A2 Tool Steel - Datasheet

Other Designations: UNS T30102, DIN 1.2363, X100CrMoV5, SKD12 BA2

A2 tool steel is a highly versatile air-hardening tool steel often regarded as a “universal” cold work steel. It offers a combination of good wear resistance (between O1 and D2) and toughness. Considered relatively easy to machine in the annealed condition, it has a high compression strength and good dimensional stability during hardening and tempering. It’s used for a wide variety of cold-work tools, from forming and cutting equipment to high wear parts.

Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>4.75-5.5%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.9-1.4%</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.95-1.05%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.4-1%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.3% max</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.15-0.5%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.1-0.5%</td>
</tr>
<tr>
<td>Iron</td>
<td>bal</td>
</tr>
</tbody>
</table>

Typical Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Markforged As-Sintered</th>
<th>Markforged Heat-Treated</th>
<th>Wrought Heat Treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Compressive Yield Strength</td>
<td>ASTM E9</td>
<td>850 MPa</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>ASTM E9</td>
<td>180 GPa</td>
<td>180 GPa</td>
<td>190 GPa</td>
</tr>
<tr>
<td>Hardness</td>
<td>ASTM E18</td>
<td>52 HRC</td>
<td>58 HRC</td>
<td>63 HRC</td>
</tr>
<tr>
<td>Relative Density</td>
<td>—</td>
<td>≥ 94.5%</td>
<td>≥ 94.5%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Heat Treatment

A2 tool steel can be heat-treated to increase hardness and durability. Markforged recommends heat-treating A2 tool steel to optimize material properties, though it can be used as-sintered.

1. Heat A2 Tool Steel part in a standard (non vacuum) furnace to 970°C (1780°F). Hold part at temperature for 30-45 minutes.
2. Air quench part to below 65°C (150°F).
3. Double temper A2 Tool Steel part in a standard furnace. For each temper, heat part to 150-550°C (302-1022°F) and temper for 2 hours, or 1 hour per inch of thickness. If double tempering, let part cool to room temperature between temps.

1. Markforged heat-treated A2 tool steel was heated to 970°C (1780°F) and single tempered at 200°C (392°F) for 30 minutes.
2. Tempering temperature has a significant effect on final material properties. For higher hardness, temper at low temperatures. For higher toughness, temper at higher temperatures.

These data represent typical values for Markforged A2 Tool Steel as-sintered. Markforged samples were printed as fully dense parts with 100% infill. Hardness data were tested in-house, and all other data were tested and confirmed by outside sources. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.
# H13 Tool Steel

## Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>4.7-5.5%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.3-1.7%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.8-1.2%</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.8-1.2%</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.3-0.45%</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.2-0.5%</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>0.03% max</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.03% max</td>
</tr>
<tr>
<td>Iron</td>
<td>bal</td>
</tr>
</tbody>
</table>

## Typical Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Markforged As-Sintered</th>
<th>Markforged Heat Treated</th>
<th>Wrought Heat Treated*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>ASTM E8</td>
<td>1420 MPa</td>
<td>1500 MPa</td>
<td>1580 MPa</td>
</tr>
<tr>
<td>0.2% Yield Strength</td>
<td>ASTM E8</td>
<td>800 MPa</td>
<td>1250 MPa</td>
<td>1360 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>ASTM E8</td>
<td>5%</td>
<td>5%</td>
<td>14%</td>
</tr>
<tr>
<td>Hardness</td>
<td>ASTM E18</td>
<td>40 HRC</td>
<td>45 HRC</td>
<td>46 HRC</td>
</tr>
<tr>
<td>Relative Density</td>
<td>—</td>
<td>≥ 94.5%</td>
<td>≥ 94.5%</td>
<td>100%</td>
</tr>
</tbody>
</table>

*These data represent typical values for Markforged H13 Tool Steel as-sintered and after heat treatment. Values were tested in house, and both material composition and “As-Sintered” data were confirmed by outside testing. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.

