food/surgical uses, machinability similar to 304</td>
</tr>
<tr>
<td>410 (mart)</td>
<td>Wear resistant, machinable, poor corrosion resistance</td>
</tr>
<tr>
<td>416 (mart)</td>
<td>+Si + S for easier machining</td>
</tr>
<tr>
<td>440 (mart)</td>
<td>Razor blade steel, high carbon content, poor machinability and weldability</td>
</tr>
<tr>
<td>17-4PH (mart)</td>
<td>Precipitation hardening, aircraft industry</td>
</tr>
</tbody>
</table>
Aluminum

- Most abundant metallic element on Earth’s crust
- Annealed state is “gummy”
- Often alloyed with Si, Mg, Zn, and/or Cu to improve physical properties
- Inexpensive

Y = 40 – 80 ksi
UTS = 45 – 80 ksi
H = B95
E = 10,000 ksi
# Types of Aluminum

<table>
<thead>
<tr>
<th>Identification</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024</td>
<td>High strength, fatigue resistance, susceptible to corrosion (due to Cu), not weldable, +Cu (4.4%), Mg (1.4%), Mn (0.5%), traces of Si, Zn, Ni, Cr, Pb, Bi</td>
</tr>
<tr>
<td>6061</td>
<td>Most common, highly machinable, weldable, can be anodized, +Si (0.4 – 0.8%), Fe (0.7%), Cu (0.4%), Mn (0.15%), Mg (1%), Cr, Zn, Ti</td>
</tr>
<tr>
<td>7075</td>
<td>Aircraft grade, high strength, Zn (6%), Mg (2.3%), Cu (1.4%), traces of Si, Fe, Mn, Ti, Cr +others</td>
</tr>
</tbody>
</table>
Magnesium

- Best strength/weight ratio of all structural materials (1/4 weight of steel, 1/3 weight of Al)
- Chips highly flammable
- Used in engine blocks (Porsche, BMW, Corvette) and German military aircraft (WWI and WWII)

\[
\begin{align*}
Y &= 7 \text{ ksi} \\
UTS &= 53 \text{ ksi} \\
H &= B70 \\
E &= 70,000 \text{ ksi}
\end{align*}
\]
Titanium

- Light and strong
- Excellent corrosion resistance
- Hard to extract and expensive
- Difficult to machine

\[
\begin{align*}
Y &= 130 \text{ ksi} \\
UTS &= 140 \text{ ksi} \\
H &= B265 \\
E &= 16,000 \text{ ksi}
\end{align*}
\]