*Wrought Heat Treated data included in table only. Data from ASM Specialty Handbook: Tool Materials page 140.
**MATERIAL - 17-4 PH Stainless Steel**

### Composion
<table>
<thead>
<tr>
<th>Element</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>15-17.5%</td>
</tr>
<tr>
<td>Nickel</td>
<td>3-5%</td>
</tr>
<tr>
<td>Copper</td>
<td>3-5%</td>
</tr>
<tr>
<td>Silicon</td>
<td>1% max</td>
</tr>
<tr>
<td>Manganese</td>
<td>1% max</td>
</tr>
<tr>
<td>Niobium</td>
<td>0.15-0.45%</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.07% max</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.04% max</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.03% max</td>
</tr>
<tr>
<td>Iron</td>
<td>bal</td>
</tr>
</tbody>
</table>

### Typical Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard ASTM E8</th>
<th>Markforged H900</th>
<th>MIM H900</th>
<th>ASTM A564 H900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>1250 MPa</td>
<td>1190 MPa</td>
<td>1170 MPa</td>
<td>1310 MPa</td>
</tr>
<tr>
<td>0.2% Yield Strength</td>
<td>1100 MPa</td>
<td>1090 MPa</td>
<td></td>
<td>1170 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>6%</td>
<td>6%</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>170 GPa</td>
<td>190 GPa</td>
<td>190 GPa</td>
<td></td>
</tr>
<tr>
<td>Hardness</td>
<td>36 HRC</td>
<td>33 HRC</td>
<td>40 HRC</td>
<td></td>
</tr>
<tr>
<td>Corrosion</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td></td>
</tr>
<tr>
<td>Relative Density</td>
<td>≥ 96%</td>
<td>95.5%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

All data and graphs on front page reflect values of H900 heat treated 17-4 PH SS. Markforged represent typical tested values, while MIM H900 and Wrought H900 represent typical reference values from MPIF Standard 35. For values of Markforged printed 17-4 PH SS as-sintered and with H1150 heat treatment, please see the reverse side. All composition and “As-Sintered” data verified by a third party test facility. All microstructure images etched and photographed at Markforged.
# 17-4 PH Stainless Steel

Values listed below compare Markforged samples processed in three different ways: As-Sintered, heat treated to H900 standard, and heat treated to H1150 standard.

<table>
<thead>
<tr>
<th>Typical Mechanical Properties</th>
<th>Standard</th>
<th>As Sintered</th>
<th>H900</th>
<th>H1150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>ASTM E8</td>
<td>1050 MPa</td>
<td>1250 MPa</td>
<td>950 MPa</td>
</tr>
<tr>
<td>0.2% Yield Strength</td>
<td>ASTM E8</td>
<td>800 MPa</td>
<td>1100 MPa</td>
<td>880 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>ASTM E8</td>
<td>5%</td>
<td>6%</td>
<td>10%</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>ASTM E8</td>
<td>140 GPa</td>
<td>170 GPa</td>
<td>170 GPa</td>
</tr>
<tr>
<td>Hardness</td>
<td>ASTM E18</td>
<td>30 HRC</td>
<td>36 HRC</td>
<td>32 HRC</td>
</tr>
<tr>
<td>Corrosion</td>
<td>ASTM F1089</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>Relative Density</td>
<td>—</td>
<td>≥ 96%</td>
<td>≥ 96%</td>
<td>≥ 96%</td>
</tr>
</tbody>
</table>

These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied, including, but not limited to, the warranties of merchantability, fitness for a particular use, or warranty against patent infringement; and assumes no liability in connection with the use of this information. The data listed here should not be used to establish design, quality control, or specification limits, and are not intended to substitute for your own testing to determine suitability for your particular application. Nothing in this sheet is to be construed as a license to operate under or a recommendation to infringe upon any intellectual property right.
Inconel 625 is a nickel-chromium based superalloy that is highly resistant to corrosion and high temperatures. It's easy to print, allowing you to make functional prototypes and end-use parts for harsh environments. Markforged Inconel 625 meets chemical requirements of ASTM B443.

**Composition**

<table>
<thead>
<tr>
<th>Composition</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>20-23%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>8-10%</td>
</tr>
<tr>
<td>Iron</td>
<td>5% max</td>
</tr>
<tr>
<td>Niobium</td>
<td>3.15-4.15%</td>
</tr>
<tr>
<td>Cobalt</td>
<td>1% max</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.5% max</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.5% max</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.4% max</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.4% max</td>
</tr>
<tr>
<td>Carbon</td>
<td>0.1% max</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.015% max</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.015% max</td>
</tr>
<tr>
<td>Nickel</td>
<td>bal</td>
</tr>
</tbody>
</table>

**Markforged Inconel 625 As-Sintered**

Inconel 625 printed on the Metal X, washed in the Wash-1, and sintered in the Sinter-1. As-Sintered microstructure captured at 100x is pictured to the right.

**Typical Mechanical Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Markforged As-Sintered</th>
<th>Wrought AMS 5599¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>ASTM E8</td>
<td>765 MPa</td>
<td>827 MPa</td>
</tr>
<tr>
<td>0.2% Yield Strength</td>
<td>ASTM E8</td>
<td>334 MPa</td>
<td>414 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>ASTM E8</td>
<td>42%</td>
<td>30%</td>
</tr>
<tr>
<td>Hardness</td>
<td>ASTM E18</td>
<td>7 HRC</td>
<td>0-19 HRC</td>
</tr>
<tr>
<td>Relative Density²</td>
<td>ASTM B923</td>
<td>96.5%</td>
<td>100%</td>
</tr>
</tbody>
</table>

1. Wrought AMS 5599 data represent minimum values, except for Hardness.
2. Relative density for Inconel 625 assumes a reference density of 8.44 g/cm³.

These data represent typical values for Markforged Inconel 625 as-sintered. Markforged samples were printed as fully dense parts with 100% infill. Hardness and density data were tested in house, and all other data were tested and confirmed by outside sources. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.
### D2 Tool Steel - Datasheet

Other Designations: DIN 12379, ASTM A681, UNS T30402, BD 2

D2 tool steel is a high carbon, high chromium air-hardening tool steel that can be heat treated to high hardness and compressive strength. D2 offers excellent wear resistance and is widely used in cold work applications that require sharp edges, abrasion resistance, and compressive strength. Markforged D2 meets chemical requirements of ASTM A681.

### Composition

<table>
<thead>
<tr>
<th>Element</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromium</td>
<td>11-13%</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.4-1.6%</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>0.7-1.2%</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.5-1.1%</td>
</tr>
<tr>
<td>Nickel + Copper</td>
<td>0.75% max</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.1-0.6%</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.1-0.6%</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.03% max</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.03% max</td>
</tr>
<tr>
<td>Iron</td>
<td>bal</td>
</tr>
</tbody>
</table>

### Typical Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Markforged As-Sintered</th>
<th>Markforged Heat-Treated</th>
<th>Wrought Heat Treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2% Compressive Yield Strength</td>
<td>ASTM E9</td>
<td>830 MPa</td>
<td>1690 MPa</td>
<td>2200 MPa</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>ASTM E9</td>
<td>170 GPa</td>
<td>187 GPa</td>
<td>210 GPa</td>
</tr>
<tr>
<td>Hardnessa</td>
<td>ASTM E18</td>
<td>54 HRC</td>
<td>60 HRC</td>
<td>62 HRC</td>
</tr>
<tr>
<td>Relative Density</td>
<td>ASTM B923</td>
<td>97%</td>
<td>97%</td>
<td>100%</td>
</tr>
</tbody>
</table>

### Heat Treatment

D2 tool steel can be heat-treated to increase hardness and durability after an optional annealing step and machining work. Markforged recommends heat-treating D2 tool steel to optimize material properties, though it can be used as-sintered.

1. Heat D2 Tool Steel part in a standard (non-vacuum) furnace to 1000°C (1830°F). Hold part at temperature for 30-45 minutes.
2. Air quench part to below 65°C (150 °F).
3. Temper D2 Tool Steel part in a standard furnace. For each temper, heat part to 200°C (392°F) and temper for 30 minutes. If double tempering, let part cool to room temperature between tempers.

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1. Markforged heat-treated D2 tool steel was heated to 970°C (1780°F) and single tempered at 200°C (392°F) for 30 minutes.
3. Markforged hardness was measured on a sample coupon that was printed at 100% infill and has a 25 mm diameter and 10 mm height.
4. Relative density for D2 assumes a density of 7.7 g/cm³.
5. Tempering temperature has a significant effect on final material properties. For higher hardness, temper at low temperatures. For higher toughness, temper at higher temperatures.

These data represent typical values for Markforged D2 Tool Steel as-sintered. Markforged samples were printed as fully dense parts with 100% infill. Hardness and density data were tested in house, and all other data were tested and confirmed by outside sources. These representative data were tested, measured, or calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.
Copper is a soft, ductile metal used primarily for its electrical and thermal conductivity. Copper’s high conductivity makes it an ideal material for many heat sinks and heat exchangers, power distribution components such as bus bars, manufacturing equipment including spot welding shanks, antennae for RF communications, and more. The ability to print pure copper using Metal X enables geometrically optimized parts that were previously expensive, time consuming, or impossible to make.

### Composition

<table>
<thead>
<tr>
<th></th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>99.8% min</td>
</tr>
<tr>
<td>Oxygen</td>
<td>0.05% max</td>
</tr>
<tr>
<td>Iron</td>
<td>0.05% max</td>
</tr>
<tr>
<td>Other</td>
<td>bal</td>
</tr>
</tbody>
</table>

### Typical Mechanical Properties

<table>
<thead>
<tr>
<th></th>
<th>Standard</th>
<th>Temp</th>
<th>As-Sintered</th>
<th>MIM Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
<td>ASTM E8</td>
<td>Room Temp</td>
<td>193 MPa¹</td>
<td>207 MPa</td>
</tr>
<tr>
<td>0.2% Tensile Yield Strength</td>
<td>ASTM E8</td>
<td>Room Temp</td>
<td>26 MPa¹</td>
<td>69 MPa</td>
</tr>
<tr>
<td>Elongation at Break</td>
<td>ASTM E8</td>
<td>Room Temp</td>
<td>45%¹</td>
<td>30%</td>
</tr>
<tr>
<td>Relative Density</td>
<td>ASTM B923</td>
<td>Room Temp</td>
<td>98%²</td>
<td>98%</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>ASTM E1004</td>
<td>Room Temp</td>
<td>84% IACS³</td>
<td>—</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>ASTM E1461</td>
<td>Room Temp</td>
<td>350 W/mK⁴</td>
<td>328 W/mK</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>ASTM E831-19⁵</td>
<td>68-100°F</td>
<td>9.6 x 10⁻⁶/°F</td>
<td>8.7 x 10⁻⁶/°F</td>
</tr>
<tr>
<td></td>
<td>ASTM E8228</td>
<td>68-150°F</td>
<td>9.7 x 10⁻⁶/°F</td>
<td>8.9 x 10⁻⁶/°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68-200°F</td>
<td>9.8 x 10⁻⁶/°F</td>
<td>9.1 x 10⁻⁶/°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68-250°F</td>
<td>9.9 x 10⁻⁶/°F</td>
<td>9.3 x 10⁻⁶/°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68-300°F</td>
<td>10.0 x 10⁻⁶/°F</td>
<td>9.4 x 10⁻⁶/°F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68-500°F</td>
<td>10.1 x 10⁻⁶/°F</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>68-750°F</td>
<td>10.5 x 10⁻⁶/°F</td>
<td>—</td>
</tr>
</tbody>
</table>
1. Tensile bars are sub-sized and are sliced with default copper settings except raft is turned off. Copper defaults to solid parts.
2. Density is based on a theoretical value of 8.96g/cc.
3. Electrical conductivity, when evaluated with eddy current instruments, is usually expressed as a percentage of the conductivity of the International Annealed Copper Standard (% IACS). The conductivity of the Annealed Copper Standard is defined to be $0.58 \times 10^8$ S/m (100 % IACS) at 20°C.
4. Thermal diffusivity measured per ASTM E1461. Diffusivity was converted to Conductivity using:
   \[ \text{Thermal Conductivity} = \text{Thermal Diffusivity} \times \text{Density} \times \text{Specific Heat} \]
   Asssuming specific heat of Copper = 0.385 J/g-K per “Handbook of Chemistry and Physics 72nd Edition.”
5. Markforged as-sintered Coefficient of Thermal Expansion (CTE) was measured by a 3rd party lab using Thermal Mechanical Analysis (ASTM E831). The MIM handbook reference used a Push Rod Dilatometer (ASTM E228).

This data represents typical values for Markforged Copper as-sintered. Markforged samples were printed with Solid Infill setting. All values based on 3rd party testing except for relative density which was tested by Markforged. These representative data were tested, measured, and calculated using standard methods and are subject to change without notice. Markforged makes no warranties of any kind, express or implied.